

UC San Diego

Fish Bulletin

Title

Fish Bulletin 179. Contributions to the Biology of Central Valley Salmonids. Volumes 1 & 2.

Permalink

<https://escholarship.org/uc/item/6sd4z5b2>

Author

Brown, Randall L

Publication Date

2001-09-01

State of California
The Resources Agency
Department of Fish and Game

FISH BULLETIN 179

CONTRIBUTIONS TO THE BIOLOGY OF CENTRAL VALLEY SALMONIDS

VOLUME 1

Edited by

Randall L. Brown
Department of Water Resources
Sacramento, California



2001

This bulletin is not copyrighted. If reproduced elsewhere, such as by photocopying, the authors, editor, and the DFG would appreciate receiving an appropriate acknowledgment.

The free mailing list is on an exchange basis and is limited by budgetary considerations to libraries, scientific institutions, and conservation agencies. Individuals may obtain copies of this bulletin by submitting a check or money order in the amount of \$25 per copy (includes sales tax and shipping cost) made out to the California Department of Fish and Game and mailing it to:

Department of Fish and Game
Fiscal and Administrative Services
1416 Ninth Street, 12th Floor
Sacramento, California 95814
Telephone: (916) 653-6281
Fax: (916) 653-4645

State of California
The Resources Agency
Department of Fish and Game

FISH BULLETIN 179

CONTRIBUTIONS TO THE BIOLOGY OF CENTRAL VALLEY SALMONIDS

VOLUME 1

Edited by

Randall L. Brown
Department of Water Resources
Sacramento, California



2001

Contents

| | |
|--|-------------|
| Preface | v |
| Dedication | vii |
| In Appreciation | xi |
| Acknowledgements | xiii |
| Foreword | xv |
| Contributing Authors | xvii |
| | |
| Central Valley Steelhead | 1 |
| <i>Dennis R. McEwan</i> | |
| | |
| Applications of Population Genetics to Conservation of Chinook Salmon Diversity in the Central Valley | 45 |
| <i>D. Hedgecock, M.A. Banks, V.K. Rashbrook, C.A. Dean, and S.M. Blankenship</i> | |
| | |
| Historical and Present Distribution of Chinook Salmon in the Central Valley Drainage of California | 71 |
| <i>Ronald M. Yoshiyama, Eric R. Gerstung, Frank W. Fisher, and Peter B. Moyle</i> | |
| | |
| Shasta Salmon Salvage Efforts: Coleman National Fish Hatchery on Battle Creek, 1895–1992 | 177 |
| <i>Michael Black</i> | |
| | |
| Factors Affecting Chinook Salmon Spawning in the Lower Feather River | 269 |
| <i>Ted Sommer, Debbie McEwan, and Randall Brown</i> | |

Preface

The Salmonid Symposium was organized by an ad hoc committee of state and federal fishery biologists concerned with the management of Central Valley (CV) salmon and steelhead trout (*Oncorhynchus* spp.) populations and their habitats. It was held at Bodega Bay, California on October 22–24, 1997. Topics covered included research on various CV salmon and steelhead populations, ocean fishery management, history of upper Sacramento River hatchery operations, and steelhead management policy.

Any statements or views expressed in these materials are those of the authors and do not necessarily represent those of the California Department of Fish and Game (DFG), which takes no responsibility for any statements or views made herein. No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by the DFG. The materials are for general information only and do not represent a standard of the DFG, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. The DFG makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

Dedication

Fish Bulletin 179 is dedicated to the memory of Nat Bingham. Zeke Grader penned the text, but the feelings and inspiration come from the California community of fishermen, salmon biologists and managers.

It was about 10 years ago, the news had just come out that only 191 winter-run chinook had returned to the Sacramento River that year, when, in a call, Nat said something to the effect: “We’ve got to do something. This run will not go extinct on our watch.” With that pronouncement, he set in motion a whirlwind of activity that, although we weren’t certain in what direction, determined this magnificent run of salmon, spawning in the tributaries of the Upper Sacramento in the heat of the summer, those fish Livingston Stone chronicled more than a century before, would not be lost.

The campaign to save the winter-run began, and the eventual captive broodstock program and all of the products of that effort, was much like FDR’s approach to the depression. That is, try something, do something, but just don’t sit there. Nat Bingham, an ardent student of history may well have thought of that. Nat was going to do something. Initially, he considered a pen-rearing program at the National Marine Fisheries Service’s Tiburon Laboratory, but after gathering the agencies and scientists together an alternate plan began to evolve. The fact that his original concept was rejected didn’t bother him. He cared more that an action plan to save the run was now in motion.

Nat also knew that to save fish—again, as a student of history—the battle had to be engaged on many fronts. A captive broodstock program might prevent extinction of the winter-run, but action had to be taken to correct the problems that had led to the drastic decline of these fish. In a score of years the number of spawners had plummeted from almost 120,000 to less than 200. Litigation, lobbying Congress, cajoling farmers and water districts became Nat’s almost daily activity until he died.

Nat had come from a famous old Connecticut family and started commercial fishing in the Bahamas as a teenager. He arrived in Berkeley in the sixties and shortly after that began commercial fishing salmon and albacore out of the East Bay. A few years later he ended up on California’s north coast where, as a salmon troller, he began to take an interest in the factors affecting salmon productivity. He familiarized himself with the watersheds and the streams and was soon working with groups such as the Salmon Unlimited and the Salmon Trollers Marketing Association. He helped install and operate hatch box programs aimed at jump-starting runs that had nearly been extirpated from damage to the watershed. He saw first hand that logging, road building and a host

of other land use activities were decimating the runs. Unlike most of his contemporaries, he would speak out. And, he railed against what he described as the “code of silence” among those in fisheries who would not actively defend the fish. “No more silence” was his mantra.

Outspoken yes, but Nat was also a gentle person who did not see those across the table as enemies but merely people who needed to be educated about the fish, who needed to understand what the fish needed. He never personalized a fight. He was never anti-logging, anti-grazing, anti-farming, or anti-urban water usage, he was just pro-fish. He never saw winning for the fish as defeating someone else. He was the practitioner of what many now call “win-win.”

He was also tireless. In the early 1980s, at the height of an El Nino, he took over as president of a beleaguered Pacific Coast Federation of Fishermen’s Associations (PCFFA), a more or less coastwide umbrella group of family-based fishing organizations. Ocean conditions associated with El Nino had devastated salmon production and left the group’s coffers nearly empty. Over the next decade he found himself fishing less and spending more time helping with the organization and working on battles to save salmon from the Central Valley to the Columbia. He worked with tribes and ranchers in the Klamath Basin and with the timber industry in coastal watersheds—always trying to save, to rebuild salmon runs. He built alliances with conservation organizations and he looked for opportunities to work with those generally considered his adversaries—from timber industry executives, to power companies, to heads of agricultural and urban water districts. There were few meetings on salmon where Nat was not present.

In the early 1990s seeing no end to the fight for salmon survival, Nat decided to step down as President of PCFFA, a job he could very well have held for life, to sell his boat and dedicate himself exclusively to efforts to restore salmon habitat and rebuild the runs. PCFFA was able to cobble some monies together from government and private foundation contracts and grants and put Nat on the road. For the next seven years his beat-up Toyota pickup, held together it seems by bumper stickers, could be seen up and down the Central Valley, in the Sierra or the Trinity or in some coastal watershed. Nat the salmon disciple, the crusader would be working patiently and in his quiet way to convince people to do things differently so salmon could not only survive, but thrive.

In the spring of 1998, things were looking up for Nat. Quietly working behind the scenes he was able in six-month’s time to help establish a winter chinook conservation hatchery on the mainstem of the Sacramento, just below Shasta Dam. Nat called it the Livingston Stone Hatchery, a name that has stuck. Moreover, negotiations with Pacific Gas & Electric were progressing for the removal of dams on Battle Creek to establish an additional “homestream” for

the winter run. But it was also a tiring period, the Pacific Fishery Management Council meetings (to which Nat was appointed to a few years before) were particularly arduous. At the end of the April Council meeting Nat's wife Kathy was diagnosed with terminal cancer and by the end of the month she was gone. Nat kept his spirits up, but he was exhausted physically and mentally and within a week of Kathy's death, he was gone too.

Nat's life is the stuff of a great book. The important thing, however, for those of us left working for the survival of the salmon to remember what he did and how he did it—and, how he lived his life. With Nat's life as our inspiration, we will win.

Zeke Grader

In Appreciation

With the release of this Fish Bulletin, we extend our appreciation and those of our fellow biologists to its editor, Dr. Randall L. Brown. As local readers are aware, Randy retired last year from State service where he was employed for over 34 years by the California Department of Water Resources.

He will be forever remembered for his great devotion to improving our understanding of salmon biology in the Central Valley and San Francisco Bay-Delta Estuary of California. Randy's professionalism, support, encouragement and friendship to all of us in the salmon community is greatly respected and appreciated. His tireless efforts to enhance salmon monitoring and research as a coordinator in the Interagency Ecological Program, Chief Biologist for the Department, member of numerous committees related to salmon and their management, and as a leader in conducting multiple workshops, meetings, conferences, and symposiums on salmon has greatly improved our knowledge of salmon. Our progress in the area of salmon population genetics, salmon-hydrodynamics interactions, monitoring and evaluation techniques, population dynamics, data management and other fields are directly related to his personal efforts and accomplishments.

We join together to thank Randy as a friend and colleague for his excellent work and wish him the best in his retirement and all future endeavors.

Marty Kjelson
Terry J. Mills

Acknowledgements

Pulling this volume together would not have been possible without the support of Marty Kjelson and Terry Mills. We first discussed the concept over Chinese food a year or so before the Bodega meeting. Periodic meetings before and after Bodega kept me on track – to the extent that is possible.

Special thanks to the symposium presenters for converting their talks to papers. Joe Miyamoto of the East Bay Municipal Utility District receives the award for being, by far, the first to submit a manuscript.

I would also like to acknowledge several authors who did not present papers at Bodega but who were willing to contribute material to help make this a more balanced compendium.

Several anonymous peer reviewers took their valuable time to review the articles and their comments made for a better product.

L.B. Boydstun, of the California Department of Fish and Game, deserves recognition for allowing us to use the Department's Fish Bulletin series and to serve as the DFG sponsor. This is in keeping with L.B.'s long history of working with his agency, NMFS and the commercial and recreational fishing industry to scientifically manage a resource of special significance to California.

Finally, we should all thank Lauren Buffaloe (DWR) for a tremendous job of editing and formatting the articles and to Barbara McDonnell (DWR) and Sam Luoma (CALFED) for funding publication of the Fish Bulletin.

Randall L. Brown

Foreword

The impetus for publication of this Fish Bulletin came from conversations among several biologists working on salmonid issues in the Central Valley and the Sacramento-San Joaquin Estuary. These discussions centered on the idea that more information being developed about these economically, environmentally, and aesthetically important species needed to be available in the open literature. Marty Kjelson, Terry Mills and I developed the concept of a symposium followed by published proceedings. The Interagency Ecological Program's Central Valley Salmonid Team endorsed the concept and a successful symposium was held at the Bodega Marine Laboratory in October 1997.

Originally Marty and Terry agreed to co-edit the proceedings. Due to the press of other work, they were unable to take on much of the day-to-day work on the volume but did provide guidance and suggestions for ways to move the publication from concept to reality. I take responsibility for the final selection of papers and the final technical editing of the papers.

As you will find, I selected papers with varied writing styles. Some papers, such as the ones by Yoshiyama and others and by Black, are longer than would be typically found in journals. I believe they make a significant contribution to our understanding and decided to publish them without major revision. Others are more succinct and could be published in the open literature.

Those readers that attended the Bodega symposium will find that not all the papers presented have been included in this volume and that papers not presented are included. Several of the presenters were unable to find the time to prepare a manuscript. On the other hand, other authors had information of interest. The blend seemed to make the best sense in view of the objective of making a wide variety of information available to salmonid biologists and managers.

This volume also includes some material that could be considered duplicative in that two different papers may discuss the same question—for example, through-Delta survival of juvenile salmonids. I included these papers to provide different perspectives on important questions. I ask the reader to consider the papers, and the data, and reach his or her conclusions as to the interpretations. As with most difficult environmental issues, one must carefully consider all the available data before deciding to accept or reject a hypothesis.

I do recommend that you consider recommendations, made specifically by L.B. Boydstun, Peter Baker, Emil Morhardt, Wim Kimmerer and others, and John Williams about the need to (1) better coordinate salmonid related work in the Valley, the estuary and the ocean; (2) focus more on collecting and analyzing data that can be used to validate conceptual and mechanistic models; and (3) make the information more readily available in the open literature. Along those lines I suggest that symposium such as this be held every two to three years, including publication of the proceedings. Authors should not stop with publication in proceedings but should also publish in appropriate journals. Hopefully the next symposium will have more than one paper dealing with steelhead.

Randall L. Brown
Fair Oaks, California
September 1, 2001

Contributing Authors

Kristen D. Arkush
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Peter F. Baker
Stillwater Ecosystem, Watershed and
Riverine Sciences
2532 Durant Avenue
Berkeley, CA 94577

Michael A. Banks
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Michael Black
756 20th Avenue
San Francisco, CA 94121

Scott M. Blankenship
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

L.B. Boydston
California Department of Fish and Game
1416 Ninth Street
Sacramento, CA 95814

Patricia L. Brandes
U.S. Fish and Wildlife Service
4001 N. Wilson Way
Stockton, CA 95205

Larry R. Brown
5083 Veranda Terrace
Davis, CA 95616

Randall L. Brown
4258 Brookhill Drive
Fair Oaks, CA 95628

Cheryl A. Dean
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Frank W. Fisher
California Dept. of Fish and Game, retired
Inland Fisheries Division
2440 N. Main Street
Red Bluff, CA 96080

Tim Ford
Turlock Irrigation District
P.O. Box 949
Turlock, CA 95380

Eric R. Gerstung
California Dept. of Fish and Game
Native Anadromous Fish and
Watershed Branch
1807 13th Street, Suite 104
Sacramento, CA 95814

Andy Hamilton
U.S. Fish and Wildlife Service
2800 Cottage Way, W-2605
Sacramento, CA 95825

Charles H. Hanson
Hanson Environmental, Inc.
132 Cottage Lane
Walnut Creek, CA 94595

Dennis Hedgecock
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Janna R. Herren
California Dept. of Fish and Game
Sacramento Valley Central Sierra Region,
Environmental Services
1701 Nimbus Road
Rancho Cordova, CA 95670-4599

Spencer S. Kawasaki
formerly with the California Dept. of
Fish and Game
Sacramento Valley Central Sierra Region
8169 Alpine Avenue, Suite B
Sacramento, CA 95826

Wim Kimmerer
Romberg Tiburon Center
San Francisco State University
P.O. Box 855, 3152 Paradise Drive
Tiburon, CA 94920

Dennis R. McEwan
California Department of Fish and Game
Native Anadromous Fish and
Watershed Branch
1807 13th Street, Suite 104
Sacramento, CA 95814

Debbie McEwan
California Dept. of Transportation
Environmental Program
1120 N Street, Room 4301, MS27
Sacramento, CA 95814

Jeffrey S. McLain
U.S. Fish and Wildlife Service
4001 N. Wilson Way
Stockton, CA 95205

Carl Mesick
Carl Mesick Consultants
7981 Crystal Boulevard
El Dorado, CA 95623

Bill Mitchell
Jones and Stokes Associates
2600 V Street, Suite 100
Sacramento, CA 95818-1914

Joseph J. Miyamoto
East Bay Municipal Utility District
500 San Pablo Dam Road
Orinda, CA 94563

J. Emil Morhardt
Claremont McKenna College
925 N. Mills Avenue
Claremont, CA 91711-5916

Peter B. Moyle
University of California, Davis
One Shields Avenue
Davis, CA 95616-8751

Vanessa K. Rashbrook
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Paul A. Siri
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Ted Sommer
California Dept. of Water Resources
Environmental Services Office
3251 S Street
Sacramento, CA 95816-7017

John G. Williams
Environmental Hydrology, Inc.
875 Linden Lane
Davis, CA 95616

Ronald M. Yoshiyama
University of California, Davis
One Shields Avenue
Davis, CA 95616-8751

Central Valley Steelhead

Dennis R. McEwan

Abstract

Before extensive habitat modification of the 19th and 20th centuries, steelhead (*Oncorhynchus mykiss*) were broadly distributed throughout the Sacramento and San Joaquin drainages. Historical run size is difficult to estimate given the paucity of data, but may have approached 1 to 2 million adults annually. By the early 1960s run size had declined to about 40,000 adults. Natural spawning populations currently exist in the Sacramento and San Joaquin river systems but at much lower levels. Coastal rainbow trout populations can be polymorphic in their life-history, and progeny of one life-history form can assume a life-history strategy different from that of their parents. A polymorphic population structure may be necessary for the long-term persistence in highly variable environments such as the Central Valley. Despite the substantial introduction of exotic stocks for hatchery production, native Central Valley steelhead may have maintained some degree of genetic integrity. Primary stressors affecting Central Valley steelhead are all related to water development and water management, and the single greatest stressor is the substantial loss of spawning and rearing habitat due to dam construction. Central Valley anadromous fish management and research is primarily focused on chinook salmon (*Oncorhynchus tshawytscha*) and has led to less emphasis on steelhead monitoring and restoration. Much of the information on historical abundance and stock characteristics that exists for Central Valley steelhead is derived from an intensive DFG research program in the 1950s. Since this time there has been relatively little research directed at steelhead in the Central Valley, and efforts to restore Central Valley steelhead have been greatly hampered by lack of information. The National Marine Fisheries Service cited the ongoing conservation efforts of the Central Valley Project Improvement Act (CVPIA) and CALFED as justification for listing Central Valley steelhead as a threatened species under the Endangered Species Act, rather than endangered as proposed. Restoration actions identified in these programs are largely directed at chinook salmon recovery with comparatively little emphasis on specific actions needed to recover steelhead, or have not yet been implemented. The structure of rainbow trout populations has important management implications that can only be addressed through an integrated management strategy that treats all life-history forms occupying a stream as a single population. However, management

agencies have generally failed to recognize this, as exemplified by the federal government's decision to exclude the non-anadromous forms in the ESA listing for steelhead, despite their recognition that they are important to the persistence of the anadromous forms. Steelhead need to be managed separately from chinook salmon stocks if recovery is to be successful, and recovery strategies must include measures to protect and restore the ecological linkages between the different life-history forms and measures to restore steelhead to some of their former habitat.

Introduction

Steelhead are the anadromous form of rainbow trout¹ (*Oncorhynchus mykiss*), a salmonid species indigenous to western North America and the Pacific coast of Asia. Recognized as a prized and sought-after game fish, steelhead are also highly regarded as a quality-of-life indicator among the non-angling public. The California Department of Fish and Game (DFG), the U.S. Fish and Wildlife Service (USFWS), and the National Marine Fisheries Service (NMFS) all assert some form of management authority over rainbow trout populations.

In this paper I discuss important aspects of steelhead ecology and population biology that have direct bearing on management effectiveness (and ineffectiveness), historical abundance and current status of Central Valley steelhead, factors that are responsible for their decline, and assessment of current monitoring and research efforts. I conclude with a description of current management and recovery efforts, a discussion of the dominant paradigm of Central Valley steelhead management and associated problems, and what I believe to be necessary if recovery is to be successful.

-
1. The terms "rainbow trout" and "resident rainbow trout" are often used to identify non-anadromous forms of *O. mykiss*. This convention is confusing and technically inaccurate because "rainbow trout" is the common name of the biological species *O. mykiss*, and the term "resident," used in this sense, ignores other, non-anadromous life-history forms and migratory behaviors. In this document, the term "rainbow trout" refers to the biological species *O. mykiss* regardless of life history, and the different life-history forms are referred to as anadromous (or steelhead), potamodromous, or resident, depending on their migratory behavior (or lack thereof in the case of residents). The term "non-anadromous" is used to refer collectively to all life-history types other than anadromous.

Biology and Status

Ecology, Life-History, and Structure of Rainbow Trout Populations

In North America, steelhead are found in Pacific Ocean drainages from southern California to Alaska. In Asia, they are found in coastal streams of the Kamchatka Peninsula, with scattered populations on the mainland (Burgner and others 1992) (Figure 1). In California, spawning populations are known to occur in coastal streams from Malibu Creek in Los Angeles County² to the Smith River near the Oregon border, and in the Sacramento and San Joaquin river systems. The present distribution and abundance of steelhead in California have been greatly reduced from historical levels (McEwan and Jackson 1996; Mills and others 1997).

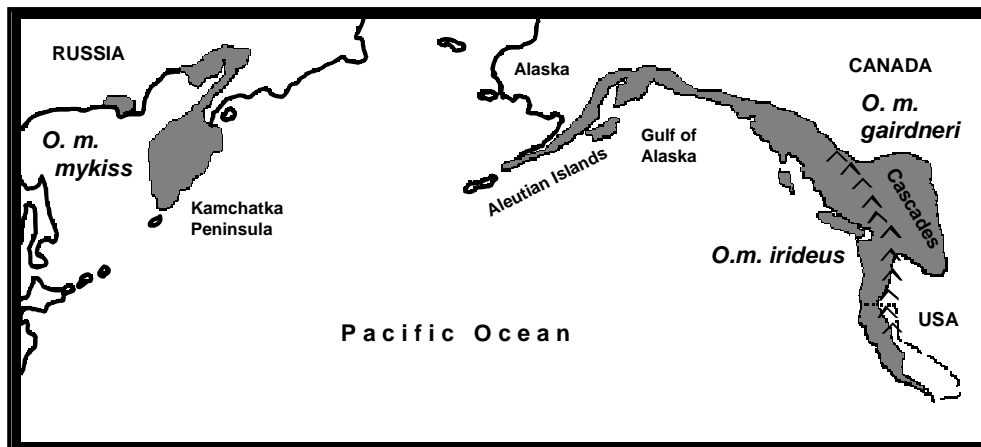


Figure 1 Endemic distribution of steelhead rainbow trout, *Oncorhynchus mykiss*. Modified from Burgner and others 1992.

2. The southernmost extent of steelhead distribution in North America is often reported as Malibu Creek because a known, persistent spawning population has been documented (McEwan and Jackson 1996; NMFS 1996a). However, streams south of Malibu Creek (for example, San Mateo Creek in San Diego County) appear to support at least occasional spawning and production (DFG 2000a) and most other streams are not adequately monitored to determine if steelhead are present. Thus, it is more correct to state that Malibu Creek is the known southern extent of persistent populations in North America.

Steelhead are similar to some Pacific salmon species in their ecological requirements. They are born in fresh water, emigrate to the ocean where most of their growth occurs, and return to fresh water to spawn. Unlike Pacific salmon, steelhead are iteroparous. Repeat spawning rates are generally low, however, and vary considerably among populations.

In California, peak spawning occurs from December through April in small streams and tributaries with cool, well-oxygenated water. The length of time it takes for eggs to hatch depends mostly on water temperature. Steelhead eggs hatch in about 30 days at 51°F (Leitritz and Lewis 1980). Fry usually emerge from the gravel four to six weeks after hatching, but factors such as redd depth, gravel size, siltation, and temperature can speed or retard this time (Shapovalov and Taft 1954).

The newly-emerged fry move to the shallow, protected areas associated with the stream margin (Royal 1972; Barnhart 1986) where they establish feeding stations (Fausch 1984) that they defend (Shapovalov and Taft 1954). Juveniles mainly inhabit riffles (Barnhart 1986) but they can use a variety of other habitat types (DFG Stream Evaluation Program, unpublished data). Relatively high concentrations occur in association with structural complexity, such as that provided by large woody debris (DFG Stream Evaluation Program, unpublished data). Juveniles also exhibit a significant movement to sites with overhead cover (Fausch 1993) and appear to select positions in streams in response to low light levels (Shirvell 1990). For juvenile steelhead, sites with light levels below a certain threshold, velocity refuges, and adjacent high velocity flows provide an optimal combination of safety from predators and aggressive conspecifics, as well as access to drifting invertebrate food resources.

The optimum water depth for steelhead spawning is approximately 14 inches and ranges from about 6 to 36 inches (Bovee 1978). Fry typically use water approximately 8 inches in depth and can use water 2 to 32 inches deep, while older juveniles typically use a water depth of about 15 inches but can use water 2 to 60 inches deep (Bovee 1978). In natural channels, water depth usually does not hinder adult migration because adult steelhead normally migrate during high flows. Depth can become a significant barrier or impediment in streams that have been altered for flood control purposes, especially those that do not have a low flow channel. It has been reported that seven inches is the minimum depth required for successful migration of adult steelhead (Thompson 1972, as cited in Barnhart 1986), although the distance fish must travel through shallow water areas is also a critical factor. Excessive water velocity and obstacles that impede swimming and jumping ability are more significant in hindering or blocking migration (Barnhart 1986).

Steelhead spawn in areas with water velocities ranging from 1 to 3.6 ft/s but most often in velocities of about 2 ft/s (Bovee 1978). The ability to spawn in higher velocities is a function of size: larger steelhead can establish redds and spawn in faster currents than smaller steelhead (Barnhart 1986). Steelhead have been reported to spawn in substrates from 0.2 to 4.0 inches in diameter (Reiser and Bjornn 1979). Based on the Bovee (1978) classification, steelhead use mostly gravel-sized material for spawning but will also use mixtures of sand-gravel and gravel-cobble. The gravel must be highly permeable to keep the incubating eggs well oxygenated.

Water temperature requirements for various life stages of steelhead have been studied (Bovee 1978; Reiser and Bjornn 1979; Bell 1986), although there are relatively little data specific to California (Myrick 1998). Egg mortality begins to occur at 56°F (Hooper 1973, as cited in Barnhart 1986), thermal stress has been reported at temperatures beginning at 66°F, and temperatures demonstrated to be lethal to adults have been reported at 70°F (Rich 2000). In California, low temperatures are not as much of a concern as high temperatures, particularly during adult migration, egg incubation, and juvenile rearing. The ability of steelhead to tolerate adverse temperatures varies depending on physiological conditions such as life stage, stock characteristics, and ecological conditions such as acclimation time, food availability, and access to cold water refugia within the stream (Nielsen and others 1994; Myrick 1998). Thus, determination of suitable temperature targets in regulated rivers is often a complex issue.

It should be noted that the preceding descriptions of habitat criteria are presented mainly as rough guidelines as determined by steelhead researchers on specific streams or under laboratory conditions. Often, temperature targets are established or proposed on regulated rivers based on laboratory studies that focus on temperature maxima that cause lethal and sublethal effects. Effects on growth rates, long-term survival, increased predation rate, and ecology usually are not addressed in these studies. Also, experimental work under controlled laboratory conditions does not take into account ecological conditions that may affect thermal tolerances, such as predation risk, inter- and intraspecific competition, and flow characteristics (Moyle and Baltz 1985, as cited in Myrick 1998). Because laboratory studies cannot approximate the complex conditions found in natural environments, water temperature requirements for steelhead in the wild are often subject to considerable debate, due primarily to misapplication and misinterpretation of thermal physiology studies and lack of standardization of methodologies (Rich 2000).

As noted above, steelhead in California exhibit life-history characteristics that are generally similar to Pacific salmon but there are some major differences: juvenile steelhead typically rear in freshwater for a longer period (usually from one to three years) and both adults and juveniles are more variable in the

amount of time they spend in fresh and salt water. Throughout their range, steelhead typically remain at sea for one to four growing seasons before returning to fresh water to spawn (Burgner and others 1992). Boydstun (1977) found that most Gualala River steelhead migrated to sea as two-year old fish and returned after spending two years in the ocean. In Scott and Waddell creeks, the majority of adults returning to the stream to spawn had spent two years in fresh water and one or two years in the ocean. However, steelhead from these streams occasionally exhibited other life-history patterns: scale analysis of adults indicated that they spent from one to four years in fresh water and from one to three years in the ocean (Shapovalov and Taft 1954).

Steelhead have traditionally been grouped into seasonal runs according to their peak migration period: in California there are well-defined winter, spring, and fall runs. This classification is useful in describing actual run timing but is misleading when it is used to further categorize steelhead. Seasonal classification does not reflect stock characteristics, spawning strategies, and run overlap between summer and winter steelhead. Run timing is a characteristic of a particular stock, but, by itself, does not constitute race or ecotype.

There are two steelhead ecotypes: stream-maturing steelhead, which enter fresh water with immature gonads and consequently must spend several months in the stream before they are ready to spawn; and ocean-maturing steelhead, which mature in the ocean and spawn relatively soon after entry into fresh water. This corresponds to the accepted classification that groups steelhead into two seasonal "races": summer and winter steelhead (Withler 1966; Royal 1972; Roelofs 1983; Barnhart 1986; Burgner and others 1992). Stream-maturing steelhead (summer steelhead) typically enter fresh water in spring, early summer, and fall. They ascend to headwater tributaries, hold over in deep pools until mature, and spawn in winter. Ocean-maturing steelhead (winter steelhead) typically begin their spawning migration in fall, winter, and spring and spawn relatively soon after freshwater entry. Ocean-maturing steelhead generally spawn January through March, but spawning can extend into spring and possibly early summer months. Before the intensive water development of this century and the resultant loss of a considerable amount of holding habitat, summer steelhead were probably more common in California than they are today. At present, summer steelhead are found only in north coast drainages, mostly in tributaries of the Eel, Klamath, and Trinity river systems. Winter steelhead are also present in north coast drainages, and are also found in the Central Valley and central and south coast drainages.

The above classification scheme is based on behavioral and physiological differences and may not reflect genetic or taxonomic relationships (Allendorf 1975; Allendorf and Utter 1979; Behnke 1992). Genetic similarity appears to be mostly a reflection of geographical relationships. For example, summer steel-

head occupying a particular river system are more genetically similar to winter steelhead of that system than they are to summer steelhead in other systems. Allendorf (1975) found that summer steelhead from several coastal streams in Washington were genetically indistinguishable from coastal winter steelhead of the same streams, but showed no genetic affinities with inland (upper Columbia River) summer steelhead.

Rainbow trout have also been classified on the basis of life history. Steelhead and non-anadromous rainbow trout were classified as two different subspecies and even different species by early researchers (Jordan and Gilbert 1882; see Allendorf 1975, Behnke 1992). However, little or no morphological or genetic differentiation has been found between anadromous and non-anadromous forms inhabiting the same stream system (Behnke 1972; Allendorf 1975; Allendorf and Utter 1979; Busby and others 1993; Nielsen 1994). Anadromous and non-anadromous rainbow trout apparently did not arise from two distinct evolutionary lines (Behnke 1992), rather, the different forms reflect the phenotypic plasticity of the species.

Behnke (1972), Allendorf (1975), Allendorf and Utter (1979), and Wilson and others (1985) conclude that rainbow trout cannot be separated taxonomically by immigration timing and status of gonadal maturity (summer vs. winter steelhead) or their tendency for anadromy (steelhead vs. non-anadromous forms). Rather, rainbow trout are taxonomically structured on a geographic basis (coastal vs. inland forms). Similarly, Behnke (1992) identifies three subspecies of rainbow trout that have anadromous life-history forms: coastal rainbow trout (*O. m. irideus*), Columbia River redband trout (*O. m. gairdneri*), and *mikizha* or Kamchatka rainbow trout (*O. m. mykiss*). All steelhead life-history forms of *O. m. gairdneri* are summer steelhead (Behnke 1992; Burgner and others 1992) and occupy upper Columbia River tributaries east of the Cascades. *Oncorhynchus m. mykiss* is found in streams along the west coast of the Kamchatka peninsula of Russia. *Oncorhynchus m. irideus* is distributed along coastal rivers and streams from California to Alaska and consists of both summer and winter steelhead (Figure 1). All steelhead in California are *O. m. irideus* (Behnke 1992).

The present taxonomic classification recognizes the extreme polymorphism that occurs among rainbow trout populations (Behnke 1992). Rather than the different life-history forms comprising distinct taxa or populations, studies and observations indicate that coastal rainbow trout can form a single, panmictic population in streams systems where there is access to the ocean. These populations are comprised of individuals with different life-history traits and a continuum of migratory behaviors, the two extremes being anadromy (strongly migratory) and residency (non-migratory). Within these extremes are potamodromous, and possibly estuarine and coastal (weakly anadromous) forms that are typical of coastal cutthroat trout (*O. clarki*) populations

(Northcote 1997). This type of population structure has been observed in Kamchatka rainbow trout populations in several rivers in western Kamchatka, where steelhead, coastal, and riverine (potamodromous and resident) life-history polymorphisms have been identified, and appear to form a single interbreeding population within each river system (Savvaitova and others 1973, 1997). Mature male parr have been observed spawning with female steelhead in California streams (Shapovalov and Taft 1954; DFG Stream Evaluation Program, unpublished data). Lack of genetic differences provides additional evidence that anadromous and non-anadromous life-history types can form a single interbreeding population within the anadromous reaches of a stream system.

In trout populations that have anadromous life-history forms, it is not uncommon for males to assume a non-anadromous life history and mature in fresh water as parr (see Thorpe 1987; Titus and others forthcoming), or for progeny of one life-history form to assume a life-history strategy that differs from their parents. On the Santa Clara River in Ventura County, for example, an annual average of 172 steelhead smolts has been captured in a downstream migrant trap at the Vern Freeman Diversion Facility from 1994 through 1997, although apparently very few adult steelhead have returned to the river. In fact, less than five adult steelhead have been observed using the diversion dam fish ladder (Entrix, Inc. 1994, 1995, 1996, 1997). A recent study that examined the microchemistry of juvenile rainbow trout otoliths has provided additional evidence for this. By comparing the ratio of strontium (Sr) to calcium (Ca) in the primordia and freshwater growth regions of the otolith, the life-history form of the maternal parent can be determined. The study found conclusive evidence that, in some populations, non-anadromous females produce steelhead progeny and steelhead females produce non-anadromous progeny (Zimmerman 2000).

A polymorphic life-history structure and resultant flexibility in reproductive strategies allows for persistence in the face of unstable and variable climatic, hydrographic, and limnological conditions that frequently exist at the margins of a species' range. For rainbow trout, this includes stream systems in the Central Valley and those south of San Francisco Bay, and Kamchatka on the other end of the range. Stream systems in California are subject to extreme variations (both within and among years) in rainfall which can result in high volume, flash flood runoff, or droughts lasting several years. Natural stream flow in these streams can vary greatly, both seasonally and annually. It is not uncommon, even under unimpaired conditions, for the lower reaches of many streams to become interrupted during the dry season (and longer), restricting the population to the perennial headwaters, and these conditions may persist for years. Thus, a polymorphic population structure allows persistence in an environment that is frequently suboptimal and not conducive to consistent, annual recruitment of migrants to the ocean, and may be necessary for the

long-term persistence of a population in these types of environments. Having several different life-history strategies among a single population effects “bet-hedging” against extinction, and has been proposed as a reason for the occurrence of similar polymorphic population structure in coastal populations of cutthroat trout (Northcote 1997) and brown trout (*Salmo trutta*) (Jonsson 1985, as cited in Northcote 1997; Titus and Mosegaard 1992) occupying highly variable environments.

Life-History of Central Valley Steelhead

Presently, the Central Valley drainages are known to contain only winter steelhead. However, there are indications from fish counts made before the era of large dam construction that summer steelhead were present in the Sacramento River system as well (Needham and others 1941; USFWS and DFG 1953). The presence of suitable over-summering habitat, a stable hydrology strongly influenced by spring snowmelt runoff, and the widespread occurrence of spring-run chinook salmon (*Oncorhynchus tshawytscha*), which have a similar life history to summer steelhead, are further indications that summer steelhead occurred throughout the Central Valley system. Because of the need of adults to over-summer in deep pools in mid- to high-elevation tributaries, summer steelhead were probably eliminated with commencement of the large-scale dam construction period in the 1930s.

The peak period of adult immigration before the occurrence of large-scale changes to the hydrology of the system appears to have been in fall, with a smaller component immigrating in winter (Bailey 1954; Van Woert 1958; Hallock and others 1961; Hallock 1989) (Figure 2A). Hallock and others (1961) found that the peak migration into the upper Sacramento River above the mouth of the Feather River from 1953 to 1959 was in late September. Adult counts at Clough Dam on Mill Creek for a 10-year period beginning in 1953 indicated that the peak of adult migration into that stream occurred in late October, with a smaller peak about mid-February (Hallock 1989). Examination of adult steelhead counts at Red Bluff Diversion Dam indicates that run timing on the upper Sacramento River does not appear to have changed appreciably: adult counts from 1969 to 1982 also show this same pattern (Hallock 1989), as do counts from 1983 to 1986 (USFWS unpublished data) (Figure 2B).

Hallock and others (1961) found that juvenile steelhead migrated downstream during most months of the year, but the peak period of emigration occurred in spring, with a much smaller peak in fall. The emigration period for naturally-spawned steelhead juveniles migrating past Knights Landing on the lower Sacramento River in 1998 ranged from late December through early May, and peaked in mid-March (DFG unpublished data). Most naturally-produced Central Valley steelhead rear in freshwater for two years before emigrating to

the ocean. Scale analysis indicated that 70% had spent two years in freshwater before emigrating to the ocean, 29% had spent one year, and 1% had spent three years (Hallock and others 1961). A current generalized life-stage periodicity for Central Valley steelhead is shown in Figure 3.

Recent microchemical analysis of Sr:Ca ratios in otoliths extracted from three rainbow trout from the Calaveras River provides evidence that some Central Valley rainbow trout populations are polymorphic. All three fish were adults with spent gonads indicating they had recently spawned. One was a 25-inch female steelhead that was the progeny of a steelhead female; one was a non-anadromous male (but whose scale circuli showed accelerated growth that may be indicative of having undertaken an estuarine migration) that was the progeny of a steelhead female; and one was a non-anadromous male that was the progeny of a non-anadromous female (Titus 2000). Thus, in a sample of just three fish from the population, we see two, possibly three different life-history expressions, at least one of which was different from that of its mother.

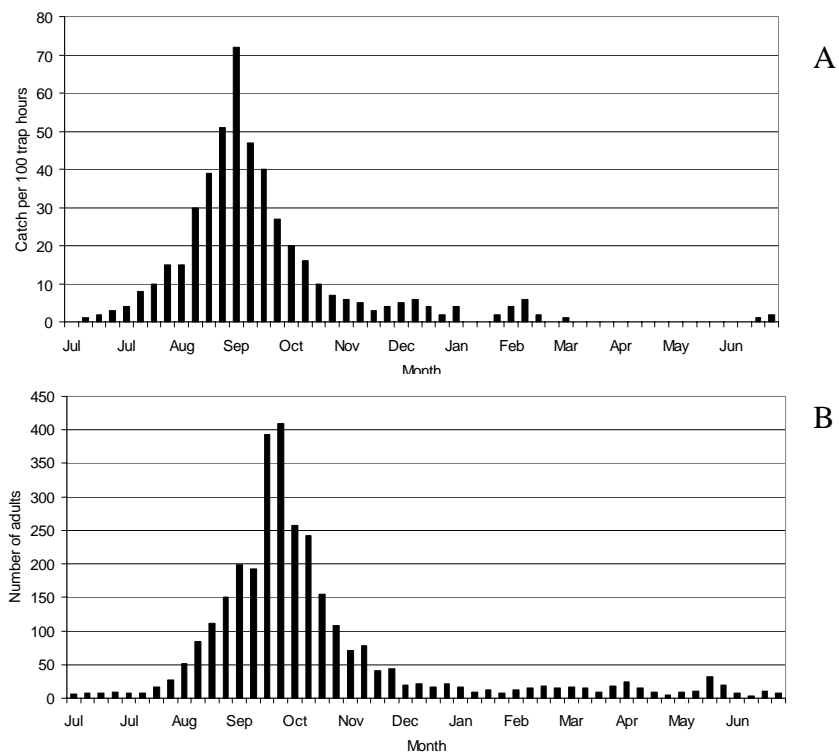


Figure 2 Time pattern of Sacramento River adult steelhead migration. Figure 2A shows migration timing from July through June of 1953 through 1959, determined by trapping upstream migrants in the Sacramento River just upstream of the confluence with the Feather River (from Hallock and others 1961). Figure 2B shows the weekly average number of adult steelhead counted at Red Bluff Diversion Dam from July through June of 1983 through 1986.

| | J | F | M | A | M | J | J | A | S | O | N | D |
|--------------------------|---|---|---|---|---|---|---|---|---|---|---|---|
| Adult migration | | | | | | | | | | | | |
| Spawning | | | | | | | | | | | | |
| Incubation and emergence | | | | | | | | | | | | |
| Rearing | | | | | | | | | | | | |
| Juvenile emigration | | | | | | | | | | | | |

Figure 3 Central Valley steelhead life stage periodicity. Shaded areas represent months when the life stage is present; black shading indicates months of peak occurrence.

Table 1 Steelhead production in Central Valley anadromous fish hatcheries

| Facility (river system) | Purpose of mitigation | Production goal (yearlings) | Average annual production, 1984-1985 through 1993-1994 | |
|--|--|-----------------------------|--|-----------|
| | | | Fingerlings ^a | Yearlings |
| Coleman National Fish Hatchery (Sacramento R.) | Shasta Dam (USBR Central Valley Project) | 700,000 to 800,000 | 245,378 | 526,602 |
| Feather River Hatchery | Oroville Dam (DWR State Water Project) | 400,000 to 450,000 | 489,366 | 406,421 |
| Nimbus Hatchery (American R.) | Folsom Dam (USBR Central Valley Project) | 430,000 | 407,381 | 369,870 |
| Mokelumne R. Hatchery ^b | Camanche Dam (East Bay Municipal Utility District) | 100,000 | 35,734 | 179,125 |
| All Hatcheries | | | 1,177,859 | 1,482,018 |

^a Includes fry, advanced fingerlings, and sub-yearlings.

^b Because the steelhead run in the Mokelumne River is so small, eggs are procured from Nimbus Hatchery.

Hallock and others (1961) reported that the composition of naturally-produced steelhead in the population estimates for the 1953-1954 through 1958-1959 seasons ranged from 82% to 97% and averaged 88%. This is probably not reflective of present stock composition in the Central Valley, due to the loss of spawning and rearing habitat and increase in hatchery production. During the period of the Hallock and others study, only Coleman and Nimbus hatcheries were in operation. Today, four Central Valley anadromous fish hatcheries (Mokelumne River, Feather River, Coleman, and Nimbus hatcheries) collectively produce approximately 1.5 million steelhead yearlings annually (Table 1, Figure 4)³.

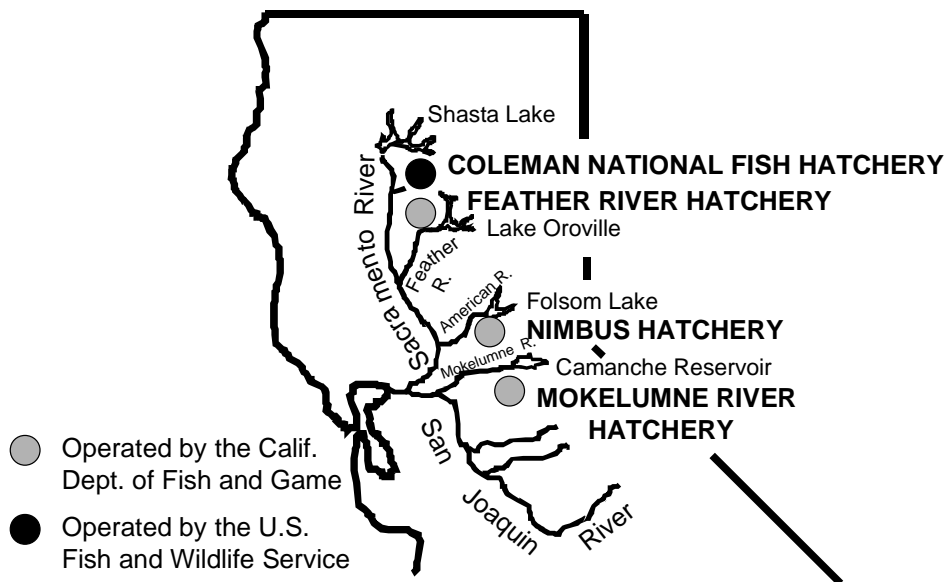


Figure 4 Central Valley anadromous fish hatcheries that raise steelhead

There has been substantial introduction of exotic steelhead stocks in the Central Valley (McEwan and Nelson 1991; NMFS 1996a). The degree of introgression or replacement of native stocks has not been determined, however, there is evidence that native Central Valley steelhead may have maintained some degree of genetic integrity. NMFS conducted a genetic analysis using allozymes from rainbow trout collected from Coleman, Nimbus, and Feather River hatcheries, Deer and Mill creeks, and the Stanislaus and American rivers. They found that the Stanislaus River, Coleman and Feather River hatcheries, and Deer and Mill creek populations formed a genetic group distinct from all

3. There are five anadromous fish hatcheries in the Central Valley; however, Merced River Hatchery does not have a steelhead program.

coastal samples of steelhead (Busby and others 1996; NMFS 1997a). In contrast, the American River samples (wild fish and those from Nimbus Hatchery) were genetically most similar to a sample from the Eel River (NMFS 1997a), which accurately reflects the founding history of Nimbus Hatchery (McEwan and Nelson 1991).

Distribution and Abundance

There is little documentation of historical steelhead distribution in the Central Valley. This is probably because it is difficult to assess or monitor steelhead (as will be discussed further). However, available information indicates that steelhead were well-distributed throughout the Sacramento and San Joaquin river systems. Steelhead were found from the upper Sacramento and Pit river systems south to the Kings River (and possibly Kern river systems in wet years) and in both east- and west- side tributaries of the Sacramento River (Clark 1929a; Wales 1939; Needham and others 1941; Murphy 1946, 1951; Beland and Braun 1952; Fry 1952; Vestal 1965; Painter and others 1977; DFG 1952, 1955, 1967, 1978a, 1978b, 1979; McEwan and Jackson 1996; Yoshiyama and others 1996; DFG unpublished data) (Figure 5).

The broad historical distribution of chinook salmon in the Central Valley (Yoshiyama and others 1996, 1998, this volume) corroborates the conclusion that steelhead were widely distributed. A comparison of the distributions of the two species in recent fish sampling in the lower Klamath River tributaries demonstrates that steelhead are present in all tributaries that contain chinook salmon, and, in nearly all cases, steelhead were found in tributaries and reaches further upstream (Voight and Gale 1998).

Further evidence supporting the assumption that steelhead distribution can be inferred from chinook salmon distribution is provided by an extensive review done by CH2M Hill (1985). In this review of salmonid distribution in the anadromous portions of the entire Klamath-Trinity river system, only one tributary containing chinook salmon but lacking steelhead was documented: all other tributaries that supported chinook salmon had steelhead as well and, in nearly all cases, steelhead were distributed at higher elevations in the stream than were chinook salmon. Thus, Yoshiyama and others' (1996) conclusion that steelhead were more broadly distributed than chinook salmon appears to be justified:

[Steelhead were] undoubtedly more extensively distributed [than chinook salmon in the Central Valley]. Due to their superior jumping ability, the timing of their upstream migration, which coincided with the winter rainy season, and their less restrictive preferences for spawning gravels, steelhead could have used at least hundreds of miles of smaller tributaries not accessible to the earlier-spawning salmon.

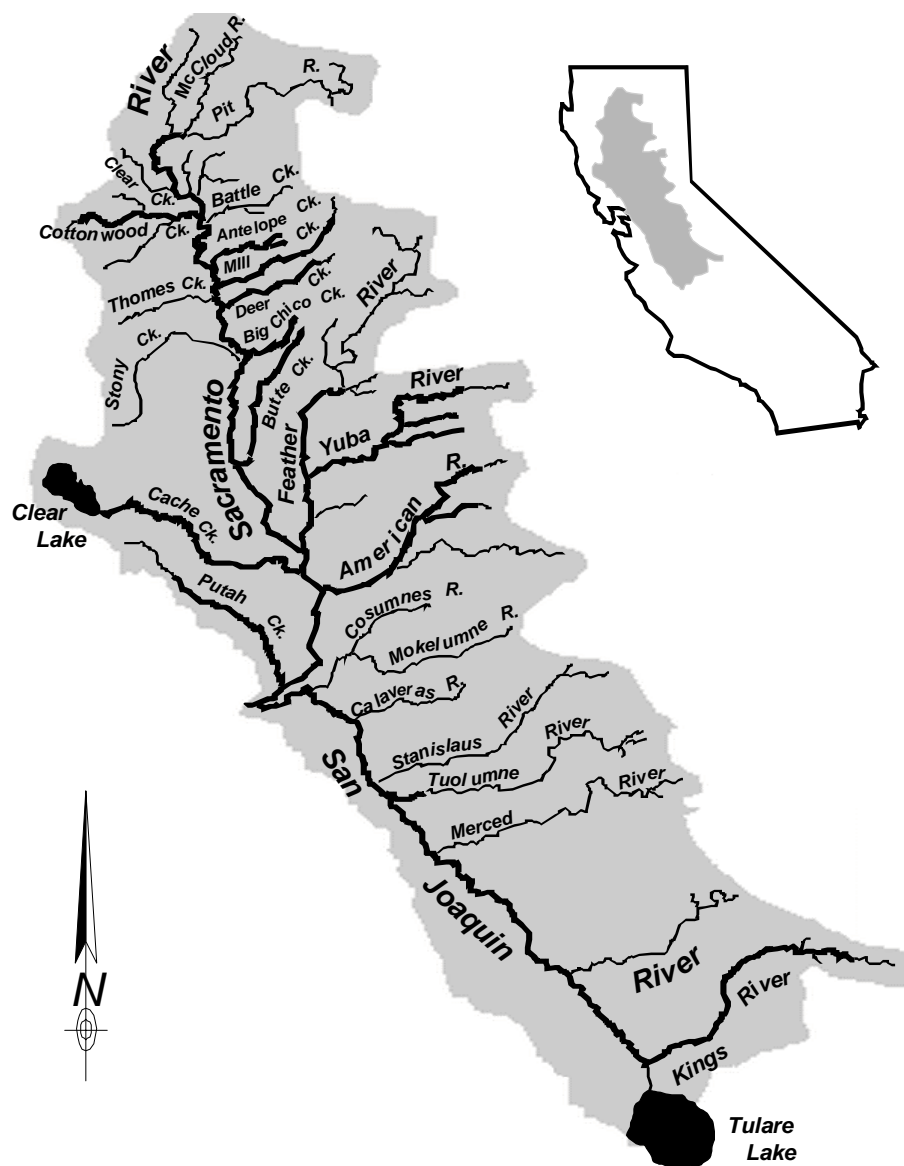


Figure 5 Historical distribution of steelhead in Central Valley drainages. Thick lines represent streams and stream reaches that have documented historical evidence of steelhead (see text for references). Thin lines represent likely distribution of steelhead based on documented occurrence of chinook salmon or lack of natural barriers above documented steelhead occurrences. Shading represents an estimation of historical range within which steelhead likely occurred in numerous small tributaries not shown on map.

The present distribution of steelhead in the Central Valley has been greatly reduced (Figure 6), mostly due to construction of impassable dams that block access to essential spawning and rearing habitat. Although a comparison of Figures 5 and 6 indicates a considerable reduction in distribution, it does not effectively convey the impact of the loss of habitat, because many of the stream reaches included as present distribution are at low elevations and were used by steelhead mostly as migration corridors. Clark (1929b) estimated that 80% of the spawning grounds in the Central Valley have been blocked due to power and irrigation dams. The California Advisory Committee on Salmon and Steelhead Trout (CACST 1988) estimated that there has been a 95% reduction in spawning habitat for Central Valley anadromous fish. Similarly, Yoshiyama and others (1996) estimated that 82% of chinook salmon spawning and rearing habitat in the Central Valley has been lost, and they state that the percentage of lost habitat for steelhead is undoubtedly higher because steelhead extended further into the drainage.

Naturally-spawning stocks of rainbow trout that support anadromy are known to occur in the upper Sacramento River and tributaries, Mill, Deer, and Butte creeks, and the Feather, Yuba, American, Mokelumne, Calaveras, and Stanislaus rivers. The presence of naturally spawning populations appears to correlate well with the presence of fish monitoring programs, however, and recent implementation of monitoring programs has found steelhead smolts in streams previously thought not to contain a population, such as Auburn Ravine, Dry Creek (DFG unpublished data) and the Stanislaus River (Demko and Cramer 1997, 1998; Demko and others 1999). It is possible that naturally spawning populations exist in many other streams but are undetected due to lack of monitoring or research programs.

Until very recently, steelhead were considered by some to be extinct in the San Joaquin River system (see Reynolds and others 1990; Cramer and others 1995). However, this conclusion was based on little information and no field studies. The presence of steelhead in the San Joaquin River is controversial, however, substantial evidence shows there is an extant, self-sustaining steelhead run in the San Joaquin River system:

- Numerous yearling-sized steelhead exhibiting smolt characteristics have been captured during an annual chinook salmon Kodiak trawl survey on the lower San Joaquin River from 1987 to the present (DFG unpublished data; USFWS unpublished data).
- A small number of steelhead smolts has been captured in rotary screw traps in two locations in the Stanislaus River every year for the past six years (Demko and Cramer 1997, 1998; S.P. Cramer & Associates unpublished data) (Figure 7). These fish do not appear to be progeny of straying adult Mokelumne River Hatchery steelhead: recent genetic analysis of

rainbow trout (discussed previously) captured in the reach below Goodwin Dam show that this population has closest genetic affinities to upper Sacramento River steelhead (NMFS 1997a). In contrast, Nimbus Hatchery steelhead, the source of eggs for the Mokelumne River Hatchery steelhead program, appear to be genetically similar to coastal steelhead, which were used to found the Nimbus Hatchery steelhead program when the hatchery first began production. Mokelumne River Hatchery is the only steelhead hatchery in the San Joaquin River system, and juvenile steelhead are not stocked anywhere in the San Joaquin basin except the Mokelumne River.

- A DFG creel census on the Stanislaus River has documented the catch of rainbow trout greater than 20 inches (DFG unpublished data). Examination of scale samples from these larger trout by DFG biologists shows an accelerated growth period typical of estuary or ocean residence (DFG 1997). DFG (1985) also observed large numbers of juvenile rainbow trout in several age classes, including young-of-the-year.
- In 1996, DFG (unpublished data) observed large numbers of rainbow trout in the Tuolumne River during a snorkel survey. In 1997, naturally spawned young-of-the-year rainbow trout were captured in the Tuolumne River by beach seining. Rotary screw trap catches in the past few years also contain young rainbow trout.
- In January 2001, a 28-inch rainbow trout was captured by a DFG fisheries biologist while angling in the lower Tuolumne River. The fish was a male with a hooked kype and prominent red coloration along the lateral line and operculae, indicating that it was ready to spawn. An 11-inch steelhead smolt was captured by the same biologist a few days later near the same location (DFG 2001).
- A 24-inch rainbow trout was captured by electrofishing at the confluence of the Merced and San Joaquin rivers in 1996-1997.
- In February 2000, an angler caught a 31-inch rainbow trout in the Calaveras River downstream of New Hogan Dam. Several weeks later, one adult female and two adult male rainbow trout were collected from the river after a fish kill occurred. Microchemical analysis of the otoliths found that the female was a spawned-out steelhead and one of the males was the progeny of a steelhead mother, but itself was non-anadromous (Titus 2000). In April 2000 a 9-inch juvenile steelhead exhibiting obvious smolt characteristics was captured (DFG 2000b).

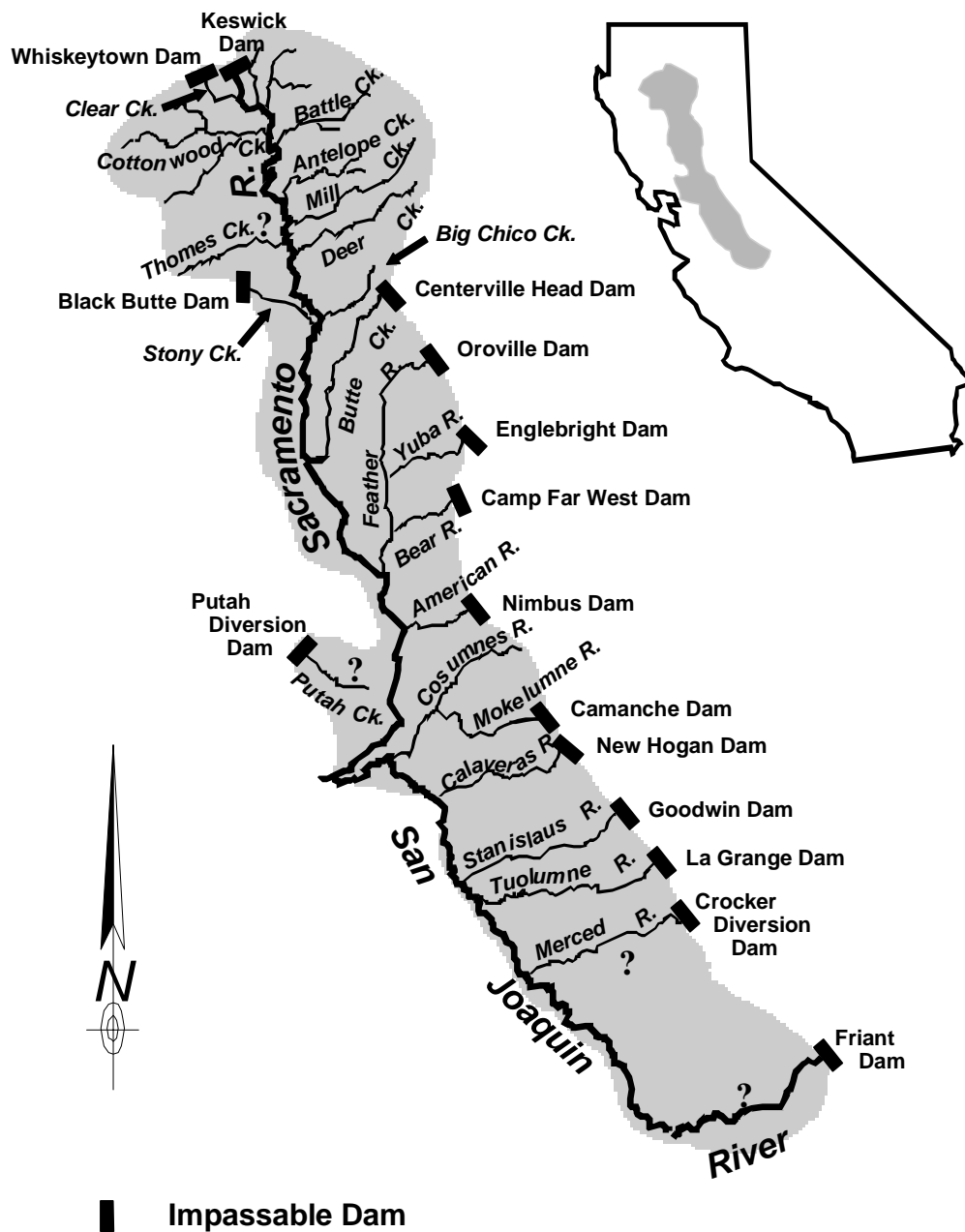


Figure 6 Present distribution of steelhead in Central Valley drainages. Shading represents an estimation of present range within which steelhead likely occur in numerous tributaries not shown on map. Question marks denote streams and stream reaches where steelhead currently have access but their presence is unknown.

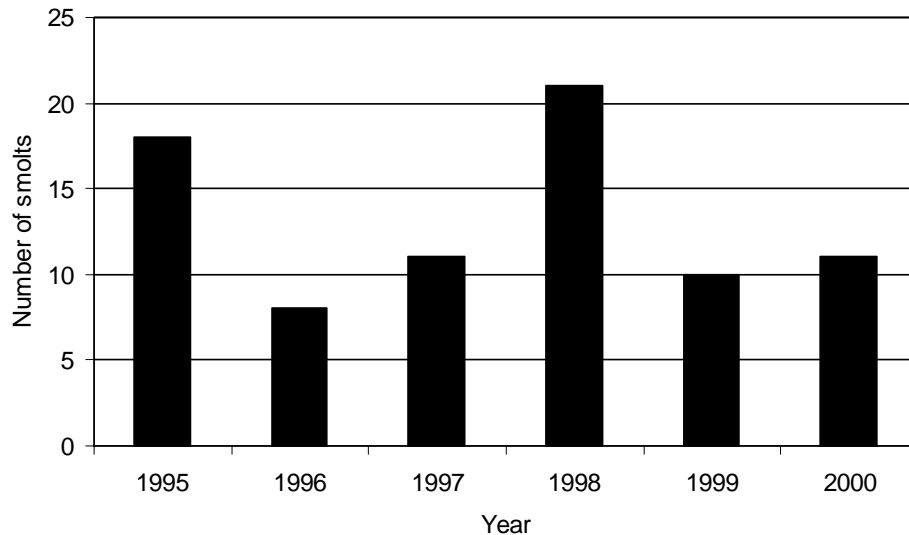


Figure 7 Number of smolt steelhead captured in rotary screw traps in the Stanislaus River. Data have not been adjusted for sampling effort, and effort has not been consistent between years. Data for 1999 is preliminary and data for 2000 is preliminary and partial.

The California Fish and Wildlife Plan (DFG 1965) estimated there were 40,000 adult steelhead in the Central Valley drainages in the early 1960s. In the 1950s, Hallock and others (1961) estimated the average annual steelhead run size was 20,540 adults in the Sacramento River system above the mouth of the Feather River. Estimating steelhead abundance before extensive water development and habitat modification is difficult given the paucity of historical information. However, historical steelhead abundance can be grossly estimated by examining chinook salmon and steelhead production in relatively unimpaired river systems.

From 1938 to 1975, counts were made of adult chinook salmon and steelhead at the Benbow Dam fishway on the South Fork Eel River. A decline in numbers of both chinook salmon and steelhead using the fishway began in the early 1960s, indicating that major effects to the Eel River probably occurred after 1960. Examination of the relative abundance of chinook salmon and steelhead during the years 1938 through 1960 shows, that of the 19 years of counts, there were two years when adult steelhead abundance was slightly less than chinook salmon, seven years when it was slightly more, and 14 years when steelhead abundance was more than twice that of chinook salmon. For the entire Eel River system, the California Fish and Wildlife Plan (DFG 1965) estimates the steelhead run size to be 160% of the chinook salmon run size.

Table S-3 of the California Fish and Wildlife Plan (DFG 1965) shows that for most northern California river systems, the steelhead run size in the early 1960s was at least that of the chinook salmon run size and in several streams steelhead were more than twice as abundant⁴. Even if a 50% ocean harvest rate for chinook salmon is considered, steelhead run size was only slightly less than chinook salmon in most streams and was the same or higher in some.

Thus, historical chinook salmon abundance may be viewed as an approximation of steelhead historical abundance. Assuming this is true, historical steelhead numbers in the Central Valley would have approached 1 to 2 million adults annually, which is the historical abundance of chinook salmon in the Central Valley estimated by Yoshiyama and others (1998). However, it should be noted that historical steelhead abundance in the Columbia River may have been significantly less than that of chinook salmon, based on historical commercial landings of chinook salmon and steelhead (R. Behnke, personal communication, see "Notes"). Also, given their larger size at ocean entry, juvenile steelhead would require greater resources than the smaller-sized salmon, therefore, fresh water habitat may not have been able to support as many juvenile steelhead as chinook salmon. The greater resource limitations for steelhead could have been attenuated by the fact that steelhead utilize the more numerous smaller tributaries for spawning and rearing than do chinook salmon, and greater ocean survival due to the larger size of steelhead smolts at ocean entry. Nevertheless, it is difficult to estimate historical abundance in the absence of any real data, so the above estimate of 1 to 2 million adult steelhead should be viewed as a best guess.

An accurate estimate of current steelhead abundance in the Central Valley is also not available. However, in the early 1990s, the total annual run size (hatchery and wild) for the entire system, based on Red Bluff Diversion Dam (RBDD) counts, hatchery counts, and past natural spawning escapement estimates for some tributaries, was estimated to be no greater than 10,000 adult fish (McEwan and Jackson 1996). A more reliable indicator of the magnitude of the decline of Central Valley hatchery and wild stocks is the trend in the RBDD counts. Steelhead counts at the RBDD have declined from an average annual count of 11,187 adults for the ten-year period beginning in 1967, to 2,202 adults annually in the 1990s (McEwan and Jackson 1996). Natural spawning escapement estimates above RBDD for the period 1967 to 1993 averaged 3,465 and ranged from 0 (1989 and 1991) to 13,248 (1968) (Figure 8). Natural escapement has shown a more substantial decline than hatchery (Coleman National Fish Hatchery) escapement.

4. The only exceptions were the Scott, Shasta, and Trinity rivers. Chinook salmon run size was estimated to be higher than steelhead in these rivers and might be explained by severely degraded conditions and blocked access in the Scott and Shasta river tributaries and chinook salmon hatchery production in the Trinity River.

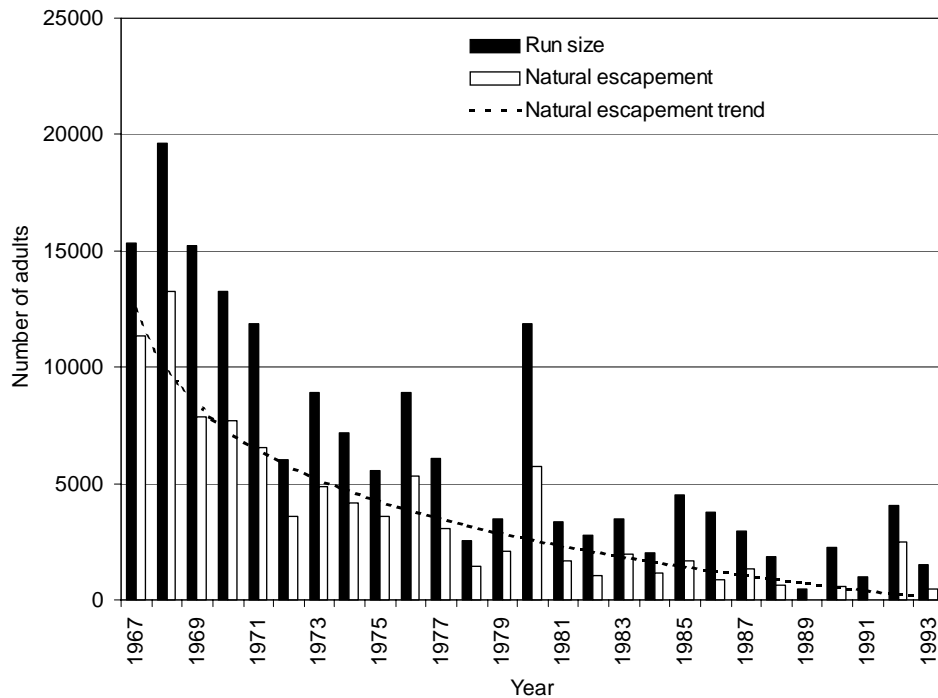


Figure 8 Steelhead population trends in the upper Sacramento River from 1967 to 1993. Run size is the adjusted steelhead counts at Red Bluff Diversion Dam and includes hatchery and natural spawners. Natural escapement was calculated by applying an estimated harvest rate of 16% (DFG unpublished data) to run size, then subtracting Coleman National Fish Hatchery escapement.

Factors Affecting the Decline of Central Valley Steelhead

Stressors affecting abundance, persistence, and recovery have been identified for anadromous fishes in the Sacramento and San Joaquin River systems and these apply reasonably well to Central Valley steelhead. Stressors affecting Central Valley anadromous fishes include water diversions and water management; entrainment; dams and other structures; bank protection; dredging and sediment disposal; gravel mining; invasive aquatic organisms; fishery management practices; and contaminants (Upper Sacramento River FRHAC 1989; Reynolds and others 1990, 1993; CALFED 2000; CMARP Steering Committee 1999). Stressors affecting steelhead on the west coast generally include the stressors listed above plus logging, agriculture, urbanization, disease, predation, and natural factors (NMFS 1996b; NMFS 1997b). McEwan and Jackson

(1996) state that the primary stressors specific to Central Valley steelhead are all related to water development and water management.

Most of the stressors commonly thought to affect Central Valley steelhead were first identified as factors that constrain chinook salmon populations and have been applied to steelhead secondarily because they are an anadromous fish with a somewhat similar life history. It is often assumed that steelhead have been affected by the identified stressors to the same degree as chinook salmon; hence, it is a common perception that alleviation of the stressor to the level that it no longer affects a chinook salmon population will result in steelhead population increases. However, some stressors cause greater effects to steelhead than they do to many chinook salmon populations. For example, high water temperatures affect juvenile steelhead to a greater degree than juvenile fall-run chinook salmon because most salmon have emigrated to the ocean by early summer before high water temperatures occur, whereas steelhead must rear through summer and fall when water temperatures are more likely to become critical.

The single greatest stressor on Central Valley steelhead is the catastrophic loss of spawning and rearing habitat due to construction of impassable dams (IEP Steelhead PWT 1999). Because juvenile steelhead must rear in fresh water for one year or longer, water temperatures must remain suitable year-round. For the most part, this occurred naturally only in the mid- to high-elevation reaches and tributaries, resulting in adult steelhead migrating higher into the drainage to spawn. Because 82% to 95% of their historical spawning and rearing habitat has been lost (Yoshiyama and others 1996; CACSST 1988), mostly due to dam construction, juvenile steelhead rearing is mostly confined to lower elevation reaches where high water temperatures during late-summer and fall are a major stressor (IEP Steelhead PWT 1999; CMARP Steering Committee 1999).

The creation of large impoundments with well-stratified waters has allowed better management of water temperatures in river reaches below large dams. However, hypolimnetic releases to create suitable water temperatures have been made mostly to benefit winter-run chinook salmon populations, and, until very recently, relatively little effort has been made to use this water to maintain suitable temperatures for rearing steelhead during the critical late summer and early fall periods. Although steelhead benefit from water temperature control actions in reaches where they are sympatric with the chinook salmon life stage that is the target of the action (such as rearing winter-run chinook salmon in the upper Sacramento River) focusing actions exclusively on chinook salmon can cause, and has caused, severe temperature effects for steelhead in tributaries where they are sympatric only with fall-run chinook salmon.

Some dams in the Central Valley were constructed with inadequate release structures that make it difficult to optimize releases from the hypolimnion. Other reservoirs may not have adequate minimum pool storage requirements. Consequently, many reservoirs currently are not able to provide releases necessary to maintain suitable temperatures for steelhead rearing through the critical summer and fall periods, especially during dry and critically-dry years. Water demands and power generation also affect the ability to provide suitable temperatures for steelhead.

In the early 1960s, all major Central Valley dams (except Oroville) and most minor dams were already in place, consequently the amount of spawning and rearing habitat available to steelhead probably has not changed appreciably from the late 1950s to the present. The greatest decline of natural steelhead in the system probably took place before the 1960s as a consequence of the reduction in habitat quantity as dam construction was incrementally isolating adults from the tributary spawning and rearing habitats. The decline since the 1960s can probably be mostly attributed to reduction in habitat quality, as increasing water demands – as reflected in the amount of water exported from the system by the State Water Project (SWP) and Central Valley Project (CVP) pumping facilities in the Sacramento-San Joaquin Delta-estuary (Figure 9) – and land use practices diminished the production capability of the existing accessible habitat. Before 1967 when the SWP began operation, the amount of water exported annually from the south Delta-estuary by the CVP pumping facility averaged 1,109,146 acre-feet per year. Since 1967 with both projects operating, the average has nearly quadrupled (4,133,516 acre-feet per year).

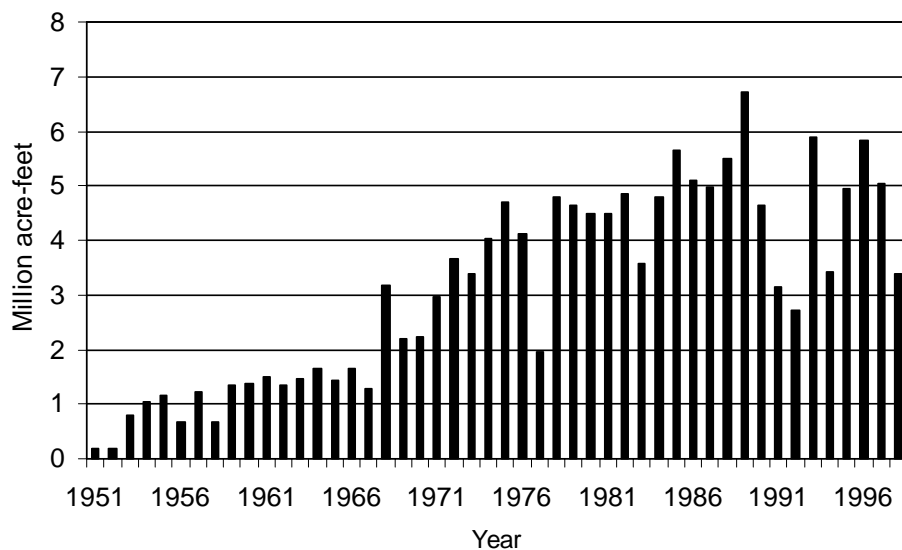


Figure 9 Combined State Water Project and Central Valley Project water exports from the Sacramento-San Joaquin Delta and Estuary, 1951 to 1998

A demographic shift towards the non-anadromous life-history forms brought about by anthropogenic effects could cause a decline in the relative abundance of the individual steelhead life-history forms, although this may not be a stressor on the population as a whole. Among polymorphic salmonid populations, the life-history fate of juveniles appears to be partially controlled by density-dependent factors: the growth rate during early life-history of a particular fish appears to be the factor that determines whether it will later smolt and migrate to the ocean, or become sexually mature in the stream as a parr (Thorpe 1987). Low juvenile densities or abundant resources leads to rapid growth rates, which triggers relatively rapid development which, in turn, leads to a higher frequency of parr maturation in the population, especially among males (Thorpe 1987; Titus and Mosegaard 1992). Conversely, it has been shown that high juvenile densities cause greater resource competition and juveniles that cannot establish and defend suitable stream positions are forced to migrate (Elliott 1994). The greater productivity and more abundant food resources in tailwater reaches may allow an increased growth potential among juvenile rainbow trout, which may skew the population towards the non-anadromous life-history forms. This may be a contributing factor in the growth of the non-anadromous "river trout" population in the upper Sacramento River below Keswick Dam.

Another potential population stressor is the disruption of interrelationships among Central Valley rainbow trout subpopulations. Due to highly variable natural conditions in the Central Valley, inter-population dynamics may be essential to the persistence of rainbow trout populations in the smaller stream systems. Historically, larger source populations occupying more stable habitats (for example, upper Sacramento, Feather, Yuba, and American rivers) provided a source for recolonization and gene flow to the smaller, less-persistent sink populations occupying more hydrologically unstable stream systems. Conversely, the long-term persistence of the source populations may be affected by the diversity and viability of the smaller subpopulations. The precipitous decline of Central Valley steelhead has been alarming not only from the standpoint of reduction in absolute numbers, but also in the elimination of the populations that occupied the many tributaries. A reduction in the large-river source populations may also explain the precipitous decline of steelhead in smaller streams, in spite of the large amount of quality habitat that still exists in these systems. Thus, restoration that focuses only on increasing absolute numbers and ignores the need to increase population diversity may be inadequate.

Monitoring and Research

Past Monitoring and Research Efforts

What is known about Central Valley steelhead is mostly due to a six-year monitoring and research program begun in 1953 by the DFG (Hallock and others 1961). The study, *An Evaluation of Stocking Hatchery-reared Steelhead Rainbow Trout (Salmo gairdnerii gairdnerii) in the Sacramento River System*, focused on hatchery steelhead but also provided valuable information on natural steelhead stocks, including status, abundance, and life history. Much of the baseline information that exists for Central Valley natural steelhead is derived from this study. Unfortunately, this program was canceled due to “lack of interest in steelhead...by administrators” (Hallock 1989). The cancellation of this program, and steelhead research programs in other areas of California, coincided with the implementation of monitoring programs to gather information to promulgate ocean harvest regulations for salmon. In more recent years, efforts to restore Central Valley steelhead has been hampered by a paucity of baseline information.

Other important steelhead investigations in the Sacramento River system include studies on the time pattern of migration of steelhead into the upper Sacramento River (Bailey 1954; Van Woert 1958); a survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers (Hallock and Van Woert 1959); an evaluation of the steelhead fishery (Smith 1950); and an investigation into the status and potential effects of Shasta Dam on upper Sacramento River steelhead (Hanson and others 1940). In addition, several significant studies were undertaken in Sacramento River tributaries, including an assessment of the Yuba River steelhead run size and harvest rates (DFG 1984); an evaluation of the effects of the Oroville Project on the Feather River (Painter and others 1977); and an evaluation of steelhead angling on the American River (Staley 1976). Apparently, no studies or reports on San Joaquin River steelhead have been done.

Recent Monitoring and Research Efforts

In response to the recent listing of Central Valley steelhead under the ESA, steelhead monitoring and research efforts have increased. However, the Hallock and others (1961) study remains the only comprehensive investigation on Central Valley steelhead. Other recent studies and monitoring programs of a broad-based nature that have been completed include an evaluation of juvenile salmonid emigration in the upper Sacramento River (Snider and Titus 1996) and the aforementioned genetic analysis (NMFS 1997a). Significant ongoing investigations include abundance and distribution patterns in juvenile salmonids near the Red Bluff Diversion Dam; a Sacramento-San Joaquin

basin-wide angler survey; upper Sacramento River juvenile salmonid monitoring; and lower Sacramento River juvenile salmonid emigration studies. In addition to these, there are currently anadromous fisheries investigations ongoing on several major tributaries such as the Feather, American, and Mokelumne rivers, and minor tributaries such as Auburn Ravine and Dry Creek. The California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR) recently completed a biological assessment of Central Valley water management operations on steelhead and spring-run chinook salmon. This document provides a good synthesis of available information on steelhead and potential impacts (DWR and USBR 1999).

The Interagency Ecological Program Steelhead Project Work Team (IEP Steelhead PWT) identified 82 Central Valley anadromous fish monitoring and research projects operating in 1998 and classified these projects into four categories based on the objectives of the project and the degree to which they obtained information on steelhead: "salmon exclusive," "salmon focused," "anadromous salmonid focused," and "steelhead focused" (IEP Steelhead PWT 1999). Of the four categories, only the latter three provided any meaningful information on steelhead.

"Salmon exclusive" monitoring and research projects had objectives aimed at obtaining information on chinook salmon, used methods and periods of operation to accomplish these objectives, and provided no meaningful information on steelhead. Of the 82 projects reviewed, 42 (51%) were of this type. "Salmon focused" projects were similar to "salmon exclusive" projects in design and scope, but some useful steelhead information was collected incidentally: 12 (15%) were of this type. "Anadromous salmonid focused" projects had objectives that were designed to collect both salmon and steelhead information and used methods and periods of operation to accomplish this: 20 (24%) were of this type. "Steelhead focused" projects had objectives designed to collect steelhead information and used methods and periods of operation designed to collect steelhead information exclusively: eight (10%) were of this type. This analysis demonstrates that despite the recent emphasis on obtaining information on steelhead, the focus of Central Valley anadromous fish monitoring and research efforts is still overwhelmingly on chinook salmon.

Constraints to Steelhead Monitoring and Research

Constraints to steelhead monitoring and research have led to significant knowledge gaps. These constraints fall mainly into two categories: institutional and biological. Institutionally, the lack of adequate funds for anadromous fish monitoring often necessitates that monitoring programs adopt a narrow focus. Because chinook salmon are commercially exploited, highly visible, and politically sensitive, they have received the majority of monitoring funds and effort. This narrow focus was reinforced by the belief among

resource agencies that steelhead suffer from the same level of impacts as do chinook salmon, and assessment of impacts would be similar for steelhead.

Life-history traits common to all Central Valley steelhead can hamper steelhead monitoring and research. Adults tend to migrate during high flow periods, making them difficult to observe. In addition, maintaining counting weirs and other monitoring equipment and structures during these high flow periods can be challenging. Carcass surveys, a reliable method to estimate chinook salmon spawning escapement, is not applicable to steelhead because many survive spawning and most others do not die on spawning grounds. Although steelhead redds can be discerned from salmon redds, they are hard to observe because steelhead spawn at higher flows than do chinook salmon. Trap efficiencies appear to be lower for juvenile steelhead because emigrating juveniles can probably escape trapping more readily because of their larger size, relative to chinook salmon (R. Titus, personal communication, see "Notes").

Knowledge Gaps

Significant knowledge gaps hinder our ability to design restoration actions and monitor their effectiveness. The most important knowledge gaps and monitoring elements needed to address them include the following.

Current Distribution and Abundance of Naturally Spawning Populations

Comprehensive Monitoring. Recent monitoring projects have shown that naturally spawning steelhead exist in the upper Sacramento River and tributaries, Mill, Deer, and Butte creeks, and the Feather, Yuba, American, and Stanislaus rivers. Naturally spawning populations may exist in many other streams as well, but are undetected due to lack of monitoring or research programs. More comprehensive monitoring is needed to determine system-wide distribution.

Run Size Estimation. From 1967 to 1993, run size estimates were generated for steelhead using counts at the fishway on the Red Bluff Diversion Dam (RBDD). From these counts, estimates of natural spawning escapement for the upper Sacramento River above RBDD were made. Because of effects to winter-run chinook salmon, the operation of RBDD was changed so that the dam gates were raised earlier in the season, and this eliminated the ability to generate run-size estimates. Another method of generating run-size estimates for the upper Sacramento River system, or perhaps an index, needs to be developed.

Determination of Origin. Beginning with broodyear (BY) 1997, all steelhead produced in Central Valley hatcheries were marked with an adipose fin clip. This program will continue as a permanent hatchery practice at these hatcheries. Marked juvenile fish were captured in smolt emigration studies in 1998 and

marked adult steelhead began returning in winter 1999 (DFG unpublished data). Capture of non-clipped juvenile steelhead will help elucidate the location of naturally spawning populations.

Life Stage Determination. The IEP Steelhead PWT has developed a Steelhead Life Stage Assessment Protocol and is proposing that it be used by all Central Valley monitoring projects (IEP Steelhead PWT 1998). The protocol classifies rainbow trout by developmental life stage and includes diagnostics for determining the degree of smolting using a set of characteristics that is well-established (for example, Folmar and Dickhoff 1980; Wedemeyer and others 1980). Implementation of a standardized protocol to assign individual fish to one of several life-stage categories (yolk-sac fry, fry, parr, silvery parr, or smolt) will yield valuable information regarding behavior, development, and disposition of juvenile steelhead and distribution of steelhead throughout the Central Valley.

Spawning and Rearing Habitat Characteristics and Use

Assessment of Habitat Structure and Availability Below Dams. Because the majority of steelhead historical habitat is inaccessible to immigrating adult steelhead, research on habitat characteristics and suitability in tailwater reaches below dams needs to be done. A suite of studies on this subject should be initiated, which includes temperature modeling (both river and reservoir); instream flow evaluations to determine suitable migration, spawning, and rearing flows; habitat preference studies to determine how juvenile steelhead use microhabitat; and assessment of habitat conditions and factors limiting steelhead production.

Determination of Temperature Requirements in Specific Streams. To gain a better understanding of thermal requirements and the relationship between water temperature and juvenile steelhead survival, growth, and productivity, thermal bioenergetic investigations need to be conducted on a site-specific basis. Methods using data collected *in situ* have been developed and would provide more accurate site-specific thermal preference information based on field (rather than laboratory) studies (A.A. Rich & Associates 2000).

Population and Habitat Assessment in Low Elevation Tributaries. Steelhead and non-anadromous rainbow trout will use seasonal habitats of intermittent streams for spawning and rearing (Shapovalov 1944; Everest 1971, 1973; Erman and Leidy 1975; Erman and Hawthorne 1976; Maslin and McKinney 1994). Also, steelhead have been found in some small, low elevation Sacramento River tributaries (for example, Dry and Auburn Ravine creeks) that do not contain suitable habitat year-round, or are limiting in one or more suitable habitat characteristics (DFG unpublished data). Habitat characteristics and use, the extent of use of these streams by steelhead, and life-history characteristics

(spawning and emigration timing, size and age at emigration, and so on) need to be determined.

Genetic and Population Structure

Assessment of Maturation Status. Determining maturation status of rainbow trout captured by the various monitoring projects is incorporated into the Steelhead Life Stage Assessment Protocol. Parr maturation, especially in males, is common in steelhead and other polymorphic salmonid populations (reviewed by Titus and others, forthcoming.). When collected systematically throughout the system in conjunction with life stage and condition, these data will provide much needed information about developmental variation in steelhead and population structure.

Central Valley Steelhead Comprehensive Genetic Evaluation. The genetic analysis done by NMFS as part of the west coast steelhead Endangered Species Act status review provided useful information for delineation of Evolutionarily Significant Units (ESUs), but did not have the detail necessary to provide meaningful information within ESUs. More comprehensive information and analysis on the relationship of Central Valley steelhead to each other and to other populations of coastal rainbow trout is needed, as is information on the phylogenetic relationships between putative native rainbow trout, naturally spawning steelhead, and presumably non-native hatchery steelhead. This information will be useful in estimating the structure and genetic diversity within and among Central Valley rainbow trout populations.

Assessment of Reintroduction of Steelhead from Non-anadromous Forms. Provided that native Central Valley rainbow trout populations isolated above artificial barriers can be identified through the comprehensive genetic analysis described above, the next step would be to determine if the steelhead life-history form can be recreated and reintroduced into stream systems where they are presently extirpated.

Miscellaneous Research

Access Restoration Evaluation. Restoring access for steelhead above impassable dams needs to be considered on some streams to address the large-scale habitat loss that has occurred in the Central Valley. Restoration of access to the upper reaches of the Yuba and American rivers has been proposed. Also, the *CALFED Ecosystem Restoration Program Plan* (CALFED 2000) identifies the Yuba River and Battle and Clear creeks as locations in which passage above existing barriers is most feasible. An evaluation should be done in two phases. The first phase would assess spawning and rearing habitat availability above the dams. If suitable habitat can be identified or restored, then a feasibility study

of the best means to provide access (dam removal, passage facility installation, trap-and-truck operation, etc.) should be initiated.

Hatchery Evaluations. Intra- and inter-specific effects of hatchery fish on naturally spawning steelhead need to be investigated. This should include an evaluation of the degree of straying of hatchery steelhead both within and between basins. If there is a significant amount of in-river spawning of hatchery adults, then the potential exists for introgression of hatchery stocks with putative native populations. This is especially of concern for hatcheries that were founded with non-native broodstock, such as Nimbus Hatchery. The degree of straying of hatchery steelhead into other basins needs to be investigated as well. This can be accomplished by applying an external mark to a constant fraction of hatchery production or through thermal mass-marking and subsequent analysis of otolith microstructure. The use of native strains as broodstock needs to be evaluated.

Evaluation of Delta Water Operations on Steelhead Emigration and Rearing. SWP and CVP water diversions from the Sacramento-San Joaquin Delta-estuary have caused significant adverse effects to many riverine, estuarine, and anadromous species (Herbold and Moyle 1989). Attempts to mitigate these adverse effects have spawned much research and monitoring, particularly for chinook salmon, striped bass (*Morone saxatilis*), and delta smelt (*Hypomesus transpacificus*). However, no studies on the effect of the Delta water operations on steelhead in the Delta have been done. The effect of water operations on emigrating juvenile steelhead needs to be assessed. Specifically, timing of smolt emigration through the Delta, magnitude of diversion and entrainment of smolts toward the SWP and CVP pumping facilities, and the effect of the loss of estuary rearing habitat should be evaluated.

Recovery and Management

Endangered Species Act and Recovery Programs

In 1994, the Oregon Natural Resources Defense Council and 15 other organizations petitioned NMFS to list all steelhead stocks in Washington, Idaho, Oregon, and California under the ESA, citing declines in numerous west coast stocks resulting from water development, logging, drought, and other activities. NMFS found that the petition contained credible information and initiated a status review. In 1996, NMFS published a proposed rule designating 15 steelhead ESUs in the four states, ten of which they proposed to list, including all six ESUs in California. They proposed to list the Central Valley ESU, which includes all anadromous reaches of the Sacramento River system and the San

Joaquin system downstream of the confluence of the Merced River (including the Merced River), as endangered.

In August 1997, NMFS published a Final Rule announcing the listing of the Southern California ESU as endangered, and the South-Central California Coast and the Central California Coast ESUs as threatened. They deferred the decisions on the other California ESUs. In May 1998, NMFS listed the Central Valley ESU citing ongoing conservation efforts as justification for listing as threatened, rather than endangered, as originally proposed. Specifically cited were the Central Valley Project Improvement Act (CVPIA), an act passed by Congress in 1992 to remedy habitat and other problems associated with the operations of the Central Valley Project, and the CALFED Bay-Delta Program, a joint State and federal program to develop a long-term solution to address Central Valley ecosystem restoration, water supply reliability, and other issues.

The Anadromous Fish Restoration Plan (AFRP) was developed in 1995 to achieve the mandated CVPIA goal of doubling the natural production of anadromous fish by 2002 (USFWS 1997). The AFRP lists actions, such as specified increased flows below CVP reservoirs, intended to recover six species of anadromous fish, including steelhead. Some measures of the AFRP have been implemented, such as increased flows for fish.

Like many other management and restoration plans for Central Valley anadromous fisheries, actions identified in the AFRP are largely driven by chinook salmon restoration, and less emphasis is placed on specific actions needed to recover steelhead. For example, minimum flows in the San Joaquin River system were set according to the needs of fall-run chinook salmon, and because juvenile fall-run chinook have largely emigrated by early summer, no provisions of flows to maintain cold water temperatures through the summer were established. AFRP-specified flows for Clear Creek and the upper Sacramento River below Keswick were also designed specifically for chinook salmon. The AFRP needs to consider rearing flows and temperatures necessary to support over-summering juvenile steelhead.

The institutional predilection for chinook salmon in monitoring and assessment efforts discussed previously is also prevalent in recovery and management strategies, and this has been the dominant paradigm in steelhead management and restoration efforts initiated in the past ten years (see Upper Sacramento River FRHAC 1989; Reynolds and others 1990, 1993; USFWS 1997)⁵. Although most restoration measures designed to recover chinook salmon stocks do benefit steelhead or are benign in that regard, focusing restoration solely on chinook salmon leads to inadequate measures to restore steelhead because of their different life histories and resource requirements, particularly that of rearing juveniles.

The other large-scale ecosystem restoration action, the CALFED Bay-Delta Program, goes much farther than the CVPIA in recognizing the need to identify and implement actions to restore steelhead, separate from those to restore chinook salmon, especially in the San Joaquin River system:

It is important to note that all of the agreed upon or proposed flows (AFRP, Tuolumne River Settlement Agreement, FERC, VAMP, Davis-Grunsky, and DFG recommended flows) in the Stanislaus, Tuolumne, and Merced rivers were designed to facilitate chinook salmon recovery, and little or no consideration was given to steelhead recovery in the design of these flow strategies. Flow and temperatures requirements of steelhead will need to be evaluated and integrated into the proposed flow regimes (CALFED 2000).

CALFED has identified specific measures for steelhead recovery in the Ecosystem Restoration Program Plan, yet this program is in its infancy, and many of the identified actions are still in their initial stages. It may be several years in the future before many of these actions are implemented.

"New" Concepts for Steelhead Management

The diverse structure of rainbow trout populations described in the preceding sections is not a new concept: the extreme variability in life history and the close relationship between non-anadromous and anadromous forms was recognized early-on (Jordan 1894, 1895; Snyder 1928; Taft 1934; Shapovalov and Taft 1954) and is illustrated by the following quote from Jordan (1895):

It is said by anglers that the brook trout exist in the mountains and the salmon trout come up from the sea and "promiscuously mix with it." This

5. Another example of the chinook salmon emphasis in Central Valley anadromous fish programs was evident at the Salmonid Symposium—of the 18 papers presented at the symposium, 14 dealt with chinook salmon exclusively, three with anadromous fish in general, and only this one addressed steelhead.

*seems another way of saying that the brook trout (irideus) and the salmon trout (gairdneri) are but forms or states of the same fish.*⁶

Although classified originally as different species and later as different subspecies, the taxonomic relationship of the anadromous and non-anadromous rainbow trout forms posed considerable difficulties to early taxonomists (Jordan 1894; Kendall 1921; Taft 1934). Taft (1934) and Shapovalov and Taft (1954) aptly described the variability in rainbow trout population structure. In recent years, these concepts appear to have been largely ignored in the application of rainbow trout management, and non-anadromous and steelhead rainbow trout are usually treated as separate stocks in management schemes.

This management dichotomy is brought about not only by an incomplete understanding or appreciation of the complexity of rainbow trout population structure, but is also largely due to institutional limitations. In many cases, such as within the DFG, coordination of management and policy development for non-anadromous and steelhead rainbow trout are under the auspices of different organizational divisions, and in the case of federal ESA jurisdiction, two different cabinet-level departments (Interior and Commerce departments, respectively).

The latter example has led to a curious and biologically questionable decision by the federal government in the promulgation of the ESA for steelhead. NMFS stated in the Final Rule listing some ESUs of steelhead (NMFS 1997b) that “available evidence suggests that resident rainbow trout should be included in listed ESU’s...where resident *O. mykiss* have the opportunity to interbreed with anadromous fish below natural or man-made barriers...”; and “NMFS believes that resident fish can help to buffer extinction risks to an anadromous population.” Further, “NMFS believes that available data suggest that resident rainbow trout are in many cases part of steelhead ESUs.” Despite these findings, NMFS deferred to USFWS, who asserted their ESA jurisdiction for resident (non-anadromous) fish. USFWS stated that there was no evidence to suggest that non-anadromous rainbow trout needed ESA protection and concluded that only the anadromous forms of each ESU could be listed under the ESA by NMFS (NMFS 1997b). Because of this, non-anadromous rainbow trout were specifically excluded from the listing. Thus, we have a unique and potentially problematic situation (from a recovery standpoint) where some individuals of a listed species may be protected under the ESA, while their progeny are not. This is also problematic from an enforcement and protection standpoint because the life-history fate of a juvenile rain-

6. Use of the specific epithets *irideus* and *gairdneri* indicates that Jordan was referring to non-anadromous and steelhead rainbow trout, not *Salvelinus fontinalis* or other Pacific salmon species.

bow trout is indeterminable unless the fish has smolted, thus ESA protection may be denied for the component of the population that most needs it.

The likelihood that anadromous and non-anadromous rainbow trout can form a single interbreeding population in a particular stream has important management implications, which can only be addressed through an integrated management strategy that treats all rainbow trout occupying a stream or continuous stream reaches as a single population, regardless of life history differences within the population. Management of steelhead must include measures to protect and restore non-anadromous rainbow trout, and especially the ecological linkages between the different forms. The large-scale disruption of this linkage that has occurred in the Central Valley through the placement of impassable dams on many streams may go a long way in explaining the significant decline of Central Valley steelhead stocks.

The necessity of a strategy that integrates the management of non-anadromous and steelhead rainbow trout was recognized by Snyder (1928) long ago, who made this insightful, yet mostly unheeded statement:

We have steelheads and stream trout, and conservation of the one depends absolutely upon conservation of the other. We burn the candle at both ends when we overfish both the steelheads and stream trout. We are awakening to the fact that we can not both destroy the steelheads and maintain the rainbows.

We may have begun to awaken in the 1920s, but apparently we hit the snooze button and went back to sleep. If we are to effectively manage and recover Central Valley steelhead, we must bring our management and restoration strategies more in line with rainbow trout population structure and dynamics and we must recognize that steelhead need to be managed separately from chinook salmon stocks. Because most of their historical habitat is now inaccessible, the most effective recovery strategies will be those that focus on restoring access to former habitats, where natural conditions are conducive to spawning and rearing and the resiliency that is inherent in a diverse population structure can be fully expressed. This may have ancillary benefits to water users as well, given that in many regulated stream systems today, steelhead can only be maintained by providing suitable flows and cool water temperatures, and this can and does exact a significant water cost. Allowing steelhead to spawn and rear in their former habitats will likely alleviate the need to provide these conditions in the downstream reaches below dams.

References

- AA Rich & Associates. 2000. The relationship between water temperature and juvenile steelhead growth and productivity in the Corte Madera Creek watershed, Marin County, California. Project proposal submitted for CALFED funding dated 5/15/2000.
- Allendorf FW. 1975. Genetic variability in a species possessing extensive gene duplication: genetic interpretation of duplicate loci and examination of genetic variation in populations of rainbow trout [Ph.D. thesis]. University of Washington. 97 p.
- Allendorf FW, Utter FM. 1979. Population genetics. In: Hoar W, Randall D, Brett J, editors. Fish Physiology. Volume VIII. New York: Academic Press. p 407–55.
- Bailey ED. 1954. Time pattern of 1953–54 migration of salmon and steelhead into the upper Sacramento River. DFG unpublished report. 4 p.
- Barnhart RA. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Southwest)—steelhead. USFWS Biol Rep 82(11.60). US Army Corps of Engineers, TR EL–82–4. 21 p.
- Behnke RJ. 1972. The systematics of salmonid fishes of recently glaciated lakes. J Fish Res Board Can 29(6):639–71.
- Behnke RJ. 1992. Native trout of western North America. American Fisheries Society Monograph nr. 6. 275 p.
- Beland TJ, Braun EL. 1952. A report on Mendocino National Forest stream improvement. Project 7X–301.
- Bell MC. 1986. Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program. Portland (OR): U.S. Army Corps of Engineers, North Pacific Division. 290 p.
- Bovee KD. 1978. Probability-of-use criteria for the family Salmonidae. Instream flow information paper 4. US Fish and Wildlife Service, FWS/OBS–78/07. 79 p.
- Boydston LB. 1977. California's steelhead program. In: Hassler T, VanKirk R, editors. Proceedings of the genetic implications of steelhead management symposium, 1977. Calif. Coop. Fish. Res. Unit special report 77–1. p. 26–30.
- Burgner RL, Light JT, Margolis L, Okazaki T, Tautz A, Ito S. 1992. Distribution and origins of steelhead trout (*Oncorhynchus mykiss*) in offshore waters of the north Pacific Ocean. International North Pacific Fisheries Commission. Bull. nr. 51.

- Busby PJ, Johnson OW, Wainwright TC, Waknitz FW, Waples RS. 1993. Status review for Oregon's Illinois River winter steelhead. US Department of Commerce, NOAA technical memo. NMFS-NWFSC-10. 85 p.
- Busby PJ, Wainwright TC, Bryant GJ, Lierheimer LJ, Waples RS, Waknitz FW, Lagomarsino IV. 1996. Status review of west coast steelhead from Washington, Idaho, Oregon, and California. US Department of Commerce, NOAA technical memo. NMFS-NWFSC-27.
- [CACST] California Advisory Committee on Salmon and Steelhead Trout. 1988. Restoring the balance. 1988 annual report. 84 p.
- [CALFED] CALFED Bay-Delta Program. 2000. Ecosystem Restoration Program Plan, volume 1. Ecological attributes of the San Francisco Bay-Delta watershed. Programmatic EIS/EIR technical application.
- [DFG] California Department of Fish and Game. 1952. Interoffice correspondence from A.C. Taft to files regarding steelhead run in Putah Creek, Yolo County dated 5 February 1952.
- [DFG] California Department of Fish and Game. 1955. Letter from L. Shapovalov to R.E. Dederick dated 2 March 1955.
- [DFG] California Department of Fish and Game. 1965. California Fish and Wildlife Plan.
- [DFG] California Department of Fish and Game, Water Projects Branch. 1967. Sacramento Valley east side investigations: Appendix C – Fish and wildlife. California Department of Water Resources. Bulletin nr. 137. p 177-295.
- [DFG] California Department of Fish and Game. 1978a. Observations on downstream migration of salmonid smolts in Cottonwood Creek. California Department of Fish and Game unpublished report.
- [DFG] California Department of Fish and Game. 1978b. Inventory of fishes of Cottonwood Creek, California. California Department of Fish and Game unpublished report.
- [DFG] California Department of Fish and Game. 1979. A summary of fish and wildlife studies and recommendations for the US Army Corps of Engineers' proposed Cottonwood Creek Project. California Department of Fish and Game unpublished report.
- [DFG] California Department of Fish and Game. 1984. Yuba River steelhead run during winter of 1976-77. Memorandum from Ron Rogers to Yuba River files dated 2 March 1984.

- [DFG] California Department of Fish and Game. 1985. Memorandum from B. Loudermilk to files regarding Stanislaus River snorkel and faceplate survey for chinook salmon dated 23 August 1985.
- [DFG] California Department of Fish and Game. 1997. Letter from J. Schafer to G. Griffen (NMFS) regarding DFG comments on Proposed Rule to list steelhead under the Endangered Species Act, dated 6 January 1997.
- [DFG] California Department of Fish and Game. 2000a. Steelhead rainbow trout in San Mateo Creek, San Diego County, California. Report submitted to the National Marine Fisheries Service. 22 p.
- [DFG] California Department of Fish and Game. 2000b. Memorandum from R. Baxter to D. McEwan regarding Calaveras River smolt steelhead sampling dated 21 April 2000.
- [DFG] California Department of Fish and Game. 2001. Memorandum from K. Kundargi to files regarding observation of steelhead in the Tuolumne River dated 21 January 2001.
- [DWR and USBR] California Department of Water Resources, US Bureau of Reclamation. 1999. Effects of the Central Valley Project and State Water Project operations from October 1998 through March 2000 on steelhead and spring-run chinook salmon. Biological Assessment. 211 p.
- CH2M Hill. 1985. Klamath River basin fisheries resource plan. Prepared for the US Department of Interior.
- Clark GH. 1929a. Sacramento-San Joaquin salmon fishery in California. California Division of Fish and Game. Fish Bulletin 137.
- Clark GH. 1929b. Sacramento River salmon fishery. California Fish and Game 15(1):1-10.
- CMARP Steering Committee. 1999. Recommendations for the implementation and continued refinement of a comprehensive monitoring, assessment, and research program. 142 p.
- Cramer SP, Alley DW, Baldrige JE, Barnard K, Demko DB, Dettman DH, Farrell B, Hagar JM, Keegan TP, Laird A, Mitchell WT, Nuzum RC, Orton R, Smith JJ, Taylor TL, Unger PA, Van Dyke ES. 1995. The status of steelhead populations in California in regards to the Endangered Species Act. Special report submitted to the National Marine Fisheries Service on behalf of the Association of California Water Agencies. 190 p.
- Demko DB, Cramer SP. 1997. Outmigrant trapping of juvenile salmonids in the lower Stanislaus River, Caswell State Park Site 1996. Final report submitted to the US Fish and Wildlife Service under subcontract to CH2M Hill. 144 p.

- Demko DB, Cramer SP. 1998. Outmigrant trapping of juvenile salmonids in the lower Stanislaus River, Caswell State Park Site 1997. Final report submitted to the US Fish and Wildlife Service under subcontract to CH2M Hill. 101 p.
- Demko DB, Gemperle G, Cramer SP, Philips A. 1999. Outmigrant trapping of juvenile salmonids in the lower Stanislaus River, Caswell State Park Site 1996. Final report submitted to the US Fish and Wildlife Service under subcontract to CH2M Hill. 131 p.
- Elliott JM. 1994. Quantitative ecology and the brown trout. Oxford University Press. 304 p.
- Entrix, Inc. 1994. Results of fish passage monitoring at the Vern Freeman Diversion Facility, Santa Clara River, 1994. Prepared for the United Water Conservation District.
- Entrix, Inc. 1995. Results of fish passage monitoring at the Vern Freeman Diversion Facility, Santa Clara River, 1994. Prepared for the United Water Conservation District.
- Entrix, Inc. 1996. Results of fish passage monitoring at the Vern Freeman Diversion Facility, Santa Clara River, 1994. Prepared for the United Water Conservation District.
- Entrix, Inc. 1997. Results of fish passage monitoring at the Vern Freeman Diversion Facility, Santa Clara River, 1994. Prepared for the United Water Conservation District.
- Erman DC, Hawthorne VM. 1976. The quantitative importance of an intermittent stream in the spawning of rainbow trout. *Trans Am Fish Soc* 105:675-81.
- Erman DC, Leidy GR. 1975. Downstream movement of rainbow trout fry in a tributary of Sagehen Creek, under permanent and intermittent flow. *Trans Am Fish Soc* 3:467-73.
- Everest FH. 1971. An ecological and fish cultural study of summer steelhead in the Rogue River, Oregon. Annual progress report. Oregon State Game Commission Anadromous Fish Project, AFS-31.
- Everest FH. 1973. Ecology and management of summer steelhead in the Rogue River. Fishery research report nr. 7. Oregon State Game Commission.
- Fausch KD. 1984. Profitable stream positions for salmonids: relating specific growth rates to net energy gain. *Can J Zool* 62:441-51.
- Fausch KD. 1993. Experimental analysis of microhabitat selection by juvenile steelhead (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*) in a British Columbia stream. *Can J Fish Aquatic Sci* 50:1198-1207.

- Folmar LC, Dickhoff WW. 1980. The parr-smolt transformation (smoltification) and seawater adaptation in salmonids. A review of selected literature. *Aquaculture* 21:1-37.
- Fry DH, Jr. 1952. Fisheries problems of the Feather River with especial reference to the proposed Oroville Dam. California Department of Fish and Game memorandum report.
- Hallock RJ. 1989. Upper Sacramento River steelhead, (*Oncorhynchus mykiss*), 1952-1988. Report to the Fish and Wildlife Service. 85 p.
- Hallock RJ, Van Woert WF. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. *California Fish and Game* 45(4):227-96.
- Hallock RJ, Van Woert WF, Shapovalov L. 1961. An evaluation of stocking hatchery-reared steelhead rainbow trout (*Salmo gairdnerii gairdnerii*) in the Sacramento River system. California Department of Fish and Game. Fish Bulletin 114. 74 p.
- Hanson HA, Smith OR, Needham PR. 1940. An investigation of fish-salvage problems in relation to Shasta Dam. 166 p.
- Herbold B, Moyle PB. 1989. The ecology of the Sacramento-San Joaquin Delta: a community profile. US Fish Wildl Serv Biol Rep 85(7.22). 106 p.
- Hooper DR. 1973. Evaluation of the effects of flows on trout stream ecology. Emeryville (CA): Pacific Gas and Electric. 97 p.
- [IEP Steelhead PWT] Interagency Ecological Program Steelhead Project Work Team. 1998. Steelhead life-stage assessment protocol. 4 p.
- [IEP Steelhead PWT] Interagency Ecological Program Steelhead Project Work Team. 1999. Monitoring, assessment, and research on Central Valley steelhead: status of knowledge, review of existing programs, and assessment of needs. In: Comprehensive monitoring, assessment, and research program plan technical appendix VII-A-11.
- Jonsson B. 1985. Life-history patterns of freshwater resident and sea-run migrant brown trout in Norway. *Trans Am Fish Soc* 114:182-94.
- Jordan DS. 1894. Salmon and trout of the Pacific coast. 13th biennial report of the State Board of Fish Commissioners of the State of California for the years 1893-1894.
- Jordan DS. 1895. Notes on the fresh-water species of San Luis Obispo County.
- Jordan DS, Gilbert CH. 1882. Synopsis of the fishes of North America. *Bull US Nat Muse*. volume III, nr. 16.

- Kendall WC. 1921. What are rainbow trout and steelhead trout? *Trans Am Fish Soc* 50:187-199.
- Leitritz E, Lewis RC. 1980. Trout and salmon culture (hatchery methods). *California Fishery Bulletin* nr. 164. University of California.
- Maslin PE, McKinney WR. 1994. Tributary rearing of Sacramento River salmon and steelhead. Interim report dated 30 October 1994. 45 p.
- Mayott CJ. 1997. Operation of the Hills Ferry Salmon Barrier, 1996. California Department of Fish and Game, Region 4 report dated 29 June 1999.
- McEwan D, Jackson TA. 1996. Steelhead restoration and management plan for California. California Department of Fish and Game.
- McEwan D, Nelson J. 1991. Steelhead restoration plan for the American River. California Department of Fish and Game. 40 p.
- Mills TJ, McEwan DR, Jennings MR. 1997. California salmon and steelhead: beyond the crossroads. In: Stouder D, Bisson P, Naiman R, editors. *Pacific salmon and their ecosystems: status and future options*. New York (NY): Chapman & Hall. p 91-111.
- Moyle PB, Baltz DM. 1985. Microhabitat use by an assemblage of California stream fishes: developing criteria for instream flow requirements. *Trans Am Fish Soc* 114:695-704.
- Murphy GI. 1946. A survey of Stony Creek, Grindstone Creek, and Thomes Creek drainages in Glenn, Colusa, and Tehama counties. California Department of Fish and Game, Inland Fisheries Branch administrative report 46-15. 16 p.
- Murphy GI. 1951. The fishery of Clear Lake, Lake County, California. *California Fish and Game* 37(4):439-84.
- Myrick CA. 1998. Temperature, genetic, and ration effects on juvenile rainbow trout (*Oncorhynchus mykiss*) bioenergetics [PhD dissertation]. University of California, Davis.
- [NMFS] National Marine Fisheries Service. 1996a. Status review of west coast steelhead from Washington, Idaho, Oregon, and California. NOAA technical memo. NMFS-NWFSC-27. 260 p.
- [NMFS] National Marine Fisheries Service. 1996b. Factors for decline: a supplement to the Notice of Determination for west coast steelhead under the Endangered Species Act. 83 p.
- [NMFS] National Marine Fisheries Service. 1997a. Status review update for deferred and candidate ESUs of west coast steelhead. Prepared by NMFS West Coast Steelhead Biological Review Team.

- [NMFS] National Marine Fisheries Service. 1997b. Endangered and threatened species: listing of several Evolutionary Significant Units (ESUs) of West Coast steelhead. Federal Register 62(159):43940-1.
- Needham PR, Smith OR, Hanson HA. 1941. Salmon salvage problems in relation to Shasta Dam, California, and notes on the biology of the Sacramento River salmon. Transactions of the American Fisheries Society. 17th annual meeting.
- Nielsen JL. 1994. Molecular genetics and stock identification in Pacific salmon (*Oncorhynchus* spp.) [Ph.D. thesis]. University of California, Berkeley. 167 p.
- Nielsen JL, Lisle TE, Ozaki V. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Trans Am Fish Soc 123:613-26.
- Northcote TG. 1997. Why sea run? An exploration into the migratory/residency spectrum of coastal cutthroat trout. In: Hall JD, Bisson PA, Gresswell RE, editors. Sea-run cutthroat trout: biology, management, and future conservation. Corvallis (OR): Oregon Chapter, American Fisheries Society. p 20-26.
- Painter RE, Wixom LH, Taylor SN. 1977. An evaluation of fish populations and fisheries in the post-Oroville project Feather River. Report submitted to the California Department of Water Resources in accordance with Federal Power Commission License nr. 2100.
- Reiser DW, Bjornn TC. 1979. Habitat requirements of anadromous salmonids. General technical report PNW-96. Portland (OR): USDA, Forest Service, Pacific Northwest Forest and Range Experiment Station. 54 p.
- Reynolds FL, Mills TJ, Benthin R, Low A. 1993. Restoring Central Valley streams: a plan for action.
- Reynolds FL, Reavis RL, Schuler J. 1990. Central Valley salmon and steelhead restoration and enhancement plan. California Department of Fish and Game. 115 p.
- Roelofs TD. 1983. Current status of California summer steelhead (*Salmo gairdneri*) stocks and habitat, and recommendations for their management. Report to the US Forest Service, Region 5. 77 p.
- Rich AA. 2000. Water temperature requirements for chinook salmon and steelhead trout. Testimony submitted to the State Water Resources Control Board, Yuba River hearings, 1 May 2000 (Exhibit S-DFG- 39). 12 p.
- Royal LA. 1972. An examination of the anadromous trout program of the Washington State Game Department. Washington Department of Game. 176 p.
- Savvaitova KA, Kuzishchin KV, Maksimov SV, Pavlov SD. 1997. Population structure of mikizha, *Salmo mykiss*, in the Utkholok River (western Kamchatka). Translated from Voprosy Ikhtiologii in volume 37 nr. 2. J Ichthyology 37(3):216-225.

- Savvaitova KA, Maksimov VA, Mina MV, Novikov GG, Kokhmenko LV, Matsuk VE. 1973. The noble trouts of Kamchatka: systematics, ecology, and possibilities of using them as the object of trout-culture and acclimatization. Russia: The Voronezh University Publishers.
- Shapovalov L. 1944. Preliminary report on the fisheries of the Santa Ynez River system, Santa Barbara County, California. Calif. Dept. of Fish and Game, Inland Fisheries Branch administrative report 44-14. 22 p.
- Shapovalov L, Taft AC. 1954. The life histories of the steelhead rainbow trout (*Salmo gairdneri*) and silver salmon (*Oncorhynchus kisutch*) with special reference to Waddell Creek, California, and recommendations regarding their management. Calif. Department of Fish and Game. Fish Bulletin 98. 373 p.
- Shirvell CS. 1990. Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying streamflows. Can J Fish Aquat Sci 47:852-61.
- Smith SH. 1950. Upper Sacramento River sport fishery. US Fish and Wildlife Service Special Scientific Report: Fisheries. Nr. 34. 44 p.
- Snider B, Titus R. 1996. Evaluation of juvenile anadromous salmonid emigration monitoring in the Sacramento River near Knights Landing, November 1995-July 1996. California Department of Fish and Game report.
- Snyder JO. 1928. California trout. California Fish and Game 14(2):121-2.
- Staley JR. 1976. American River steelhead, *Salmo gairdnerii gairdnerii*, management, 1956-1974. California Department of Fish and Game Anadromous Fisheries Branch administrative report nr. 76-2. 41 p.
- Taft AC. 1934. California steelhead experiments. Transactions of the American Fisheries Society. 64th annual meeting.
- Thompson K. 1972. Determining stream flows for fish life. In: Proceedings, Instream Flow Requirement Workshop. Vancouver (WA): Pacific NW River Basin Comm. p 31-50.
- Thorpe JE. 1987. Smolting vs. residency: developmental conflict in salmonids. In: Dadswell MJ, Klauda RJ, Moffitt CM, Saunders RL, Rulifson RA, Cooper JE, editors. Common strategies of anadromous and catadromous fishes. Proceedings of the American Fisheries Society Symposium 1. Boston, MA. p 244-252.
- Titus RG. 2000. Adult steelhead collected in the Calaveras River below New Hogan Dam in March 2000. California Department of Fish and Game Stream Evaluation Program report. 9 p.
- Titus RG, Erman DC, Snider WM. History and status of steelhead in California coastal drainages south of San Francisco Bay. Forthcoming.

- Titus RG, Mosegaard H. 1992. Fluctuating recruitment and variable life history of migratory brown trout, *Salmo trutta* L., in a small, unstable stream. *J Fish Biol* 41:239-55.
- [Upper Sacramento River FRHAC] Upper Sacramento River Fisheries and Riparian Habitat Advisory Council. 1989. Upper Sacramento River Fisheries and Riparian Habitat Management Plan. Report prepared for The Resources Agency, State of California. 158 p.
- [USFWS] US Fish and Wildlife Service. 1997. Revised draft restoration plan for the anadromous fish restoration program.
- [USFWS and DFG] US Fish and Wildlife Service, California Department of Fish and Game. 1953. A plan for the protection and maintenance of salmon and steelhead in the American River, California, together with recommendations for action. Unpublished report dated 20 July 1953. 47 p.
- Van Woert W. 1958. Time pattern of migration of salmon and steelhead into the upper Sacramento River during the 1957-58 season. California Department of Fish and Game, Inland Fisheries Branch administrative report nr. 58-7.
- Vestal EH. 1965. Observations on the fish and wildlife resources of the upper Kings River, middle and south forks, Fresno County, with recommendations for management. California Department of Fish and Game unpublished report.
- Voight HN, Gale DB. 1998. Distribution of fish species in tributaries of the lower Klamath River: an interim report, FY 1996. Technical Report No. 3. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. 71 p.
- Wales JH. 1939. General report of investigations of the McCloud River drainage in 1938. *California Fish and Game* 25(4):272-309.
- Wedemeyer GA, Saunders RL, Clarke WC. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. *Mar Fish Rev* 42:1-14.
- Wilson GM, Thomas WK, Beckenbach AT. 1985. Intra- and inter-specific mitochondrial DNA sequence divergence in *Salmo*: rainbow, steelhead, and cutthroat trouts. *Can J Zool* 63:2088-94.
- Withler IL. 1966. Variability in life-history characteristics of steelhead trout (*Salmo gairdneri*) along the Pacific coast of North America. *J Fish Res Board Can* 23(3):365-93.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Sierra Nevada ecosystem project: final report to Congress. Volume III: assessments, commissioned reports, and background information. Davis (CA): University of California, Centers for Water and Wildlife Resources. p 309-61.

- Yoshiyama RM, Fisher FF, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. *N Am J Fish Manage* 18:487-521.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 2001. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids*. Volume 1. Sacramento (CA): California Department of Fish and Game.
- Zimmerman CE. 2000. Ecological relation of sympatric steelhead and resident rainbow trout in the Deschutes River, Oregon [PhD thesis]. Corvallis (OR): Oregon State University. 116 p.

Notes

- Titus R. (California Department of Fish and Game). Telephone conversation with author in November 1999.
- Behnke R. (Colorado State University). Written correspondence with author in February 2001.

Applications of Population Genetics to Conservation of Chinook Salmon Diversity in the Central Valley

D. Hedgecock, M.A. Banks, V.K. Rashbrook, C.A. Dean,
and S.M. Blankenship

Uses of Modern Population Genetics in Conservation

Population genetics is playing an increasingly important role in the conservation of salmonid resources in the Pacific Northwest. The National Marine Fisheries Service considers a salmon population worthy of conservation under the U.S. Endangered Species Act if it represents an Evolutionary Significant Unit (ESU), "...a population (or group of populations) that (1) is substantially reproductively isolated from other conspecific population units, and (2) represents an important component in the evolutionary legacy of the species" (Waples 1991, 1995). Genetic data provide an important, though indirect means for establishing the degree of reproductive isolation between conspecific populations. Indeed, numerous studies of electrophoretically detectable protein polymorphisms carried out over the past 30 years on Pacific salmon species have shown that a high degree of spatial substructure and reproductive isolation results from their homing behavior (Utter 1991). With the advent of DNA markers, particularly mitochondrial and microsatellite DNA markers, resolution of reproductively isolated or partially isolated populations has become more precise. Here, we describe progress resolving chinook salmon diversity and stock structure in the Central Valley of California.

Modern tools of population genetics, for example, using polymorphic protein markers, also allow us to address problems that could not formerly be approached. Whereas protein markers had long supported the statistical allocation of catch in mixed ocean fisheries to contributing spawning populations (Utter and Ryman 1993), highly polymorphic microsatellite DNA markers now enable us to ascertain the origins of individual fish. We describe how individual assignment of salmon, first achieved for Central Valley chinook salmon, has become an integral part of a hatchery supplementation program for the endangered Sacramento River winter chinook salmon. Individual assignment is also being used to identify winter-run juvenile migration patterns through the Sacramento-San Joaquin Delta and in assigning ocean catches to various Central Valley stocks, some of which are threatened or endangered.

The use of highly polymorphic DNA markers has also enabled tremendous improvements in identifying parentage and kinship. Indeed, determining the parentage of hatchery-reared winter chinook in the supplementation program was our original motivation for developing microsatellite DNA markers. Since then, microsatellite markers have provided, aside from a description of genetic diversity within and among Central Valley stocks, an important validation of the demographic model used to assess the genetic effect of the hatchery supplementation program for winter run. Microsatellite markers also allow the assessment of kinship in juvenile samples, which often are the only material that can be collected from small, threatened, or endangered populations. In the past, population geneticists advised against using juvenile samples because of the potentially confounding effects of family structure on the estimation of adult allele frequencies (Allendorf and Phelps 1981). Now, however, highly polymorphic markers enable the kinship of juveniles to be detected and the effects of family structure to be removed. Such data not only allow the genotypes and allele frequencies of the unobserved adult population to be reconstructed but also shed light on the reproductive behavioral ecology of salmon populations.

Genetic Diversity of Chinook Salmon in the Central Valley

Phenotypic Diversity

Major spawning subpopulations among California's Central Valley chinook salmon have very similar anatomical and morphological features but marked differences in timing of spawning, juvenile emergence, early rearing and migration from the freshwater habitat to the ocean. Four runs have been named—winter, spring, fall, and late-fall—based on the season when most individuals from a subpopulation return to freshwater for spawning (Stone 1874; Fry 1961). Spawning not only occurs at a distinct time for each run, with only partial overlap between temporally adjacent runs, but, historically at least, often in a distinct habitat (for example, major rivers compared with higher elevation streams; see Fisher 1994). This natural, spatial and temporal isolation of the various spawning habitats has been greatly perturbed by human activity. For example, 150 years ago, spring and fall runs overlapped in spawning time but were geographically isolated; spring run spawned in the upper headwaters and fall run, in rivers and major streams of the lower valley floor. Forced co-existence of these two runs caused by substantial damming and loss of habitat in recent years, however, has led to concern for their genetic integrity (Cope and Slater 1957; Banks and others 2000).

Several studies have focused on genetic characterization of California's Central Valley chinook salmon using of a variety of genetic marker types. Results will be presented for each type, separately, followed by a synthesis across marker types. Wright's (1931) standardized variance of allele frequencies among subpopulations, F_{ST} , is used to measure genetic diversity among runs and to compare results from different marker classes.

Allozymes

A study of 39 allozyme loci (Bartley and others 1992) revealed little divergence between fall and winter-run chinook salmon, with Wright's standardized allele-frequency variance, $F_{ST} = 0.01$. However, the authenticity of winter-run samples used in this study has been questioned (D. Teel and G. Winans, personal communication, see "Notes"). A more recent study (Winans and others forthcoming), based on more extensive sampling, indicates significant genetic structure among Central Valley chinook runs, in accord with results based on other marker types (Figure 1A).

Mitochondrial DNA

Nielsen and others (1994) reported substantial divergence in frequencies of six mtDNA haplotypes ($F_{ST} = 0.24$) among recognized Central Valley chinook stocks (Figure 1B). However, the probability that any two Central Valley chinook haplotypes are identical is 0.7, precluding use of this marker alone for individual identification. Further, maternal inheritance of mtDNA limits use of this marker type for genetic inference related to family structure.

Microsatellites

The listing of winter run under the federal and California endangered species acts increased the need to discriminate among subpopulations of Central Valley chinook. Banks and others (1999) cloned and developed ten new microsatellites for this task, verifying that their inheritance was Mendelian. A subsequent study used these and other microsatellites from the literature to characterize 41 population samples taken throughout the valley between 1991 and 1997 (Banks and others 2000; Figure 2). Samples encompassed geographic and temporal variation within subpopulations. Maximum likelihood methods were used to correct for family structure among samples comprised of juveniles (see "Parentage and Kinship"), as well as to correct for run admixture in adult samples (see "Avoiding Hybridization in the Winter Run Supplementation Program"). This extensive sampling and sample adjustments established a database of accurate and precise estimates of microsatellite allele frequencies for Central Valley chinook.

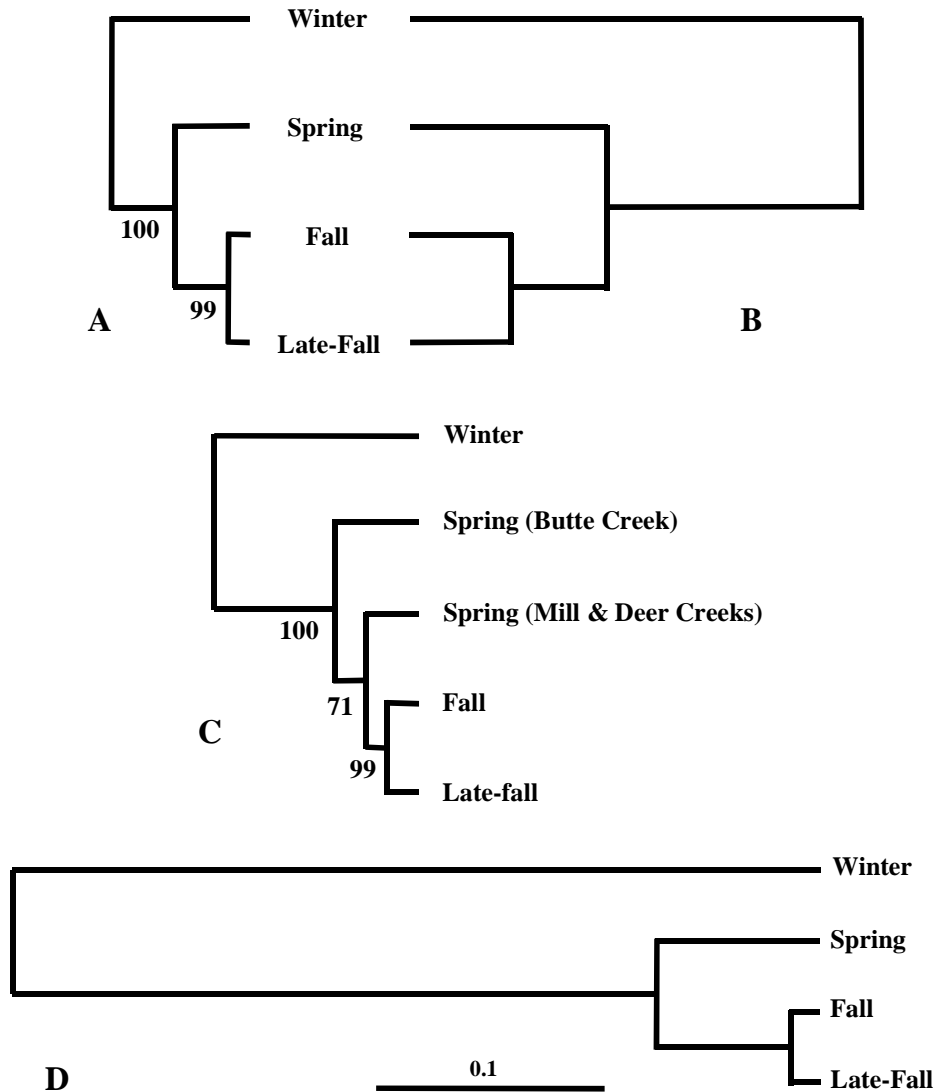


Figure 1 Genetic distances among subpopulations of Central Valley chinook salmon calculated from data on four genetic markers, (A) allozymes or proteins (after Winans and Teal, unpublished); (B) control region sequences of mitochondrial DNA (after Nielsen and others 1994); (C) microsatellite DNA markers (after Banks and others 2000); (D) a class II member of the Major Histocompatibility Complex (after Kim and others 1999). Numbers next to nodes in (A) and (C) are the percentages of 1,000 bootstrapped trees showing that same node.

The most important finding of this study is that chinook salmon of the Central Valley in California have substantial genetic diversity and structure (Figure 1C). Except for discovery of two distinct lineages of spring run, this study revealed a genetic structure congruent with the recognized winter, spring, fall and late-fall spawning runs (Fisher 1994). It is, perhaps, surprising but encouraging that such biological diversity has survived more than 100 years of massive habitat destruction, exploitation, and artificial propagation (Yoshiyama and others 1998, this volume). Moreover, the data retrospectively support the designation of winter run and spring run as Evolutionary Significant Units protected under the U.S. Endangered Species Act (Waples 1995; NMFS 1994, 1999). Winter run, whose blend of ocean- and stream-type life-history characteristics is unique in the species (Healey 1991), is the most distinctive of the subpopulations in the Central Valley. The next most distinctive subpopulations are the spring runs, particularly those in Butte Creek, which have unique life-history adaptations (Yoshiyama and others 1996). Formerly the most abundant chinook salmon throughout the Central Valley, spring chinook are presently found in only a few tributaries of the Sacramento River, primarily those considered in this study (Fisher 1994; Yoshiyama and others 1996, 1998). Finally, fall and late-fall runs, though closely related, are significantly different at 10 microsatellite markers (Figure 1C) and differ in geographic range, run timing, and size at maturity (Fisher 1994).

Winter run, and to a lesser extent spring run from Butte Creek, show lower levels of allelic diversity than other runs, suggesting that these populations experienced past reductions in size (bottlenecks). This may also explain a part of their divergence from the other runs in the Central Valley (Hedrick 1999). Despite spatial and temporal overlap of chinook salmon spawning runs in the Central Valley, no evidence for natural hybridization among runs was found by Banks and others (2000). A commonly held view is that most spring-run populations have hybridized with fall run and that Butte Creek spring run, in particular, has hybridized with the Feather River fall hatchery stock (Yoshiyama and others 1998). However, two observations contradict this hypothesis. First, genotypic proportions in the Butte Creek spring run mostly conform to random mating expectations. Second, Butte Creek spring clusters farther from the fall run than does spring run from Deer and Mill creeks (Figure 1C), not closer as expected under the hybridization hypothesis. Run-admixture can nevertheless occur and appears a likely cause for significant linkage disequilibrium in hatchery populations (see "Avoiding Hybridization in the Winter Run Supplementation Program") and, to a lesser extent, in samples from certain populations spawning in the wild.

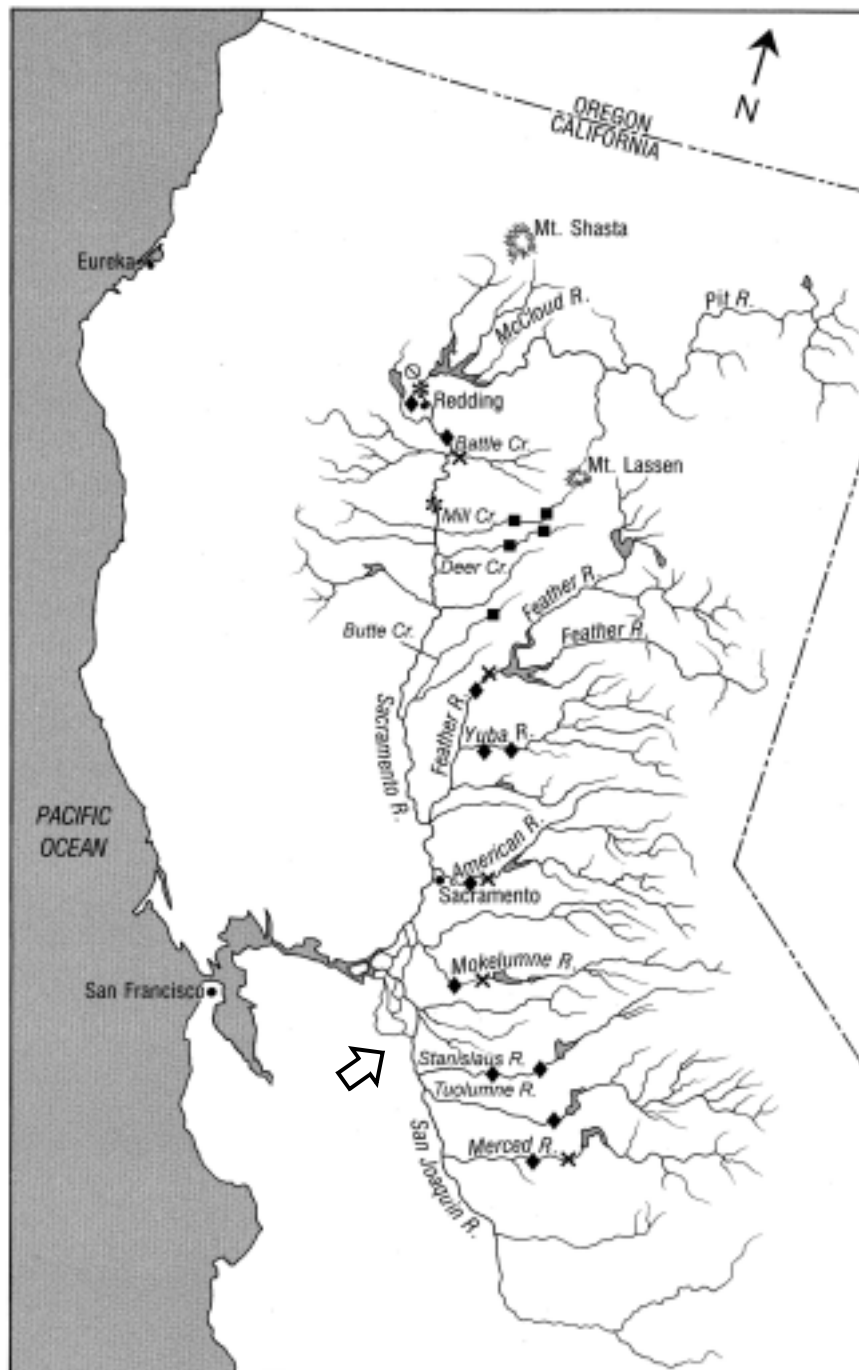


Figure 2 Map of the Central Valley, showing the localities from which chinook salmon were sampled for genetic analysis (from Banks and others 2000). The open arrow indicates the general location of the SWP and CVP water pumping plants in the Sacramento-San Joaquin Delta.

Nielsen and others (2000) also characterized Central Valley chinook using 10 microsatellites, five of which were in common with those used by Banks and others (2000). Overall relationships between major subpopulations revealed by this study were the same as described by Banks and others (2000), the two studies both verifying the distinctiveness of winter and spring runs. In contrast to Banks and others (2000), however, Nielsen and others (2000) found that year-to-year variation within runs was substantial (nearly 11% of the total variance) though not significant. Moreover, they found significant heterogeneity within fall-run hatchery samples as well as within spring run samples from Mill, Deer, and Butte creeks. However, Nielsen and others (2000) used samples of juveniles and did not correct for the potential effects of kinship within such samples.

A Class II Gene of the Major Histocompatibility Complex

Characterization of class II MHC variation for Central Valley chinook salmon also found significant frequency differences among runs ($F_{ST} = 0.129$) except between fall and late-fall (Kim and others 1999). Thus, in consensus with other marker types, MHC variation demonstrates the distinctiveness of the endangered winter run (Figure 1D), with no evidence for significant variation among winter run samples from different years.

Concordance Across Marker Types

The pictures of divergence among chinook salmon runs in the Central Valley painted by the above marker types are concordant. Winter run is the most distinctive subpopulation, followed by spring run, then fall and late fall. There is substantially less variation among the geographic samples within a subpopulation than among subpopulations, even for the fall run, which is presently the most widely distributed. Finally, most studies have not detected significant temporal variation within a spawning population.

Mitochondrial DNA and MHC appear, at first glance, to show greater divergence among runs than do microsatellite markers (compare Figures 1B and 1D with 1C). The average 0.078 F_{ST} estimate for 10 microsatellite loci from Banks and others (2000) is less than the F_{ST} of 0.24 from the mtDNA data of Nielsen and others (1994) or the 0.129 estimate from the MHC class II b1 exon (Kim and others 1999). However, some microsatellite markers do show comparable levels of divergence (for example, Ots-2 with F_{ST} of 0.169). Another difference among microsatellites, MHC, and mitochondrial DNA, which may account for different levels of among-subpopulation divergence, is in numbers of alleles. The last two marker types have substantially fewer alleles than is typical of microsatellites. Several researchers (Hedrick 1999 and references therein) have shown that, for highly variable loci such as microsatellites, F_{ST} is constrained by high within-population diversity. This problem can be overcome

to some extent by using different distance metrics, including the percentage of individuals correctly assigned to their sample of origin, as discussed in the next section.

Mixed Stock Analysis and Individual Assignment

Mixed Stock Analysis vs. Individual Assignment

Distinguishing among the five morphologically similar subpopulations (fall, winter, late fall, Butte Creek, and Mill and Deer Creek springs) of chinook salmon in the Central Valley is important in fisheries management and conservation, particularly because some stocks are protected and others are not. Population genetics has been applied to this problem, in several different contexts, involving adult and juvenile phases of the life cycle. Run identification is made possible by the baseline survey of microsatellite DNA variation in population samples from the Central Valley (Banks and others 2000). Two population genetic methods are used to distinguish among the different spawning runs: mixed stock analysis (MSA) and individual assignment to population of origin. MSA is a population-based method that has been widely used to estimate the relative contributions of salmon stocks to random samples of adults taken in mixed ocean harvests (Milner and others 1985; Utter and Ryman 1993). In the Central Valley, MSA can be applied to mixtures of chinook salmon juveniles from different spawning populations, which co-mingle in the Sacramento-San Joaquin Delta during emigration from the freshwater habitat. Individual assignment, on the other hand, estimates the most likely population of origin for an individual, based on the odds that its genotype belongs to one rather than to another subpopulation (Paetkau and others 1994; Banks and Eichert 2000). Individual assignment is useful when adults are collected for hatchery propagation or when the presence of protected runs must be ascertained in small samples from fish salvage operations at Delta pumping facilities. Actually, as we shall illustrate, a combination of the two methods is needed to analyze mixtures in the Delta and the ocean fishery.

The Central Valley chinook baseline can be used in computer simulations to illustrate the two methods and to demonstrate their relative merits and effectiveness. The baseline data are randomly permuted to produce 200 individuals from each of the five populations: winter, spring from Mill and Deer creeks, spring from Butte Creek, fall and late fall. Each individual has been genotyped for seven of the 10 markers studied by Banks and others (2000). This creates a mixed stock of 1,000 individuals of known population descent, with which to evaluate the characteristics and performance of each method. MSA uses the Statistical Package for Analysis of Mixture (SPAM, version 3.2, available at <http://www.cf.adfg.state.ak.us/geninfo/research/genetics/soft->

ware/spamPage.htm). Individual assignment is performed following procedures described by Banks and Eichert (2000). Statistical power of assignment is then assessed through population simulations (Banks and others forthcoming). Results of both MSA and individual assignment are presented in Table 1. MSA accurately estimates the contributions from all runs; the actual contribution of each subpopulation, 0.2, lies within two standard errors of the estimated contribution. On the other hand, although 99.7% of simulated winter-run individuals are correctly assigned, only 60% to 80% of non-winter individuals are correctly assigned. The poorer assignment of non-winter fish is attributable to the smaller genetic distances separating the non-winter runs from one another. MSA is better at identifying the contributions of all runs because it uses not only the information present in the baseline but also the information in the mixed population sample. Individual assignment, like MSA, uses the baseline information but has only the limited information from the single individual being assigned.

Although the five subpopulations contribute equally to our example mixture, they are likely to contribute very unequally to most samples from natural populations. The accuracy of individual assignment based strictly on the likelihood of genotypes in baseline populations is affected by the relative contribution from source populations. If genotype A is relatively common in run 1 but quite rare in run 2, individuals with genotype A will be assigned to run 1 in the absence of information on the relative abundance of the two runs. However, if run 2 is 1000 times more abundant than run 1, then the likelihood that genotype A belongs to run 2 increases. Prior information on the relative abundance of runs can be used to correct the individual assignment, using Bayesian statistical methods (Shoemaker and others 1999). We shall show that MSA can provide estimates of relative run abundance that are, in turn, used to adjust the assignment.

Individual assignment for spring, fall, and late-fall populations could be improved with additional markers that increase the genetic distance among these runs. New microsatellite markers have been developed for spring-run characterization (Greig and Banks forthcoming), and additional markers for Pacific salmon are being developed by West Coast laboratories at an increasing rate. A program for evaluating the power of alternate sets of markers through re-sampling simulations (WHICHLOCI, Banks and others forthcoming) now facilitates the choice of markers needed to reach a given level of accuracy and precision of individual assignment. The cost of assigning individuals to non-winter runs will be greater, of course, than the cost of assigning winter run individuals, because more markers will be required.

Table 1 Results for assigning components of a mixed stock to population origin using mixed stock analysis and individual assignment^a

| Mixed Stock Analysis | | | |
|------------------------------|------------------|---------------------------|-----------------------|
| Population | Expected | Estimate | Standard Error |
| Winter | 0.2000 | 0.2009 | 0.0126 |
| SP-MD | 0.2000 | 0.2185 | 0.0122 |
| SP-B | 0.2000 | 0.1899 | 0.0122 |
| Fall | 0.2000 | 0.1874 | 0.0093 |
| Late fall | 0.2000 | 0.2033 | 0.0122 |
| Individual Assignment | | | |
| Population | % Correct | Standard Deviation | |
| Winter | 99.7226 | 0.508 | |
| SP-MD | 77.5115 | 4.0626 | |
| SP-B | 90.4935 | 2.9192 | |
| Fall | 69.7285 | 4.5995 | |
| Late fall | 80.0215 | 4.0677 | |

^a A mixed stock was composed of 200 individuals from each of five populations created through permutation of baseline populations. The mean, standard deviation, and standard error estimated from 1,000 bootstrap samples.

Avoiding Hybridization in the Winter-run Supplementation Program

In 1991, the U.S. Fish and Wildlife Service initiated a hatchery supplementation program aimed at helping to prevent the Sacramento River winter chinook salmon from going extinct. Research on the genetic effect of the program is described in the next section. Here, we consider a problem that became apparent in 1995, namely, how to distinguish winter run from non-winter run in selecting broodstock for the hatchery supplementation program.

In 1995, 38 of 85 fish collected by the USFWS for the winter-run supplementation program failed to mature in the hatchery. These non-maturing fish appeared to have phenotypic and genotypic affinities with spring chinook. A re-investigation of 140 winter-run brood stock that had been used for winter-run supplementation from 1991 to 1995 revealed strong, non-random associations (called gametic-phase or linkage disequilibria or LD) of allelic combinations at pairs of microsatellite loci. Typically, adults from naturally spawning populations show random associations of allelic combinations at pairs of loci, because mating of Pacific salmon occurs randomly with respect to genetic

markers (Figure 3). One significant cause of LD in samples from salmon populations, particularly hatchery populations, is admixture of non-interbreeding populations (Waples and Smouse 1991). Mixture was already evident from the spring-run affinities of non-maturing brood fish captured in 1995. The implication of finding significant levels of LD in the spawning fish was that spring run had been hybridized with winter run in the supplementation program and that possibly all samples of winter-run had actually been mixtures of two or more distinct runs.

By identifying and removing individuals with multiple, pairwise allelic combinations typical of spring run, it was possible to divide the mixture into winter and spring components, each of which is in linkage equilibrium. A multifactorial analysis of individual genotypes confirms the separation based on analysis of LD (Figure 4). Nineteen of the 140 winter brood fish clearly cluster with 37 of 38 non-maturing 1995 brood fish (one of the non-maturing fish clusters with the true winter-run fish). The remaining 121 “true” winters show only 2% of loci-pairs with significant gametic-phase disequilibria when 5% are expected by chance (Figure 4). The winter-run baseline population now comprises these “true” winters plus samples of carcasses obtained from the Sacramento River, which were similarly purged of a few, admixed non-winters.

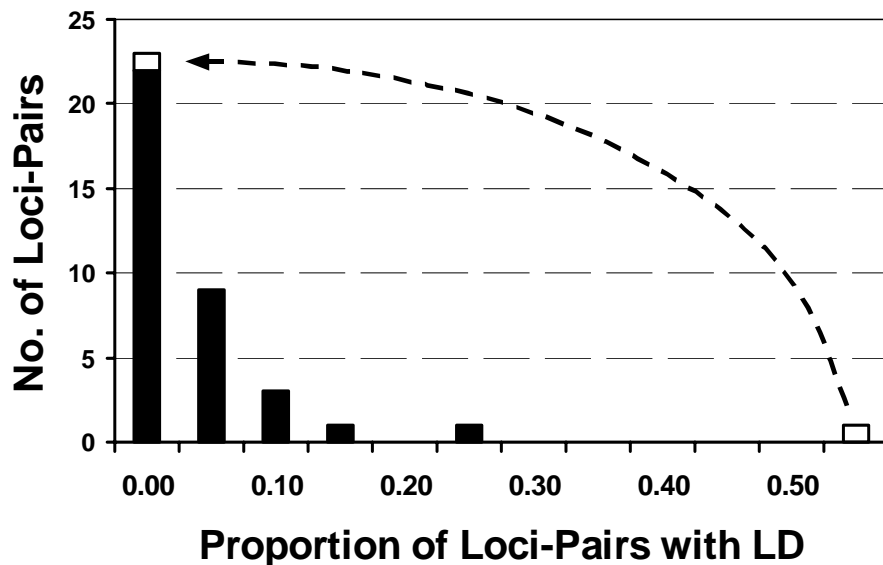


Figure 3 The proportion of loci-pairs with significant associations (linkage disequilibrium or LD) in 36 samples of non-winter chinook salmon from the Central Valley (black bars). The extremely high proportion of significant associations in winter chinook captured for a hatchery supplementation program (white bar) is greatly reduced after likely non-winter fish are removed from the sample (dotted arrow).

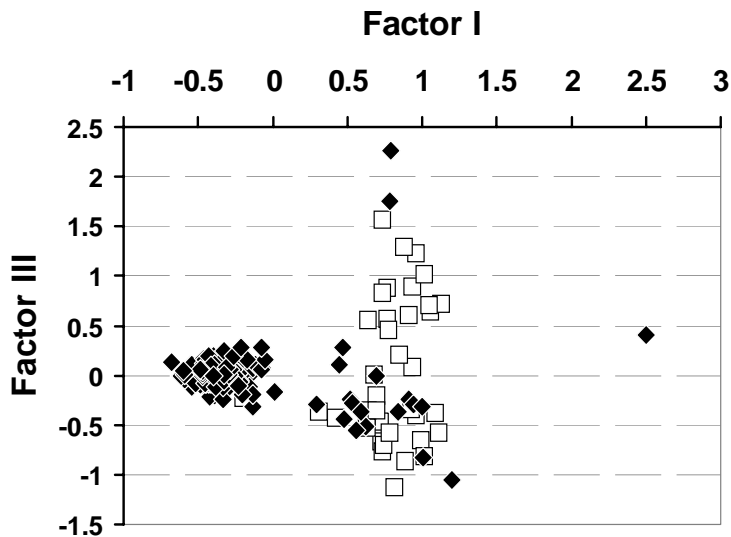


Figure 4 Genetic clustering of chinook salmon captured for hatchery-propagation of the winter run. Scores of each fish on the first and third factors derived from factorial correspondence analysis of genotypes at 13 loci are plotted. Black diamonds denote the 140, putative winter run spawned from 1991 through 1995. White boxes denote adults captured in 1995 that did not mature and that clustered closely with spring-run populations (not shown). Note that 19 of the putative winter run adults cluster with the non-maturing, spring-run fish, while one of the non-maturing fish clusters with the true winter run.

The discovery of unwitting winter-spring hybridization in 1995, together with the observation in the same year that hatchery-spawned fish were returning to Battle Creek rather than the Sacramento River (where they had been released as fry), caused the USFWS to temporarily halt the supplementation program. The program resumed in 1998, after construction of the Livingston Stone Fish Culture Facility on the Sacramento River solved the imprinting problem and development of sufficient microsatellite markers and baseline data permitted accurate assignment of brood stock. A “rapid response” program was implemented in 1998 to genotype potential brood stock caught at the fish traps at the Keswick and Red Bluff diversion dams on the Sacramento River, as well as fish returning to the Coleman National Fish Hatchery on Battle Creek. A caudal fin clip is taken from each trapped fish and sent to the Bodega Marine Laboratory for analysis of seven microsatellite markers. Simulation results suggest that 99.1% (s.d. = 0.91%) of true winter run are correctly identified when the criterion for assignment is 10:1 or greater odds that a given genotype belongs to the winter run. More importantly, the percentage of non-winter run incorrectly assigned to winter run under this criterion is 0.02% (s.d. = 0.16%). Thus, a threshold of 10:1 or greater odds provides ample protection against incorporating non-winter run adults into the hatchery supplementa-

tion program for winter run. We typed 356 fish from the winter spawning runs of 1998 to 2000, of which 240 were assigned to the winter run (Table 2). From 1997 to 2000, we continued to monitor fish returning to the Coleman National Fish Hatchery; out of 357 examined, 108 were winters, most of which were relocated to spawning habitat in the Sacramento River.

Table 2 Numbers of chinook adults caught at the Keswick Dam (Sacramento River) and at the Coleman National Fish Hatchery (Battle Creek) subsequently genotyped and assigned to winter run

| Year | <i>Keswick Dam (Sacramento River)</i> | | <i>Coleman National Fish Hatchery (Battle Creek)</i> | |
|------|---|------------------------------|--|------------------------------|
| | <i>Number genotyped</i> | <i>Number winter run</i> | <i>Number genotyped</i> | <i>Number winter run</i> |
| 1997 | --- | --- | 116 | 89 |
| 1998 | 152 | 107 | 117 | 15 |
| 1999 | 42 | 24 | 70 | 0 |
| 2000 | 162 | 109 | 54 | 4 |

Juvenile Emigration and Delta Salvage

We have applied both MSA and individual assignment methods to juvenile chinook emigrating from California's Central Valley. Though peak times of emigration for the different subpopulations differ, all five populations potentially intermix in the Sacramento-San Joaquin Delta (Fisher 1994). Understanding the timing of winter-run emigration and their occurrence at the State Water Project (SWP) and the Central Valley Project (CVP) is essential to evaluating the effects of these water-pumping facilities on the endangered Sacramento River winter-run chinook salmon. More than 5,000 samples were collected and genotyped over five consecutive seasons (1995–2000) at two large water pumping facilities in the Sacramento-San Joaquin Delta. In this application, in contrast to the selection of hatchery brood stock, we use an assignment criterion of even or better odds, rather than 10:1 odds, that a given genotype belongs to the winter run. The aim of this criterion is to protect all winter run at the expense of also protecting some non-winter run fish incorrectly assigned by the inclusive criterion.

The contributions of various spawning populations to the mixture of juveniles in the Delta are expected to be unequal and variable with the season. Winter run contributes a large number of samples early in the season and fewer samples later, when fall run dominates fish salvage. However, as mentioned above, the relative abundance of the various subpopulations can have a sub-

stantial effect on individual assignment. To correct for this, we use MSA to estimate the relative abundance of the runs among juveniles of similar size caught around the same time as each individual whose genotype alone suggests winter-run provenance. In other words, MSA establishes the prior probability for the runs and, using a Bayesian statistical approach, serves to correct the individual population assignment for unequal relative frequencies of subpopulation (Dean and others forthcoming). In practice, the assignment of relatively few individuals is affected by this correction (Figure 5). Having thus identified which emigrating juveniles are winter run, we see that the results do not accord with the growth model predicting the relationship of juvenile size and provenance. Winter juveniles are caught at similar sizes throughout the season of emigration, in contrast to the growth curves that presently define the subpopulations for purposes of determining take of protected winter run (Figure 5). The growth curves clearly overestimate the losses of winter-run in the Delta. These results further suggest the hypothesis that the winter run does not use the lower Delta as rearing habitat.

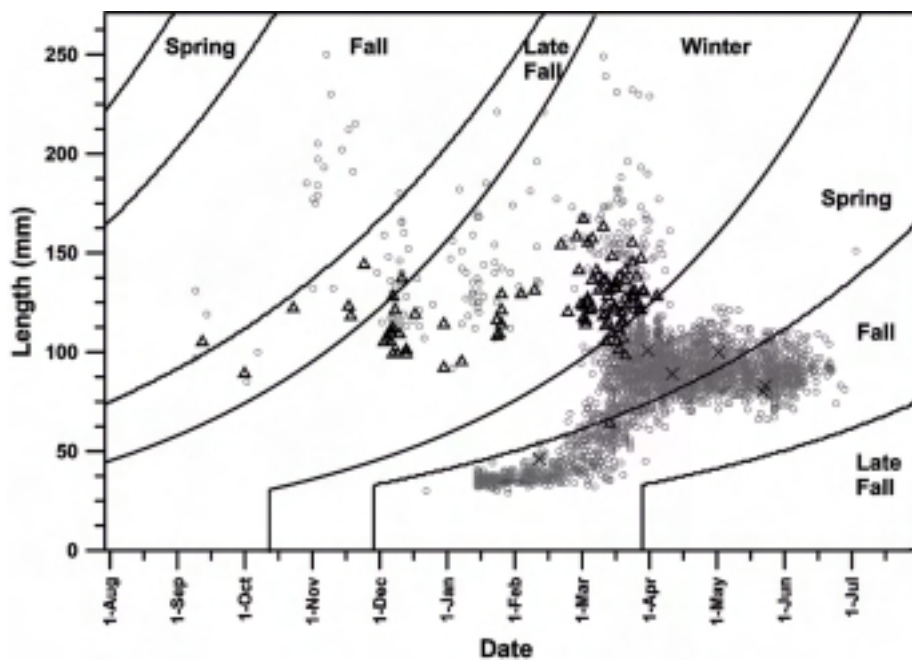


Figure 5 Size and date of salvage for 4,045 chinook juveniles genotyped between 1995 and 1999. Those individuals with greater than even odds of being assigned to the winter run, adjusted for the abundance of all runs at the time of sampling, are indicated with triangles. Six individuals, whose assignments to winter were overturned by adjustment for relative run-abundance, are indicated with an "X." All other genotyped samples are indicated with small open circles. Curved lines represent the confidence limits around the expected growth curves for each of the named runs.

Ocean Catch

Another area where the use of genetic stock identification can help protect threatened stocks is in the monitoring of ocean catches. A recent study considers data from an experimental fishery conducted for seven days (April 15–21, 1997) between Lopez and Magu points in southern California (Banks and others forthcoming). As above, both MSA and individual assignment were applied in this study, as was the Bayesian correction of individual assignment for the actual abundance of contributing stocks. Three data sources were used, microsatellites, allozymes and coded-wire tag recoveries, and all indicated a surprisingly large harvest of the endangered winter run in this short fishery (about 2%). Precise identification of protected subpopulations within watersheds, such as winter run from the Central Valley, could lead to more refined fishery management. For example, it should be possible to determine the specific conditions and/or locations that minimize the harvest of protected runs, so that a more targeted fishery on non-threatened stocks could be sustained. Real-time genetic monitoring could be used to verify run composition of harvest, and effort could be re-directed as necessary to ensure maximum harvest of chosen runs. Such use of population genetics for adaptive fisheries management could facilitate sustainable salmon harvests even in areas where threatened stocks exist.

Genetic Impact of Supplementation

Ryman-Laikre Models

Having plummeted from annual runs of nearly 100,000 fish in the late 1960s to less than 200 fish in 1991, the winter chinook was protected under both California and federal endangered species laws in the early 1990s. A hatchery supplementation program was initiated with broodstock captured from the Sacramento River and taken to the Coleman National Fish Hatchery on Battle Creek for maturation and spawning. Progeny were tagged internally with coded-wire tags, marked externally by clipping of adipose fins, and released into the Sacramento River as juveniles (smolts). Hedrick and others (1995, 2000a, 2000b) have used a demographic population genetics model (Ryman and Laikre 1991) to evaluate the potential genetic effect of this hatchery supplementation program from 1991 through 1995. One danger of hatchery supplementation is that it could dilute the gene pool by flooding the natural population with the offspring of a few individuals. However, this dilution need not occur.

The effect of hatchery supplementation on genetic diversity is mediated through effects on the effective size (N_e) of the natural population. N_e is the size of a mathematically ideal population that has rates of genetic drift and

inbreeding equivalent to those in the actual population under study. In the mathematically ideal population, there are equal numbers of both sexes, adults mate at random, and variance in number of offspring per adult is binomial or Poisson. The number of adults N in the ideal population is, by definition, equal to the effective size, and the ratio of $N_e:N = 1.0$. In actual populations, the sexes may not be in equal numbers, mating may not be at random, or the variance in offspring number may be larger than binomial or Poisson.

For a hatchery-supplemented population, N_e depends on the effective sizes of the hatchery and wild components of the population and on the relative proportion of hatchery origin fish (after Ryman and Laikre 1991):

$$N_e = \frac{N_{eh} \times N_{ew}}{x^2 N_{ew} + y^2 N_{eh}}$$

N_{eh} and N_{ew} are the effective sizes of the hatchery and wild components of the population, respectively, while x and y are their relative contributions to the total ($x + y = 1.0$). For each year, we calculate N_{eh} from data on the number of progeny contributed by each male and female brood fish to the release of juveniles. The $N_e:N$ ratio for the naturally spawning population is assumed to have a lower bound of 0.10 (Bartley and others 1992) and an upper bound of 0.33 (R.S. Waples, personal communication, see Notes). These ratios are multiplied by the run-size estimate in any year to obtain N_e before capture of adults (that is, what the effective size would have been without supplementation). The N_{ew} after capture of adults for supplementation discounts N_e by the number of adults taken to the hatchery. Estimates of the Ryman-Laikre model parameters from 1991 through 1995 for the winter-run supplementation program are given in Table 3. There are four important points to note:

1. The supplementation program likely had little, or perhaps a slightly positive effect on winter-run effective population size in all years. N_e with supplementation is higher than N_e without supplementation in all years, if $N_e:N = 0.1$; N_e with supplementation is higher than without in three of five years at $N_e:N = 0.33$ (Table 3).
2. The proportion of fish contributed by the hatchery, x , tends to be high in years when the run size was low (1994), and low when the run size was high (1992, 1995). Estimates of x are based on numbers of females, their egg production, and the survival of these progeny from egg to smolt stages. For hatchery stocks, the egg to smolt survival is esti-

mated to be 28.5%, about twice as high as estimates for egg to smolt survival in the wild, 14.7% (Hedrick and others 2000). Of course, this boost in early survival is precisely what makes hatchery supplementation such an attractive recovery option in the first place.

3. The genetic effect of supplementation depends critically on x , unless run size is very small. For example, if x in 1995 had been 10% higher, the effect would have been negative, at $N_e/N = 0.33$, rather than positive. On the other hand, in years of low run size, the hatchery program increases effective population size over a broad range of parameter combinations.
4. Ratios of effective to actual numbers of captive broodstock, $N_{eh}:N_{hr}$ ranged from 0.47 to 0.8, much higher than the $N_e:N$ ratio assumed for the naturally spawning population (0.1 to 0.33). This boost in $N_e:N$ ratio of the hatchery component is what counterbalances the dilution of natural genetic diversity that seemingly ought to occur in a simple view of supplementation.

Table 3 Effect of hatchery supplementation on the effective size of Sacramento River winter chinook salmon, 1991-1995

| <i>Parameter</i> | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---------------|----------------|---------------|--------------|---------------|
| Naturally spawning run size | 191 | 1180 | 341 | 189 | 1361 |
| No. taken captive (N_h) | 23 | 29 | 18 | 29 | 47 |
| No. of breeding parents ($N_f + N_m$) | 15 | 26 | 12 | 26 | 42 |
| Hatchery effective size (N_{eh}) | 7.02 | 19.07 | 7.74 | 23.2 | 29.2 |
| (95% confidence interval) | (3.58, 12.22) | (12.67, 26.68) | (3.20, 13.34) | (15.9, 30.8) | (21.3, 37.8) |
| N_{eh}/N_h ratio | 0.468 | 0.733 | 0.645 | 0.8 | 0.62 |
| Relative contribution from hatchery (x) | 0.159 | 0.061 | 0.130 | 0.407 | 0.083 |
| N_e without hatchery (lower & upper bounds) | 19.1 – 63.7 | 118 – 393.3 | 34.1 – 113.7 | 18.9 – 63.0 | 136.1 – 453.7 |
| N_{ew} (lower & upper bounds) | 16.8 – 56.0 | 115.1 – 383.6 | 32.3 – 107.7 | 16.0 – 53.3 | 131.4 – 438 |
| N_e with hatchery (lower & upper bounds) | 21.9 – 61.6 | 127.3 – 401.0 | 39 – 108.6 | 34.3 – 72.8 | 150.7 – 463.6 |

Since N_{eh} is based on adult contributions at release rather than at return and spawning, the above calculations are predictions of N_e . By typing microsatellite DNA markers (Banks and others 1999, 2000) on all returning, adipose fin-clipped adults, we were able to assign 93 fish from the 1994 year class to family (Hedrick and others 2000b). We found that the contributions at release of each fish spawned in the hatchery remained approximately the same at return (Table 4) and that the N_{eh} calculated for spawning adults was within the predicted 95% confidence intervals (Hedrick and others forthcoming).

As illustrated in this example, higher survival and higher $N_e:N$ ratios of hatchery offspring, combined with contributions that are inversely proportional to the wild stock size, can increase variance effective size and conserve more of the natural biodiversity than would have been conserved in the absence of supplementation. Hatchery enhancement does not necessarily constitute a threat to genetic resources; indeed, hatchery supplementation can help to retain biodiversity that would otherwise be lost from threatened and endangered populations without intervention. However, we agree with Waples and Do (1994) that supplementation programs are likely to succeed only when the initial environmental causes of population decline are ameliorated.

Table 4 The proportions of progeny released and returning from the different female and male parents of the 1994 brood year

| <i>Female</i> | <i>Releases</i> | <i>Returns</i> | <i>Male</i> | <i>Releases</i> | <i>Returns</i> |
|---------------|-----------------|----------------|-------------|-----------------|----------------|
| 3 | 0.080 | 0.108 | B | 0.102 | 0.097 |
| 4 | 0.070 | 0.054 | C | 0.073 | 0.097 |
| 5 | 0.058 | 0.075 | D | 0.107 | 0.172 |
| 6 | 0.054 | 0.065 | E | 0.139 | 0.086 |
| 7 | 0.056 | 0.032 | F | 0.120 | 0.161 |
| 8 | 0.053 | 0.022 | G | 0.128 | 0.065 |
| 9 | 0.054 | 0.054 | H | 0.102 | 0.108 |
| 11 | 0.054 | 0.075 | I | 0.147 | 0.172 |
| 12 | 0.062 | 0.032 | J | 0.070 | 0.032 |
| 13 | 0.092 | 0.086 | K | 0.029 | 0.011 |
| 14 | 0.032 | 0.022 | | | |
| 15 | 0.079 | 0.108 | | | |
| 16 | 0.066 | 0.108 | | | |
| 17 | 0.064 | 0.075 | | | |
| 18 | 0.071 | 0.043 | | | |
| 19 | 0.057 | 0.043 | | | |
| Total | 43,346 | 93 | Total | 43,346 | 93 |

Domestication Selection?

Concern is often expressed about genetic changes in supplemented populations resulting from artificial or domestication selection for survival in the hatchery environment or from shielding of adults or hatchery-reared progeny from natural selection (for example, Waples 1999). While this is undoubtedly true for production hatchery stocks of fall chinook salmon in the Central Valley, conservation hatcheries get brood stock continually from the wild and do not typically use hatchery-reared progeny to propagate the next generation. In this case, the efficiency of selection on a single pass through a hatchery is likely to be low, especially if differential survival among families is minimized.

Equivalence in the relative proportions of winter-run families at spawning, release, and return suggests low additive genetic variance for survival in the hatchery or at sea. Moreover, data on the relative numbers of naturally spawned and hatchery fish returning to the Sacramento River, though subject to large uncertainty (Botsford and Brittnacher 1998), suggest the hatchery contribution is not consistently less at return than at release. For 1995 through 1998, the proportions of hatchery-origin winter run, at return compared to release (three years before), are 6.1% vs. 6.1%, 20.1% vs. 16.1%, and 25.0% vs. 41.7% (addendum to USFWS ESA Section 10 Permit Supplement, dated February 20, 1998). These data suggest the relative survival of hatchery and wild fish in the wild is not grossly different, given the large uncertainty in the escapement estimates. In this one example, at least, we see little evidence for selection as the result of a single pass through a supplementation hatchery. The long-term risk to diversity from over-propagating a few adults appears to far outweigh the risk from artificial selection, at least in the winter-run propagation program. This need not be the finding in other programs, however. The important point is that data on family proportions at spawning, release, and adult stages allow evaluation of the relative strengths of selection and random drift and should be required for supplementation programs.

Hybridization in Production Hatcheries

Hybridization in the Coleman National Fish Hatchery Fall Stock

Analyses of linkage disequilibrium in samples of fall and late-fall chinook stocks propagated or heavily influenced by hatcheries show higher levels of LD than typically observed in naturally spawning stocks of chinook salmon (Figure 6). The median proportion of pairwise combinations of loci showing significant LD is 0.069 for hatchery stocks and 0.025 for naturally spawning adult chinook populations. A likely explanation for this slight elevation of LD in production hatchery stocks is recent admixture and hybridization between

fall and spring or between fall and late-fall stocks in the hatchery programs for fall and late-fall chinook. Because of the high genetic similarity of these stocks, however, information from many more loci will likely be needed to test this hypothesis. New microsatellite loci being developed for the diagnosis of spring chinook may help resolve the causes of LD in production hatchery stocks.

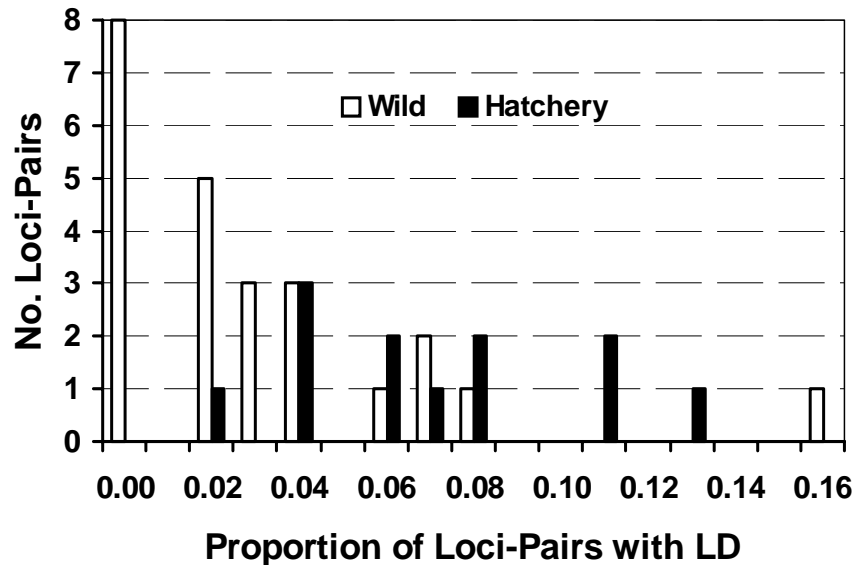


Figure 6 The proportion of loci-pairs with significant linkage disequilibrium in non-winter chinook stocks of the Central Valley. Hatchery populations (black bars) appear to have higher levels of linkage disequilibrium than naturally spawning populations (white bars). Hatchery populations include hatchery stocks as well as populations likely to be heavily affected by hatchery operations, such as late-fall in the Sacramento River. The wild population with significant LD at about one-sixth of the loci-pairs is a sample of spring run from Butte Creek that may have been contaminated with a few fall-run fish.

Hybridization of Fall-run and Spring-run in the Feather River Hatchery?

Hybridization of fall and spring run is thought to have occurred in the Feather River Hatchery, based on returns of tagged fall progeny during the spring-run spawning season and vice versa. Our analyses of samples from hatchery and naturally spawning chinook populations in the Feather River do not support this hypothesis, however. First, none of these populations shows significant linkage disequilibrium, unlike the winter and fall chinook stocks discussed above. Lack of LD suggests either that hybridization of fall with spring runs, such as those observed in Mill, Deer, and Butte creeks, has not occurred or that it has not occurred recently. Several generations of random mating fol-

lowing some past hybridization event could have reduced initial LD to non-detectable levels. Second, chinook in the Feather River cluster with the fall-run lineage in the Central Valley (Figure 7), not with the spring chinook lineages observed in Mill, Deer, and Butte creeks. This proximity of Feather River chinook to the fall-run lineage is observed when samples, whose origin is marked “unknown” by DFG collectors, are pooled after testing for and failing to find any significant heterogeneity among these samples. Still, few of the “unknown” samples can be included in the homogeneous pool of fall samples, so some slight but statistically significant genetic differentiation does exist between many of these unknown samples and fall chinook populations. The nature of this differentiation is still under investigation, but it seems not to be the result of hybridization. Finally, under the hypothesis of past hybridization followed by random mating, one might expect to see Feather River populations occupying a genetically intermediate position between fall and spring runs. Yet, there is no consistent tendency for Feather River “unknown” samples to have frequencies intermediate to fall and spring frequencies.

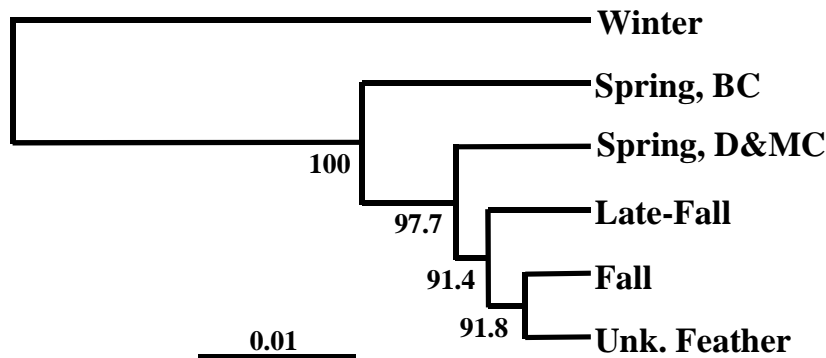


Figure 7 Clustering of Central Valley chinook samples by similarity at seven microsatellite loci shows chinook of unknown (spring?) race in the Feather River to be most closely related with fall chinook

Parentage and Kinship

One of the exciting new areas in population genetics is the application of highly polymorphic microsatellite DNA markers to questions of parentage and kinship in natural populations (O’Reilly and others 1998; Goodnight and Queller 1999; Bentzen and others 2000). These methods and markers are equally applicable to hatchery populations, in which the parents or potential parents are often known, as in the case of the winter-run hatchery supplementation program. In this case, the parents of any given progeny can be identi-

fied by simple matching algorithms; WHICHPARENT, a program facilitating such matching of progeny and parents, is available at <http://www-bml.ucdavis.edu/imc/Software.html>.

More difficult is ascertaining kinship when parents are unknown. In the course of our survey of variation in the Central Valley, for example, we had several samples of the threatened spring run that comprised only juveniles. In the past, population geneticists advised against using such samples because the presence of full- or half-sibs could bias allele-frequency estimates (Allendorf and Phelps 1981). Indeed, these samples showed significant departures from single locus and pairwise linkage equilibrium, compared to samples from naturally spawning adult populations. We investigated kinship in these spring-run chinook juvenile samples and attempted to estimate the allele frequencies of the adult spawning population from which they were derived (Banks and others 2000). This was done by first identifying groups of individuals showing significant odds of being full-sibs. Of the 206 individuals in these samples with sufficient genotypic information, 114 were involved in pairwise comparisons for which the hypothesis of a full-sib relationship was significantly more likely ($P < 0.01$) than the hypothesis that they were unrelated. Next, we determined the mating type or combination of parental genotypes at each locus with the maximum likelihood of producing the array of genotypes in each full-sib group. We then replaced these 114 individuals with 86 inferred parents. After adjustment of juvenile samples for kinship, the proportions of single- and multiple-locus genotypes within each conformed to random mating expectations. This procedure allowed us to use the information gained from juvenile samples in our Central Valley baseline data set.

These procedures for adjusting estimates of allele frequencies for kinship should be generally applicable to salmon molecular ecological studies. This is an active area of research, and several laboratories, including ours, are presently refining statistical approaches that will accurately recover parental genotypes from juvenile samples.

Conclusions

Population genetic analysis of highly polymorphic microsatellite DNA markers confirms the existence of genetically diverse subpopulations of chinook salmon in the Central Valley. These subpopulations correspond to the traditional seasonal runs, winter, spring, fall, and late-fall, though two distinct lineages of spring run have been identified, one in Mill and Deer creeks, the other in Butte Creek. The availability of a high quality genetic database for Central Valley chinook populations now enables identification of the run-composition of mixtures, which can occur at all stages of the life-cycle, using the traditional method of Mixed Stock Analysis (MSA). Moreover, the high

level of diversity among runs at microsatellite DNA markers enables the assignment of individuals to run with an unprecedented degree of accuracy and precision. Individual identification is useful in determining the presence of winter run at all phases of the life cycle. Confirming the run-origin of putative winter chinook brood stock is essential for the hatchery supplementation program. Identifying protected runs in the fish salvage operations at the CVP and SWP in the Delta and in ocean harvests are other important application of microsatellite DNA markers. Thus, the development and application of microsatellite DNA markers has significantly advanced knowledge of winter-run biology as well as conservation efforts. Extension of the methods developed for winter-run identification to threatened spring-run populations should now be straightforward.

References

- Allendorf FW, Phelps SR. 1981. Use of allelic frequencies to describe population structure. *Can J Fish Aquat Sci* 38:1507-14.
- Banks MA, Eichert W. 2000. WHICHRUN (Version 3.2): a computer program for population assignment of individuals based on multilocus genotype data. *J Hered* 91:87-9.
- Banks MA, Blouin MS, Baldwin BA, Rashbrook VK, Fitzgerald HA, Blankenship SM, Hedgecock D. 1999. Isolation and inheritance of novel microsatellites in chinook salmon (*Oncorhynchus tshawytscha*). *J Hered* 90:281-8.
- Banks MA, Rashbrook VK, Calavetta M J, Dean CA, Hedgecock D. 2000. Analysis of microsatellite DNA resolves genetic structure and diversity of chinook salmon (*Oncorhynchus tshawytscha*) in California's Central Valley. *Can J Fish Aquat Sci* 57:915-27.
- Bartley D, Gall GAE, Bentley B, Brodziak J, Gomulkiewicz R, Mangel M. 1992. Geographic variation in population genetic structure of chinook salmon from California and Oregon. *Fish Bull US* 90:77-100.
- Bentzen P, Olsen JB, McLean J, Seamons TR, and Quinn TP. 2000. Kinship analysis of Pacific salmon: insights into mating, homing and timing of reproduction. *J Heredity*. Forthcoming.
- Botsford LW, Brittnacher JG. 1998. Viability of Sacramento River winter-run chinook salmon. *Conserv Biol* 12:65-79.
- Fisher FW. 1994. Past and present status of Central Valley chinook salmon. *Conserv Biol* 8:870-3.

- Fry DH. 1961. King salmon spawning stocks of the California Central Valley, 1949-1959. *California Fish and Game* 47(1):55-71.
- Goodnight KF, Queller DC. 1999. Computer software for performing likelihood tests of pedigree relationship using genetic markers. *Mol Ecol* 8:1231-4.
- Healey MC. 1991. The life history of chinook salmon. In: Groot C, Margolis L, editors. *Pacific salmon life histories*. Vancouver, BC: University of British Columbia Press. p 39-52.
- Hedrick PW. 1999. Perspective: highly variable genetic loci and their interpretation in evolution and conservation. *Evolution* 53:313-8.
- Hedrick PW, Hedgecock D, Hamelberg S. 1995. Effective population size in winter-run chinook salmon. *Conserv Biol* 9:615-24.
- Hedrick PW, Hedgecock D, Hamelberg S, Croci SJ. 2000. The impact of supplementation in winter-run chinook salmon on effective population size. *J Hered* 9:112-6.
- Hedrick PW, Rashbrook VK, Hedgecock D. Effective population size of winter-run chinook salmon based on microsatellite analysis of returning spawners. *Can J Fish Aquat Sci*. Forthcoming.
- Kim JT, Parker KM, Hedrick PW. 1999. MHC differentiation in Sacramento River chinook salmon. *Genetics* 151:1115-22.
- Milner GB, Teel DJ, Utter FM, Winans GA. 1985. A genetic method of stock identification in mixed populations of Pacific salmon, *Oncorhynchus* spp. *Mar Fish Rev* 47:1-8.
- [NMFS] National Marine Fisheries Service. 1994. Endangered and threatened species; status of Sacramento River winter-run chinook salmon. *Federal Register* 59(2):440-50.
- [NMFS] National Marine Fisheries Service. 1999. Endangered and threatened species; Threatened status for two chinook salmon evolutionary significant units (ESUs) in California. *Federal Register* 64(179):50394-415.
- Nielsen JL, Fountain MC, Sundermeyer DR, Heine EL, Malone CL, Avelino OL. 2000. Microsatellite variation in chinook salmon spawning runs from the Central Valley, California, 1992-1997. Report to the California Department of Fish and Game. 38 p.
- Nielsen JL, Tupper D, Thomas WK. 1994. Mitochondrial DNA polymorphism in unique runs of chinook salmon (*Oncorhynchus tshawytscha*) from the Sacramento-San Joaquin river basin. *Conserv Biol* 8:882-4.
- O'Reilly PT, Herbinger C, Wright JM. 1998. Analysis of parentage determination in Atlantic salmon. *Anim Genet* 29:363-70.

- Paetkau D, Waits L, Clarkson P, Craighead L, Strobeck C. 1997. An empirical evaluation of genetic distance statistics using microsatellite data from bear (*Ursidae*) populations. *Genetics* 147:1943-57.
- Ryman N, Laikre L. 1991. Effects of supportive breeding on the genetically effective population size. *Conserv Biol.* 5:325-9.
- Shoemaker JS, Painer IS, Weir BS. 1999. Bayesian statistics in genetics: a guide for the uninitiated. *Trends in Genetics* 15:354-8.
- Stone L. 1874. Report of operations during 1872 at the United States salmon hatching establishment on the McCloud River. U.S. Commission on Fish and Fisheries, Report for 1872 and 1873, Part II: 168-215. Washington, D.C.
- Utter FM, Ryman N. 1993. Genetic markers and mixed stock fisheries. *Fisheries* 18:11-21.
- Utter FM. 1991. Biochemical genetics and fishery management: an historical perspective. *J Fish Biol* 39(Suppl A):1-20.
- Waples RS. 1991. Definition of "species" under the Endangered Species Act: application to Pacific salmon. National Oceanic and Atmospheric Administration Technical Memorandum, National Marine Fisheries Service F/NWC-194. Seattle (WA): Northwest Fisheries Science Center.
- Waples RS. 1995. Evolutionary significant units and the conservation of biological diversity under the Endangered Species Act. *Amer Fish Soc Symp* 17:8-27.
- Waples RS. 1999. Dispelling some myths about hatcheries. *Fisheries* 13:12-21.
- Waples RS, Do C. 1994. Genetic risk associated with supplementation of Pacific salmonids: Captive broodstock programs. *Can J Fish Aquatic Sci* 51:310-29.
- Waples RS, Smouse PE. 1990. Gametic disequilibrium analysis as a means of identifying mixtures of salmon populations. *Amer Fish Soc Symp* 7:439-58.
- Wright S. 1931. Evolution in Mendelian populations. *Genetics* 16:97-159.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. Sierra Nevada Ecosystem Project: final report to Congress. In: University of California, Center for Water and Wildlife Resources, Davis. Assessments, commissioned reports, and background information. p 309-362.
- Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. *N Am J Fish Manage* 18:487-521.

Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 2001. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1. Sacramento (CA): California Department of Fish and Game.

Notes

Teel D. (National Marine Fisheries Service, NW Fisheries Science Center, Seattle, Washington). June 1999 poster at the Coastwide Salmon Genetics meeting, University of Montana, Missoula, Montana.

Waples RS. (National Marine Fisheries Service, NW Fisheries Science Center, Seattle, Washington.) Personal communication with D. Hedgecock at December 1992 meeting of the Genetics subcommittee of the winter chinook captive breeding committee, UC Davis, with P. Hedrick, L. Botsford, and D. Hedgecock attending.

Winans G. (National Marine Fisheries Service, NW Fisheries Science Center, Seattle, Washington). June 1999 poster at the Coastwide Salmon Genetics meeting, University of Montana, Missoula, Montana.

Historical and Present Distribution of Chinook Salmon in the Central Valley Drainage of California

Ronald M. Yoshiyama, Eric R. Gerstung, Frank W. Fisher,
and Peter B. Moyle

Abstract

Chinook salmon (*Oncorhynchus tshawytscha*) formerly were highly abundant and widely distributed in virtually all the major streams of California's Central Valley drainage—encompassing the Sacramento River basin in the north and San Joaquin River basin in the south. We used information from historical narratives and ethnographic accounts, fishery records and locations of in-stream natural barriers to determine the historical distributional limits and, secondarily, to describe at least qualitatively the abundances of chinook salmon within the major salmon-producing Central Valley watersheds. Individual synopses are given for each of the larger streams that historically supported or currently support salmon runs.

In the concluding section, we compare the historical distributional limits of chinook salmon in Central Valley streams with present-day distributions to estimate the reduction of in-stream salmon habitat that has resulted from human activities—namely, primarily the construction of dams and other barriers and dewatering of stream reaches. We estimated that at least 1,057 mi (or 48%) of the stream lengths historically available to salmon have been lost from the original total of 2,183 mi in the Central Valley drainage. We included in these assessments all lengths of stream that were occupied by salmon, whether for spawning and holding or only as migration corridors. In considering only spawning and holding habitat (in other words, excluding migration corridors in the lower rivers), the proportionate reduction of the historical habitat range was far more than 48% and probably exceeded 72% because most of the former spawning and holding habitat was located in upstream reaches that are now inaccessible for salmon. Individual stream assessments revealed substantial differences among streams in the extent of salmon habitat lost. Some streams experienced little or no reduction (for example, Bear River, Mill Creek) while others were entirely eliminated from salmon production (for example, McCloud, Upper Sacramento, and Upper San Joaquin rivers.)

The river cañons, where the old bars were located, were romantic places previous to being disturbed and torn up by the gold-digger. The water was as clear as crystal, and above each ripple or rapid place was a long, deep pool, with water blue as turquoise, swarming with fish. Salmon at that time ran up all the streams as far as they could get, until some perpendicular barrier which they could not leap prevented further progress. (Angel 1882, p 402)

Introduction

The broad expanse of the Central Valley region of California once encompassed numerous salmon-producing streams that drained the Sierra Nevada and Cascade mountains on the east and north and, to a lesser degree, the lower-elevation Coast Range on the west. The large areal extent of the Sierra Nevada and Cascades watersheds, coupled with regular, heavy snowfalls in those regions, provided year-round streamflows for a number of large rivers which supported substantial—in some cases prodigious—runs of chinook salmon (*Oncorhynchus tshawytscha*). No less than 26 main Central Valley tributaries supported at least one annual chinook salmon run, with at least 23 of those streams supporting two or more runs each year.

In the Sacramento River basin, constituting the northern half of the Central Valley system (covering about 24,000 square miles; Jacobs and others 1993), most Coast Range streams historically supported regular salmon runs; however, those “westside” streams generally had streamflows limited in volume and seasonal availability due to the lesser amount of snowfall west of the valley, and their salmon runs were correspondingly limited by the duration of the rainy season. Some westside streams, such as Cache and Putah creeks, did not connect with the Sacramento River at all during dry years, and salmon runs only entered them opportunistically as hydrologic conditions allowed. In the San Joaquin River basin, composing much of the southern half of the Central Valley system (covering approximately 13,540 square miles; Jacobs and others 1993), a number of major streams such as the Merced, Tuolumne and upper San Joaquin rivers sustained very large salmon populations, while other streams with less regular streamflows (for example, Calaveras, Chowchilla and Fresno rivers) had intermittent salmon runs in years when rainfall provided sufficient flows. However, all of the westside San Joaquin basin streams, flowing from the Coast Range, were highly intermittent (Elliott 1882) and none are known to have supported salmon runs or any other anadromous fishes to any appreciable degree.

The great abundance of chinook salmon of the Central Valley was noted early in the history of colonization of the region by Euro-American people. The pioneer John Marsh, for example, wrote in 1844: “The magnificent valley through which flows the rivers San Joaquin and Sacramento is 500 miles long It is

intersected laterally by many smaller rivers, abounding in salmon” (Elliott 1882, p 44). However, following the California Gold Rush of 1849, the massive influx of fortune seekers and settlers altered the salmon spawning rivers with such rapidity and so drastically that the historic distributions and abundances of anadromous fish can be determined only by inference from scattered records, ethnographic information, and analysis of the natural features of the streams. Probably the only species for which adequate information exists to develop a reasonably complete picture is the chinook salmon – the most abundant and most heavily used of the Central Valley anadromous fishes.

In this report, we consolidate historical and current information on the distribution of chinook salmon in the major streams of the Central Valley drainage to provide a comprehensive assessment of the extent to which salmon figured historically in the regional landscape. This paper is based and expands on an earlier work (Yoshiyama and others 1996) to include additional historical information as well as more recent data on chinook salmon abundances. Hereafter, references to “salmon” pertain to chinook salmon.

The Four Runs of Central Valley Chinook Salmon

Four seasonal runs of chinook salmon occur in the Central Valley system – or more precisely, in the Sacramento River drainage – with each run defined by a combination of adult migration timing, spawning period, and juvenile residency and smolt migration periods (Fisher 1994). The runs are named after the season of adult upstream migration – winter, spring, fall and late-fall. The presence of four runs in the Sacramento River lends it the uncommon distinction of having some numbers of adult salmon in its waters throughout the year (Stone 1883a; Rutter 1904; Healey 1991; Vogel and Marine 1991). The fall and late-fall runs spawn soon after entering the natal streams, while the spring and winter runs typically “hold” in their streams for up to several months before spawning (Rutter 1904; Reynolds and others 1993). Formerly, the runs also could be differentiated to various degrees on the basis of their typical spawning habitats – spring-fed headwaters for the winter run, the higher-elevation streams for the spring run, mainstem rivers for the late-fall run, and lower-elevation rivers and tributaries for the fall run (CFC 1900a, 1900b; Rutter 1904; Fisher 1994). Different runs often occurred in the same stream – temporarily staggered but broadly overlapping (Vogel and Marine 1991; Fisher 1994), and with each run utilizing the appropriate seasonal streamflow regime to which it had evolved. On the average, the spring-run and winter-run fish generally were smaller-bodied than the other Central Valley chinook salmon, and late-fall run fish were the largest (Stone 1874; F. W. Fisher unpublished data).

Before the (US) American settlement of California, most major tributaries of the Sacramento and San Joaquin rivers probably had both fall and spring runs of chinook salmon. The large streams that lacked either adequate summer flows or holding habitat to support spring-run salmon, which migrate upstream during the spring and hold over the summer in pools, had at least a fall run and in some cases perhaps a late-fall run. The fall run undoubtedly existed in all Central Valley streams that had adequate flows during the fall months, even if the streams were intermittent during other parts of the year. Generally, it appears that fall-run fish historically spawned in the valley floor and lower foothill reaches (Rutter 1904)—below 500 to 1,000 ft elevation, depending on location—and probably were limited in their upstream migration by their egg-laden and deteriorated physical condition.

The spring run, in contrast, ascended to higher-elevation reaches—judging from spawning distributions observed in recent years and the reports of early fishery workers (Stone 1874; Rutter 1904). The California Fish Commission noted, “It is a fact well known to the fish culturists that the winter and spring run of salmon, during the high, cold waters, go to the extreme headwaters of the rivers if no obstructions prevent, into the highest mountains” (CFC 1890, p 33). Spring-run salmon, entering the streams while in pre-reproductive and peak physical condition well before the spawning season, were understandably better able to penetrate the far upper reaches of the spawning streams than were fall-run fish. Their characteristic life-history timing and other adaptive features enabled spring-run salmon to use high spring-time flows to gain access to the upper stream reaches—the demanding ascent facilitated by high fat reserves, undeveloped (and less weighty) gonads, and a generally smaller body size. The spring run, in fact, was generally required to use higher-elevation habitats—the only biologically suitable places—given its life-history timing. Spring-run fish needed to ascend to high enough elevations for over-summering to avoid the excessive summer and early-fall temperatures of the valley floor and foothills—at least to about 1,500 ft elevation in the Sacramento drainage and most likely correspondingly higher in the more southerly San Joaquin drainage¹. If the spring-run fish spawned in early fall, they needed to ascend even higher—at least to about 2,500 to 3,000 ft in the Sacramento drainage—to be within the temperature range (35 to 58 °F) required for successful egg incubation. Spring-run fish that spawned later in the season did not have to ascend quite so high because ambient temperatures would have started to drop as autumn progressed—but presumably there were constraints on how long they could delay spawning, set by decreasing stream-

1. English units of measurement for distances and elevations are used in this paper for ease of comparison with information quoted from earlier published work. Some locations are given by “river miles” (rm)—the distance from the mouth of the stream under discussion to the point of interest.

flows (before the onset of the fall rains), ripening of eggs, and deteriorating body condition.

The spring run probably was originally most abundant in the San Joaquin system, ascending and occupying the higher-elevation streams fed by snowmelt where they over-summered until the fall spawning season (Fry 1961). The heavy snowpack of the southern Sierra Nevada was a crucial feature in providing sufficient spring and early summer streamflows, which were the highest flows of the year (F. W. Fisher unpublished data). The more rain-driven Sacramento system was generally less suitable for the spring run due to lesser amounts of snowmelt and proportionately lower flows during the spring and early summer, but the spring run nonetheless was widely distributed and abundant in that system (Campbell and Moyle 1991). Some notable populations in the Sacramento drainage occurred in Cascades streams where cold-water springs provided adequate summer flows (for example, Upper Sacramento and McCloud rivers, Mill Creek). These coldwater springs emanated from the porous lava formations around Mount Shasta and Mount Lassen and were ultimately derived from snowmelt from around those peaks and also from glacial melt on Mount Shasta.

The winter run—unique to the Central Valley (Healey 1991)—originally existed in the upper Sacramento River system (Little Sacramento, Pit, McCloud and Fall rivers) and in nearby Battle Creek. There is no evidence that winter runs naturally occurred in any of the other major drainages before the era of watershed development for hydroelectric and irrigation projects. Like the spring run, the winter run typically ascended far up the drainages to the headwaters (CFC 1890). All streams in which populations of winter-run chinook salmon were known to exist were fed by cool, constant springs that provided the flows and low temperatures required for spawning, incubation, and rearing during the summer season (Slater 1963)—when most streams typically had low flows and elevated temperatures. The unusual life-history timing of the winter run, requiring cold summer flows, would argue against such a run occurring in other than the upper Sacramento system and Battle Creek, apparently the only areas where summer flow and water temperature requirements were met. A possible exception was the Big Meadows area (now Lake Almanor) on the North Fork Feather River where extensive cold-water springs provided year-round flows with “temperature[s] not higher than sixty degrees Fahrenheit” (CFC 1884, p 16), which theoretically might have been suitable for the winter run; however, we have seen no historical records or suggestions of winter-run salmon occurring in that drainage. A similar environmental constraint may apply to some extent to the late-fall run, of which the juveniles remain in freshwater at least over the summer and therefore require coldwater flows (Vogel and Marine 1991; Fisher 1994)—whether from springs or from late snowmelt. The late-fall run probably spawned originally in the mainstem Sacramento River and major tributary reaches now blocked

by Shasta Dam (Fisher 1994) and perhaps in the upper mainstem reaches of other Sacramento Valley streams such as the American River (Clark 1929). There are indications that a late-fall run possibly occurred also in the San Joaquin River, upstream of its major tributaries at the southern end of that drainage (Hatton and Clark 1942; Van Cleve 1945; Fisher 1994).

Distributional Survey: General Background and Methods

As summarized by Clark (1929), makeshift barriers were built across Sierra Nevada streams as early as the Gold Rush period when mining activities significantly impacted salmon populations in a number of ways—for example, by stream diversions, blockages, and filling of streambeds with debris. Hydropower projects appeared in the 1890s and early 1900s, although most of the large irrigation and power dams were constructed after 1910 (F. W. Fisher unpublished data). The early hydropower dams of the early 1900s were numerous, however, and collectively they eliminated the major portion of spawning and holding habitat for spring-run salmon well before the completion of the major dams in later decades.

The early distributional limits of salmon populations within the Sierra Nevada and some Cascade drainages are poorly known, if at all, because of the paucity of accurate scientific or historical records pre-dating the heavy exploitation of populations and the destruction or degradation of stream habitats. It was not until after the late 1920s that reliable scientific surveys of salmon distributions in Central Valley drainages were conducted. Reports by Clark (1929) and Hatton (1940) give information on the accessibility of various streams to salmon and they identify the human-made barriers present at those times. They provide a valuable “mid-term” view of what salmon distributions were like in the first half of the 20th century after major environmental alterations had occurred and salmon populations were significantly depleted compared to earlier times. However, the survival of the runs was not yet imperiled to the extent it is presently. Those reports also give limited qualitative information on salmon abundance.

Fry (1961) provided the earliest comprehensive synopsis of chinook stock abundances in Central Valley streams, covering the period 1940–1959. Quantitative data were given by Fry (1961) for both spring and fall runs, but the fall-run estimates also included the winter and late-fall runs for the streams where those other runs occurred. Since then, fairly regular surveys of spawning runs in the various streams have been conducted by the California Department of Fish and Game and periodically summarized in the Department’s “Administrative Reports.”

In the following section we synthesize the earlier information with that available from more recent sources, with the aim of providing comprehensive descriptions for the major salmon-supporting streams of the Central Valley. For each of the major streams (excepting some tributaries in the upper Sacramento River system, for which little data exist) that are known to have had self-sustaining chinook salmon populations, we provide a narrative including their probable “original” distributions and later “mid-term” 1928-1940 distributions as indicated by published literature and unpublished documents. The probable original distributions were determined by considering the presence of obvious natural barriers to upstream salmon migration together with historical information (for example, accounts of gold miners and early settlers) and they apply to the salmon populations up to the period of intensive gold mining, around 1850-1890, when massive environmental degradation by hydraulic mining activities occurred. We also drew from ethnographic studies of Native American people. Much information on the material culture of the native peoples of California had been obtained by ethnographers who interviewed elder Native Americans of various tribal groups during the early part of the 20th century. That information pertains to the life-experiences and traditions of the native informants during the period of their youth and early adulthood and to the mid-life periods of their parents and grandparents from whom they received information and instruction-i.e., spanning essentially the middle and latter parts of the 19th century (Beals 1933; Aginsky 1943; Gayton 1948a). Generally, we quoted the original statements of earlier observers (both Native Americans and immigrants) on salmon and steelhead as fully as seemed informative so that readers may assess for themselves the meaning and credibility of those statements. The known or inferred historical upstream limits of salmon in Central Valley streams are compiled in Table 1.

Table 1 Historical upstream limits of chinook salmon in the California Central Valley drainage ^a

| <i>Stream</i> | <i>Upstream distributional limit ^b</i> |
|---------------------------------|--|
| Sacramento River Basin | |
| Pit River | Mouth of Fall River |
| Fall River | Source springs near Dana, about nine miles above mouth |
| McCloud River | Lower McCloud Falls |
| Upper (Little) Sacramento River | Vicinity of Box Canyon Dam (Mt. Shasta City) and Lake Siskiyou (that is, Box Canyon Reservoir) |
| Cow Creek | |
| North Fork (Little Cow) | Falls near Ditty Wells fire station |
| South Fork | Wagoner Canyon |
| Battle Creek | |
| North Fork | Falls three miles above Volta Powerhouse |
| Digger Creek | Vicinity of Manton, possibly higher |
| South Fork | Falls near Highway 36 crossing |
| Antelope Creek | Up North and South forks to present Ponderosa Way crossings |
| Mill Creek | Morgan Hot Spring |
| Deer Creek | Lower Deer Creek Falls |
| Big Chico Creek | Higgins Hole, about one mile above present Ponderosa Way crossing |
| Butte Creek | Centerville Head Dam (DeSabra) |
| Feather River | |
| West Branch | Vicinity of Stirling City |
| North Fork | Six miles above Lake Almanor, three miles up Hamilton Branch, and to Indian Falls on East Branch of North Fork |
| Middle Fork | Bald Rock Falls |
| South Fork | Upper limit of Lake Oroville (six miles above former mouth of South Fork) |
| Yuba River | |
| North Fork | Mouth of Salmon Creek, near present Sierra City |
| Middle Fork | Falls about one miles above juncture with North Fork |
| South Fork | Falls 0.5 mi below Humbug Creek |
| Bear River | Waterfall at vicinity of Camp Far West Reservoir |

^a Upper stream limits pertain to the farthest migrating seasonal run—meaning, either the spring run in most streams or the winter run where it occurred with the spring run, or the fall and late-fall runs in streams where spring and winter runs were absent.

^b Sources are given in the text.

Table 1 Historical upstream limits of chinook salmon in the California Central Valley drainage ^a (Continued)

| <i>Stream</i> | <i>Upstream distributional limit ^b</i> |
|---|---|
| American River | |
| North Fork | Mumford Bar |
| Middle Fork | Mouth of Rubicon River |
| South Fork | Waterfall near Eagle Rock |
| Clear Creek | French Gulch, above Whiskeytown Dam |
| Cottonwood Creek | |
| North Fork | Five miles above Ono |
| Middle Fork | Eight miles into Beegum Creek |
| South Fork | Maple Gulch |
| Stony Creek | Juncture of Little Stony Creek, five miles below Stonyford |
| Cache Creek | Vicinity of Capay Dam |
| Putah Creek | Vicinity of Monticello |
| San Joaquin River Basin and Sacramento-San Joaquin Delta | |
| Cosumnes River | Falls 0.5 mi below Latrobe Highway Bridge |
| Mokelumne River | Bald Rock Falls, seven miles upstream of Electra |
| Calaveras River | At least to site of New Hogan Dam |
| Stanislaus River | |
| North Fork | Makays Point, eight miles above juncture with Middle Fork |
| Middle Fork | Near Spring Gap Powerhouse, two miles below Beardsley Reservoir |
| South Fork | Presumably not used by salmon |
| Tuolumne River | |
| Mainstem | Preston Falls |
| North Fork | One mile above mouth |
| Middle and South forks | Presumably not used by salmon |
| Merced River | |
| Mainstem | Vicinity of El Portal |
| North Fork | Not used by salmon |
| South Fork | Peach Tree Bar |
| Upper San Joaquin River | Midway (3 mi) up length of Mammoth Pool Reservoir |
| Kings River | Mouth of North Fork |
| ^a Upper stream limits pertain to the farthest migrating seasonal run—meaning, either the spring run in most streams or the winter run where it occurred with the spring run, or the fall and late-fall runs in streams where spring and winter runs were absent. | |
| ^b Sources are given in the text. | |

For the mid-term salmon distributions, we relied heavily on the papers of Clark (1929) and Hatton (1940) and retained much of their original wording to faithfully represent the situation they reported at those times. We also give more recent and current (1990s) salmon spawning distributions based on government agency reports, published papers, and interviews with agency biologists². The stream accounts are presented starting with the southernmost Sierra streams and proceeding northward. We also include accounts for several streams on the west side of the Sacramento Valley which are known to have had chinook salmon runs. They are representative of other small west-side or upper Sacramento Valley streams that formerly sustained salmon stocks, if only periodically, but lost them because of extensive stream diversions and placement of man-made barriers. More detailed physical descriptions of Central Valley salmon streams, factors limiting their salmon production, and management recommendations are given in Reynolds and others (1993) and USFWS (1995).

For each stream account, we attempted to identify which seasonal salmon runs were historically present, given the available information. Remember that the lack of historical documentation for certain runs in some watersheds does not necessarily mean that those runs were absent from those watersheds in past times. The late-fall run, for example, was not even recognized as a distinct run until the late-1960s after seasonal salmon counts were initiated at Red Bluff Diversion Dam on the mainstem Sacramento River. The presence of the late-fall run in several Sacramento River tributaries during recent decades (Reynolds and others 1993) might argue for its historical occurrence in some of those streams, assuming that streamflow conditions during the time of year when late-fall salmon were present were not substantially altered after the emplacement of dams and diversion projects. We also provide information on historical salmon abundances in individual streams where possible. While usually highly incomplete or anecdotal, the early statements and estimates on salmon abundances nonetheless indicate those watersheds which historically supported substantial, or in some cases enormous, salmon runs and also demonstrate that chinook salmon existed at viable population levels in streams through much of the Central Valley drainage. We have drawn particularly from Fry (1961) for earlier quantitative data.

We mention steelhead trout in several stream accounts, particularly where information on salmon is lacking. The intent is to show that certain stream reaches were accessible to at least steelhead and, hence, may have been reached also by chinook salmon – particularly spring-run fish, which typically

2. Agency abbreviations are as follows: California Department of Fish and Game (DFG); California State Board of Fish Commissioners (CFC); Federal Energy Regulatory Commission (FERC); United States Commission for Fish and Fisheries or U.S. Fish Commission (USFC); United States Fish and Wildlife Service (USFWS).

migrated far upstream. However, the correspondence between the occurrence of steelhead and spring-run salmon in stream reaches was by no means complete. Steelhead aggressively ascend even fairly small tributary streams, in contrast to chinook salmon which generally use the mainstems and major forks of streams (E.R. Gerstung, personal observation). The migration of steelhead during the peak of the rainy season (January-March) aided their ascent into the small tributaries. Steelhead also are able to surmount somewhat higher waterfalls—perhaps up to about 15 ft high—while chinook salmon in California appear to be stopped by falls greater than 10 to 12 ft high (E.R. Gerstung, personal observation), depending on the abruptness of the drop. Furthermore, steelhead do not require as much gravel for spawning. For example, steelhead formerly used streams in the upper Sacramento River drainage (near Shasta Reservoir) that had small patches of gravel interspersed among boulder substrate, which salmon generally shunned (E.R. Gerstung, personal observation). Yet, in terms of ascending the main stream reaches, it may be reasonably assumed that where steelhead were, spring-run salmon often were not far behind. Using the advantage of high spring flows, the salmon could have surmounted obstacles and reached upstream areas not much lower than the upper limits attained by steelhead in some streams.

Non-game fishes such as hardhead (*Mylopharodon conocephalus*), Sacramento pikeminnow (*Ptychocheilus grandis*) and Sacramento sucker (*Catostomus occidentalis*) also provide hints about salmon distribution. Those species are typical of valley floor and low- to mid-elevation foothill streams (Moyle 1976), and their recorded presence in stream reaches that are not blocked by obvious natural barriers is a good indication that anadromous salmonids likewise were able to ascend at least as far, and possibly even farther upstream. The presence of non-game native fish populations above obvious natural barriers in some streams suggests that at least some of the barriers were formed after the initial dispersal of those species into the upper watersheds.

Distributional Synopses of Salmon Streams

Kings River (Fresno County). Spring and fall runs of chinook salmon are known to have occurred at least periodically in the Kings River, the southernmost Central Valley stream that supported salmon. In the past, the Kings River flowed into the northeast part of Tulare Lake, and its waters occasionally ran into the San Joaquin River during wet periods when water levels became high enough in Tulare Lake to overflow and connect the two drainages (Carson 1852; Ferguson 1914). Streamflows would have been greatest during the spring snowmelt period, so it is most likely that the spring run was the predominant run to occur there. Spring-run salmon would have had to ascend to high enough elevations (probably >1,500 ft) to avoid excessive summer water temperatures, going above the area presently covered by Pine Flat Reservoir. The

mainstem upstream of Pine Flat Reservoir is of low gradient (E.R. Gerstung, personal observation) and free of obstructions for some distance (P. Bartholomew, personal communication), so salmon probably were able to ascend about 10 to 12 mi beyond the present upper extent of the reservoir. The bulk of salmon migration in the Kings River probably ascended no farther than the confluence of the North Fork (Woodhull and Dill 1942), which we take as the upper limit. There is an undocumented note of "a few salmon" having occurred much farther upstream at Cedar Grove (28 mi above present-day Pine Flat Reservoir) in the past—"before Pine Flat Dam was constructed" (DFG unpublished notes). However, it is not clear if salmon actually could have reached that far, due to the presence of extensive rapids below around the area of Boyden Cave (3,300 ft elev.) and below Cedar Grove. The North Fork Kings River is very steep shortly above its mouth, and salmon most likely did not enter it to any significant distance (P. Bartholomew, personal communication, see "Notes").

Native American groups had several fishing camps on the mainstem Kings River downstream of Mill Flat Creek, including one used by the Choinimni people (a tribelet of the Northern Foothills Yokuts) at the junction of Mill Creek (about two miles below the present site of Pine Flat Dam). There, the "spring salmon run" was harvested and dried for later use (Gayton 1948b). Gayton (1946, p 256) wrote:

On the lower Kings River, the Choinimni (Y) [Y denoting Yokuts] and probably other tribes within the area of the spring salmon run (about May) held a simple river-side ritual at their principal fishing sites. The local chief ate the first salmon speared, after cooking it and praying to Salmon for a plentiful supply. Then others partook of a salmon feast, and the season, so to say, was officially open.

The existence of a well-established salmon ritual among the native people seems to indicate that salmon runs in the Kings River were not uncommon, even if they did not occur every year (for example, in years of low precipitation). Furthermore, in regard to inter-tribelet relations among the Northern Foothills Yokuts, Gayton (1948b, p 143) stated: "While the Choinimni felt the north bank of Kings River to be theirs, ... the Gashowa were welcome to occupy their fish camp ... during the spring salmon run. These neighbors remained there while the fish dried, which they then took home to store." This statement indicates that there was a fairly regular granting of salmon-fishing privileges between some native groups around the Kings River.

The Tachi Yokuts, located on the Central Valley floor around the north shore of Tulare Lake and the lower reaches of the Kings River (Gayton 1948a; Cook 1955, 1960), also caught salmon as well as other fishes. The Spanish Lieutenant José Mariá Estudillo observed Tachi tribesmen catching fish by means of hand

nets from the Kings River on 2 November 1819: “This they did before my very eyes, with great agility, diving quickly and staying under the water so long that I prayed After having caught sufficient large fish, salmon and others very palatable ...” (translation by Gayton 1936, p 78). Given the date, those salmon were undoubtedly of the fall run. Steelhead also appear to have entered the Kings River drainage, at least to some extent. The pioneer Thomas Jefferson Mayfield, who was raised amongst the Choinimni people during the 1850s, recollected that “There were many pools of water in Sycamore creek, and in them we caught trout and speared a fish we called a steel head” (Latta 1929, p 15). Mayfield evidently was referring to the present Sycamore Creek which enters the Kings River above Trimmer (compare his description with map 2 of Gayton 1948a), at the upper part of Pine Flat Reservoir. Mayfield also stated that “Trout and other large fish were speared with a gig almost like a modern salmon gig” (Latta 1977, p 509). The ethnographer Frank Latta, a noted authority on the Yokuts nationality, added: “Many of the fish obtained in this manner were known as steelheads. They are a large fish resembling both salmon and trout. The meat of these, as well as others, was dried and smoked in large quantities” (Latta 1977, p 511).

Drawing on testimony from a Native American informant, Gayton (1948a) reported that “Salmon (*da'tu*) were well known and greatly depended upon” by the Chunut people (a subgroup of the Southern Valley Yokuts) who dwelt on the eastern shore of Tulare Lake—essentially the downstream terminus of the Kings River. A second Chunut informant interviewed by Latta (1977, p 722) similarly attested to the presence of salmon, and evidently steelhead, in the lake:

There were lots of fish in Tulare Lake. The one we liked best was a-pis, a bit [sic] lake trout. They were real big fish, as big as any salmon, and good meat Sometimes the steelheads came in the lake too; so did the salmon. We called the steelheads tah-wah-aht and the salmon ki-uh-khot. We dried lots of fish. When it was dried and smoked, the salmon was the best.

The common “lake trout” of Tulare Lake was not a salmonid, but most likely the Sacramento pikeminnow. State Fish Commissioner B.B. Redding described it as “a fine large white-fleshed fish, about 2 feet 6 inches long, ... It looks to me to be a carp, and of finer flavor than any I ate in Europe” (USFC 1876b, p 480). It is evident, however, that both salmon and steelhead entered Tulare Lake at least on occasion, where they were taken by Chunut fishers. It seems unlikely that the Chunut traveled out of their territory to the Kings River to obtain salmon, nor have we found any indication in the ethnographic literature that they did so. There would have been little reason for the Chunut to make regular fishing excursions to areas away from Tulare Lake, given that the lake contained an abundance and variety of high-quality fish resources (Gayton 1948a; Latta 1977), and in fact it was the Kings River Choinimni peo-

ple (and perhaps others) who made seasonal trips downriver to Tulare Lake for fishing (Latta 1929; Gayton 1948b).

Furthermore, an early newspaper article mentioned the probable occurrence of salmon in Tulare Lake and its environs:

The abundance of fish of all kinds in these waters is absolutely astonishing. ...Pike, perch, bass, salmon trout [probably steelhead or perhaps salmon grilse], eels [lampreys], suckers, and many other kinds, ... are caught with the greatest of ease, and we have no doubt that the lordly salmon himself frequents the lakes in his proper season (San Francisco Picayune, 15 November 1851; reprinted in Heizer 1976, p 59).

Diversions from the Kings River and other streams for agricultural irrigation occurred from the early years of American settlement and farming in the San Joaquin Valley. The reduced streamflows undoubtedly diminished the frequency of salmon runs—and perhaps extinguished them altogether—for a period spanning the late-19th to early-20th centuries. The California Fish and Game Commission reported that after a channel was dredged out between the Kings and San Joaquin rivers in about 1911, salmon began appearing in the Kings River—“a few” in the spring of 1911, a “very considerable run” in 1912, which ascended to Trimmer Springs (river mile [rm] 125) near the upper end of present-day Pine Flat Reservoir, and another “very considerable run” in June 1914 (Ferguson 1914). Several small chinook salmon were caught by a DFG biologist in the fall of 1942 near the town of Piedra on the mainstem Kings River (about two miles downstream of the mouth of Mill Creek; W. Dill, personal communication, see “Notes”); those fish were notable in that they were precociously mature males—in other words, running milt (W. Dill, personal communication, see “Notes”). A single, approximately five-inch chinook salmon (with “very enlarged testes”) was later captured in September 1946 in the mainstem “about eight miles above the junction of the North Fork Kings River” (W. Dill DFG letter). Moyle (1970) later collected juvenile chinook salmon (about four inches total length) in April 1970 from Mill Creek, just above its mouth. Salmon that spawned in Mill Creek likely ascended the stream at least several miles to the vicinity of Wonder Valley (P. Bartholomew, personal communication, see “Notes”). Salmon runs in the Kings River were observed to occur more frequently after the construction of the Kings River Bypass in 1927, with “especially noticeable runs” in 1927, 1938, and 1940 (Woodhull and Dill 1942).

The Kings River salmon run was probably bolstered by, or perhaps even periodically reestablished from, the San Joaquin River population, particularly after series of dry years during which the run would have progressively diminished. After 1946, the termination of most natural streamflows down the channel of the San Joaquin River, except during exceptionally wet years,

resulted in the extirpation of salmon runs in both the Kings and upper San Joaquin rivers.

San Joaquin River (Fresno County). Spring and fall runs of salmon formerly existed in the major San Joaquin River tributaries and in the upper San Joaquin River (Clark 1943; Fry 1961), and there also may have been a late-fall run present in the mainstem. However, all salmon runs in the San Joaquin River above the confluence of the Merced River were extirpated by the late-1940s.

The Spanish explorers and missionaries of Old California, probing the inner San Francisco Bay and Sacramento-San Joaquin Delta region, encountered evidence of salmon. In early April 1776, an expedition led by Captain Juan Bautista de Anza observed salmon (evidently spring-run) being harvested by the native people near present-day Antioch at the mouth of the San Joaquin River. De Anza wrote:

We have noted that the fish most abundant at present from the mouth of the bay to here are the salmon. They are very red in color, and are tender, and none of those we have seen is less than five quarters long [about 40 inches; based on Latta 1977, p 64]. ... At the village which we passed there were so many that it seems impossible that its residents could eat them, ... (Bolton 1930a, p 146).

Father Pedro Font, diarist for that party, further noted that on April 2:

The soldiers purchased four fish somewhat more than a vara long [one Spanish vara equals about 33 inches; Cutter 1957, p 34] and about a third of a vara wide. At first we did not recognize it, but on opening it, and especially when we ate it, we saw that it was salmon, tenderer, fatter, and more savory than that which we ate at the mission of Carmelo [Carmel],... Bolton 1930b, p 377).

Spanish exploration did not fully encompass the San Joaquin Valley until October 1806, when a party led by Ensign Gabriel Moraga traversed the eastern side of the San Joaquin River. Records of the expedition do not mention actual observations of salmon, but Father Pedro Muñoz noted that “Beaver abound and also salmon, according to what was told us by the Indians native to this country” (Diary of Father Pedro Muñoz, translation by Cook 1960, p 248). Moraga’s expedition discovered and named the three major tributaries of the San Joaquin River—the River of Our Lady of Guadalupe (Stanislaus River), the River of Our Lady of Sorrows (Tuolumne River), and the River of Our Lady of Mercy (Merced River) (Cutter 1950; Cook 1960)—and those three streams now remain the southernmost streams supporting chinook salmon in North America.

On a later expedition in 1810, Father José Viader recorded that on October 20 at the village of Cholvones (or Pescadero) on Old River (the West Branch of the lower San Joaquin River), "...we rested here and passed time well with fresh salmon and wild grapes"; and, on October 23, "Indians ...from the village of Cuyens, came out to meet us, bearing as a gift three very big, red, salmon" (Report of Father José Viader, translation by Cook 1960, p 259, 260). Cuyens (or Guyens) was located just downstream of the Stanislaus River mouth (Cook 1955; Bennyhoff 1977). The dates given in that report indicate that the salmon were of the fall run, which is perhaps the earliest explicit record of fall-run salmon for the San Joaquin River basin.

There are virtually no historical references to salmon occurring on the western side of the San Joaquin Valley, where the streams were seasonally prone to dry out. One enigmatic exception is the diary entry for 26 August 1810 by Father José Viader, when the expedition passed the area of San Luis Creek, just east of Pacheco Creek: "We stopped at the foot of the range along a creek which had no more water than a few scattered pools. In just one of these we caught forty fish including six trout or little salmon" (Cook 1960, p 259). Conceivably, those latter six fish might have been steelhead.

An American traveler, John Woodhouse Audubon, provided an early testimony of fall-run salmon in the San Joaquin River basin which he observed sometime after mid-November 1849 in a reach several days travel above the confluence of the Stanislaus River:

The water is beautifully clear now, and is full of fine-looking fish; the large salmon of these rivers is a very sharky-looking fellow and may be fine eating; but as yet we have not been fortunate enough to get one, though several have been shot by Hudson and Simson as they lay in the shallows (Audubon 1906, p 185).

Likewise, the naturalist John Muir, while boating on the San Joaquin River just above the confluence of the Tuolumne river, observed on 18 November 1877 that "Salmon in great numbers are making their way up the river for the first time this season, low water having prevented their earlier appearance" (Muir 1938, p 244)—further attesting to a numerous fall salmon run. Muir found on that day a "salmon trout" carcass—possibly a steelhead—"new killed and dressed and laid out on the bank for me by fish hawks" (Muir 1938, p 243). Livingston Stone of the US Fish Commission stated, "...in regard to this [San Joaquin] river that it is much warmer than the Sacramento, but is frequented somewhat by salmon, especially in the fall, which are killed in considerable quantities on some of its tributaries" (Stone 1874, p 176). The California Fish Commission noted: "This [San Joaquin River] is a very good stream for the Fall run of salmon, the ascent being not very steep, and the cur-

rent, especially the first seventy-five miles, not being very strong" (CFC 1884, p 15).

While the uppermost distribution of salmon in the San Joaquin River in earlier years is not known with certainty, the US Fish Commission (USFC 1876a, p xxviii) noted that salmon went up "...to the headwaters of the San Joaquin, about two hundred and fifty miles." The California Fish and Game Commission reported:

These [spring-run] salmon ascend the river during May, June and the first part of July. In the foot hills near Friants they congregate in the large pools and remain until such time in the fall as the temperature is right for them to spawn, then they ascend the river into the gorge of the San Joaquin River where they spawn in the fall. This is the result of our observations and data gathered from the residents and deputies who have lived in that vicinity for years (CFGC 1921a, p 21).

It was reported that the spring run historically ascended the river past the present site of Kerckhoff Power House to spawning grounds in the higher reaches (CFGC 1921b). A natural barrier shortly upstream of Willow Creek near present-day Redinger Lake may have posed an obstruction to salmon (E. Vestal, personal communication, see "Notes"). However, there is evidence that salmon traveled considerably farther upstream at least to the vicinity of present-day Mammoth Pool Reservoir (about 3,300 ft elev.). The oral history of Native American residents in the region includes references to salmon occurring there (P. Bartholomew, personal communication, see "Notes" based on interviews with Native American informants). Lee (1998, p 87), drawing from family reminiscences, stated that salmon ascended to "their old spawning grounds upriver from *Cha:tiniu* [Logan Meadow, adjacent to Mammoth Pool Reservoir]...[where] our ancestors speared salmon only a few hundred yards from the meadow where they lived." Hence, we take the point about three miles up the length of Mammoth Pool Reservoir as the (minimal) upstream historical limit of salmon.

Based on the absence of natural barriers, it may be inferred that salmon probably entered two small tributaries of the upper San Joaquin River near Miller-ton Reservoir – Fine Gold Creek, perhaps "as far upstream [about six miles] as opposite Hildreth Mtn," and Cottonwood Creek probably at least two miles (E. Vestal unpublished notes and personal communication, see "Notes"). Also, salmon evidently entered two larger, intermittent tributaries farther downstream on the valley floor – the Chowchilla and Fresno rivers – which probably had only occasional runs during the wet years. The Fresno River arises "far back in the Sierra" and long ago was described as "carrying an immense body of water down toward the plains" (Elliott 1882, p 20), so the occasional past occurrence of salmon would not be surprising. In passing ref-

erence to those streams, B.B. Redding of the California Fish Commission wrote to US Fish Commissioner Spencer Baird in April 1875:

Formerly there was considerable work done in the catching of salmon in the San Joaquin, but of late years it has been abandoned, ...I suppose that the fish are still going up the San Joaquin to spawn, but, if taken at all, are only now taken by Indians on the Merced, the Chowchilla, the Fresno, and the other branches of the San Joaquin, and I have no doubt they continue to do so (USFC 1876b, p 479).

As recently as the 1980s, a few salmon—presumably strays from other streams—have been observed by anglers in the Chowchilla and Fresno rivers during years of high streamflows (R. Kelly, personal communication, see “Notes”). Because of the uncertainty of how far salmon formerly ascended the intermittent or small tributaries of the upper San Joaquin River, we exclude them from our tabulation of stream lengths historically used by salmon. Hence, our assessment of the distributional limits of salmon in the upper San Joaquin River drainage is conservative.

Native people of the Northern Foothill Yokuts groups, including the Chukchansi from Coarse Gold Creek and the Fresno River, traveled to and fished for salmon in the San Joaquin River near the area of Friant (Gayton 1948b). According to Gayton’s (1948b, p 165) ethnographic account, the salmon were watched for “when the Pleiades were on the western horizon at dusk,” and a first salmon ritual for the spring run was held by several different Yokuts groups when the first salmon of the season was caught. Large quantities of salmon were dried for storage: “They were put in a sack [skin?] and packed home with a tumpline. A man carried about two hundred pounds of fish” (Gayton 1948b, p 185). The zoologist-ethnographer C. Hart Merriam recorded in his field notes for 30 October 1903: “...a few Pit-kah'-te and Kosho'-o Indians [Yokuts groups] were fishing on a stretch of the river from Pullasky [later named Friant] upstream for a mile or so. They were spearing salmon and drying them for winter use” (Heizer 1967, Part III, p 416). Given the date, those salmon undoubtedly were the fall run. The ethnographer Frank Latta (1977, p 511) noted: “We are assured that along the San Joaquin River, many tons of salmon were taken during the annual ‘run’ and that the bushes and banks about the villages and camps were red with drying fish.”

The areas farther up the upper San Joaquin River, above the Yokuts, were occupied by Western Mono groups. The “Northfork Mono” people (or Nüm), who lived on the “North Fork” San Joaquin River (also called Northfork Creek or Willow Creek), Whiskey Creek and nearby areas, caught “Steel-head trout (*Salmo rivularis*), rainbow trout, and the Sacramento salmon” which “were eaten with acorn mush” Gifford (1932, p 21). Fishing for salmon was done primarily in the mainstem upper San Joaquin River, rather than in the small trib-

utaries. Lee (1998, p 89) identified the crossing at *Samhau* (just above present-day Redinger Lake) and *Pakapanit* (north of Italian Bar Road) as the preferred fishing spots in the old days, and he also noted that his grandfather and great-grandfather “speared salmon, suckers and trout” at “Pasagi, near *Chu:wani*” (on Ross Creek). Excursions also were made “to the river where Kerckhoff Dam is, to fish for salmon” (Lee 1998, p 87). We have found no references which indicate how far up Willow Creek salmon ascended, if at all, so we presently do not include it as a former salmon stream. The Northfork Mono people were said to have held first salmon rites (Aginsky 1943).

As early as 1884, the California Fish Commission noted that the salmon runs had been detrimentally affected because of “dams on the headwaters of the Stanislaus, Tuolumne, San Joaquin, and the upper Sacramento Rivers ...a great drawback to the salmon interest, as the spawning grounds are, for the most part, above the dams” (CFC 1884, p 15). On the upper San Joaquin River, the construction and operation of Kerckhoff Dam (about 1920) for power generation permanently blocked the spring-run salmon from spawning areas upstream and seasonally dried up about 14 mi of stream below the dam, where pools formerly provided over-summering habitat for the salmon (CFGC 1921b). Later in that decade, Clark (1929) reported that the salmon spawning beds were located in the stretch between the mouth of Fine Gold Creek and Kerckhoff Dam and in the small tributary streams within that area, covering a stream length of about 36 mi; a few scattered beds also occurred below the town of Friant. At the time of Clark’s (1929) writing, there were four dams on this river that impeded the upstream migration of salmon: the “Delta weir” (in a slough on the west side of the river, 14 mi southeast of Los Banos); Stevenson’s weir (on the main river east of Delta weir); Mendota weir (1.5 mi from the town of Mendota); and the impassable Kerckhoff Dam, 35 mi above Friant. The first three dams were irrigation diversion projects. Friant Dam had not yet been constructed. In addition to the barriers themselves, reduced streamflows due to irrigation diversions impeded and disoriented uncounted numbers of migrating salmon which went astray in the dead-end drainage canals on the valley floor, where they abortively spawned in the mud (Clark 1930).

Hatton (1940, p 358) considered the upper San Joaquin River in 1939 to possess the “most suitable spawning beds of any stream in the San Joaquin system,” and “even in the dry year of 1939, most of the suitable areas were adequately covered with water and the water level was satisfactorily constant.” The spawning beds in the San Joaquin River were located along the 26 mi from Lane’s Bridge up to the Kerckhoff Power House, all of which were accessible, and the “best and most frequently used areas” were between Lane’s Bridge and Friant. The stream just above Friant, where it entered a canyon, was viewed as generally unsuitable, comprising mainly bedrock, “long, deep pools” and “short stretches of turbulent water” (Hatton 1940, but see

CFGC 1921a and above). The planned Friant Dam would cut off an estimated 16 mi of stream where spawning occurred, representing about 36% of the spawning beds, but at that time Hatton considered the spawning beds below Friant Dam to be "so underpopulated that even after the completion of the dam more than adequate areas will still be available, if water flows are adequate." The expected negative impact of Friant Dam was not so much the elimination of spawning areas above the dam as the diversion of water from the stream channel downstream. However, quoting Hatton (1940, p 359), it was "hoped that seepage from the dam and returned irrigation water will provide sufficient flow to make spawning possible." Evidently, the deleterious consequences of vestigial streamflows and polluted irrigation drainage on salmon were not yet fully appreciated at that time.

Hatton (1940) reported that the stretch of the San Joaquin River where spawning occurred was "singularly free of obstructions and diversions," but there were obstructions farther downstream. The lowermost barrier below the spawning beds was the "sack dam" of the Poso Irrigation District, "several miles below Firebaugh" (near Mendota). He stated: "In the average water year this dam destroys any possibility of a fall run up the San Joaquin. The complete diversion of water leaves the stream bed practically dry between that point and the mouth of the Merced River" (Hatton 1940, p 359). The sand bags constituting this dam were left in place until they were washed out by the winter floods. The only other obstruction below the spawning beds was the Mendota weir, which was equipped with a "satisfactory fishway"; however, there were eight unscreened diversions above the dam which Hatton viewed as "a serious menace to the downstream migrants."

The numbers of salmon that at one time existed in the San Joaquin River were, by some accounts, tremendous. Clark (1929, p 31) stated that, "Fifty or sixty years ago, the salmon in the San Joaquin were very numerous and came in great hordes." Indeed, the early residents of Millerton on the banks of the San Joaquin were kept awake by the migrating spring-run salmon (Vandor 1919; CSHA 1929), because "their leaping over the sandbars created a noise comparable to a large waterfall" (NCHRSP 1940, p 13). The historian Vandor (1919, p 106) wrote:

The San Joaquin was a stream of pure icy water, and clear as a crystal where not muddied by mining. Salmon ascended to the spawning grounds by the myriads, and, when the run was on, the fish were hunted with spear, pitchfork, shovel, even with shotgun and revolver. Salmon appeared in such shoals that as late as July, 1870, it was recorded that restful sleep was disturbed because 'myriads of them can be heard nightly splashing over the sand bars in the river opposite town as they make their way up.'

The site of Millerton is now covered by Millerton Reservoir. In reference to the fall-run salmon (and perhaps steelhead), one correspondent wrote to State Fish Commissioner B.B. Redding: "...in the fall the salmon and salmon-trout find their way up here in large quantities. Last fall I helped to spear quite a number, as that is about the only way of fishing in this part of the county; but below the San Joaquin bridge I understand they were trapped in a wire corral by ranchers and fed to hogs; they were so plentiful" (USFC 1876b, p 480).

The former spring salmon run of the San Joaquin River has been described as "one of the largest chinook salmon runs anywhere on the Pacific Coast" and numbering "possibly in the range of 200,000 to 500,000 spawners annually" (DFG 1990). During a reconnaissance in late-July 1853 in the vicinity of Fort Miller (just upstream of Millerton), Blake (1857, p 20) observed, in reference to spring-run salmon: "During our stay at this camp we purchased fresh salmon of the Indians, who catch them in the river. It is probable, however, that they are not abundant, as the mining operations along the upper part of the stream and its tributaries sometimes load the water with impurities." While Blake's conjecture regarding the spring-run salmon evidently was not accurate at the time, it foreshadowed events to come.

By the end of the 19th century, the California Fish Commission observed:

Formerly there was a considerable run of salmon in the San Joaquin River, but as a result of mining and the diverting of water for irrigation, the run has decreased until now [1897-1898] it is confined to a short period in the fall. This fall run does not seek the extreme headwaters to spawn as formerly, and while a few enter the Stanislaus and Merced rivers, the majority seem to prefer the San Joaquin proper. ...Why the spring run does not go up this stream [San Joaquin River] instead of preferring the Sacramento, while some of the fall run continue up this river...remains unresolved. That the condition described is well recognized by the net-fishermen is proved by the fact that none of them are to be found above Jersey Island in the spring, while a number of boats are used above that point in the fall (CFC 1900a, p 24).

The Fish Commission of that time apparently did not fully realize that it was the spring run, rather than the fall run, that had formerly ascended to the headwaters and, hence, had been more drastically affected by the mining and the water diversions, although previous state fish commissioners were well aware of the detrimental impact of dams which had cut off the upper spawning grounds in the San Joaquin basin tributaries (for example, CFC 1884, p 15). Later, Clark (1929, p 31) reported that a "very good run" of salmon was seen at Mendota in 1916-1917 and a "fairly good" one for 1920, but thereafter the runs declined so that by 1928 "very few" fish were seen and the salmon of the San Joaquin River seemed to be "fast decreasing." By then there was essen-

tially only a spring run, the water being too low to support any appreciable fall run (Clark 1929).

The decline of the salmon resource of the upper San Joaquin River was, of course, noted by the river inhabitants. Particularly affected were Native Americans who depended upon the runs for sustenance. In the words of a Yokuts man named Pahmit (William Wilson) in 1933:

Long time 'go lots salmon in San Joaquin River. My people – maybe two to three thousand come Coo-you-illik catch salmon – catch more salmon can haul in hundred freight wagons. Dry 'em – carry 'em home. ...[Since 1909] no salmon in river. White man make dam at old Indian rancheria Käh-wäh-chu – stop fish – now Indian got no fish. Go river – water there, but no fish. White man got no fish. White man got no money. Injun got no fish – Injun got no money – everybody broke. That's bad business (F. Latta unpublished field notes).

Coo-you-illik (“Sulphur Water”) was a Dumna Yokuts village at the later site of Fort Miller (Latta 1977). The salmon were also well remembered by non-Native Americans in later decades: “The salmon fishing in the San Joaquin River was out of this world. It was one of the finest spawning rivers for salmon....There were hundreds and hundreds.... The salmon looked like silver torpedoes coming up the river” (Anthony Imperatrice interview, 11 February 1988; in Rose 1992, p 119).

In spite of the general decline of salmon in the upper San Joaquin River due to increasingly inhospitable environmental conditions, particularly for the fall run, a substantial spring run and even a remnant fall run managed to persist for a time. Hatton (1940, p 359) reported that the fall run occurred in “some years...making a hazardous and circuitous journey through a series of natural sloughs and irrigation laterals [canals], beginning near the mouth of the Merced [River] and miraculously entering the [San Joaquin] river through the main canal above Mendota Weir.” Clark (1943) stated that in 1942, the upper San Joaquin River had “a fair-sized spring run of king [chinook] salmon for many years” and a fall run that had “been greatly reduced.”

Fry (1961) also reported that during the 1940s before the construction of Friant Dam, the San Joaquin River had “an excellent spring run and a small fall run” and that its spring run was probably “the most important” one in the Central Valley. The spring run amounted to 30,000 or more fish in each of three years of that decade and a minimum of 56,000 spawners which passed Mendota weir in 1945 (DFG 1946; Fry 1961), with an annual value of “almost one million dollars” (Hallock and Van Woert 1959, p 246). In 1946, the sport fishery in the San Joaquin Valley took an estimated 25,000 salmon produced by the upper San Joaquin River, with perhaps another 1,000 caught in the ocean

sport fishery (DFG 1955 unpublished document). In addition, the commercial harvest (averaged for the period 1946–1952) accounted for another 714,000 pounds of salmon that originated from the San Joaquin River (DFG 1955 unpublished document). However, both the spring and fall salmon runs were extirpated from the upper San Joaquin River above the confluence with the Merced River as a direct result of the completion of Friant Dam (320 ft high) in 1942 and its associated water distribution canals (namely, Madera and Friant-Kern canals) by 1949 (Skinner 1958). Friant Dam itself cut off at least a third of the former spawning areas, but more importantly, the Friant Project essentially eliminated river flows below the dam, causing about 60 miles of river below “Sack Dam” to completely dry up (Skinner 1958; Hallock and Van Woert 1959; Fry 1961). During the relatively dry winter of 1946–1947, the US Bureau of Reclamation allowed no more than 15,000 acre-feet of water to be released from Friant Dam for the spring run, and only 6,000 salmon were counted passing Mendota weir in 1947 (DFG 1948). The last substantial spring-run spawning cohort (numbering >1,900 fish) occurred in 1948 (Warner 1991). While not attributing the collapse of the Sacramento-San Joaquin River spring-salmon fishery solely to Friant Dam, Skinner (1958) noted the “striking coincidence” that in the 1916–1949 (pre-Friant) period, the spring-run catch averaged 664,979 pounds (31% of the total Sacramento-San Joaquin River commercial catch) and in 1950–1957 (post-Friant) it averaged 67,677 pounds (6% of the total catch)—a 90% reduction in absolute poundage. Skinner (1958) further chronicled the telling correlation between events in the development of the Friant Project, their effects on year-classes of fish, and the rapid deflation of the spring in-river fishery—the latter falling from a high catch of 2,290,000 pounds in 1946 to a low of 14,900 pounds in 1953. “Last-ditch” efforts by DFG biologists to preserve the last cohorts of the upper San Joaquin River spring-run salmon in 1948, 1949, and 1950 were foiled by insufficient streamflows and excessive poaching, thereby resulting in the extinction of the run (DFG 1950; Warner 1991).

Since the closure of Friant Dam, polluted irrigation drainage during much of the year has comprised essentially all of the water flowing down the course of the San Joaquin River along the valley floor until it is joined by the first major tributary, the Merced River (San Joaquin Valley Drainage Program 1990). In only very wet years in recent decades have a few salmon occasionally ascended the San Joaquin River below Friant Dam, the latest record being that of a single 30-inch male (possibly spring-run) caught by an angler on 1 July 1969 below Friant Dam (Moyle 1970).

The former San Joaquin River salmon runs were the most southerly, regularly occurring large populations of chinook salmon in North America, and they possibly were distinctly adapted to the demanding environmental regime of the southern Central Valley. The California Fish Commission regarded the

migration of the fall salmon run during the seasonally hot portion of the year as extraordinary:

Large numbers pass up the San Joaquin River for the purpose of spawning in July and August, swimming for one hundred and fifty miles through the hottest valley in the State, where the temperature of the air at noon is rarely less than eighty degrees, and often as high as one hundred and five degrees Fahrenheit, and where the average temperature of the river at the bottom is seventy-nine degrees and at the surface eighty degrees (CFC 1875, p 10; USFC 1876b, p xxv).

The Commissioners noted that during August-September of 1875-1877, the average monthly water temperatures for the San Joaquin River where two bridges of the Central Pacific Railroad crossed (at 37°50'N, 121°22'W and 36°52'N, 119°54'W) were within 72.1 to 80.7 °F (considering both surface and bottom water) and maximal temperatures were 82 to 84 °F (CFC 1877). The high temperature tolerance of the San Joaquin River fall-run salmon inspired interest in introducing those salmon into the warm rivers of the eastern and southern United States (CFC 1875, 1877; USFC 1876a, 1876b). Quoting the California Fish Commission (CFC 1875, p 10):

Their passage to their spawning grounds at this season of the year, at so high a temperature of both air and water, would indicate that they will thrive in all the rivers of the Southern States, whose waters take their rise in mountainous or hilly regions, and in a few years, without doubt, the San Joaquin Salmon will be transplanted to all of those States.

Perhaps it was this hardiness of the fall-run fish that enabled them to persist through years of depleted streamflows, “miraculously” negotiating the sloughs and irrigation ditches from about the mouth of the Merced River up the San Joaquin River drainage as mentioned by Hatton (1940, p 359). Yet, nothing is known of the physiological and genetic basis of the seemingly remarkable temperature tolerances of San Joaquin River fall-run salmon because that population was driven to extinction decades ago. It is not known to what degree the remaining fall-run populations in the major tributaries of the San Joaquin River possess the temperature tolerances and genetic characteristics of the original San Joaquin River fall run. Because of extreme fluctuations in year-to-year run sizes in recent times and the probable loss of genetic variation during population bottlenecks, it is likely that present-day fall-run salmon of the San Joaquin tributaries are genetically different from their forebears, or at least from the former San Joaquin River fall run. Similarly, the spring-run fish of the San Joaquin River perhaps also were physiologically and genetically distinctive due to their extreme southerly habitation. After completion of Friant Dam, spring-run fish began to use areas below the dam (Clark 1943). Approximately 5,000 spring-run fish were observed over-sum-

mering in pools below the dam during May through October 1942, where water temperatures had reached 72 °F by July. The fish remained in “good condition” through the summer, and large numbers were observed spawning in riffles below the dam during October and November (Clark 1943, p 90). A temperature of 80 °F has been regarded as the upper thermal limit for San Joaquin River spring-run fish, above which most of them would have died (DFG 1955 unpublished document), although much lower temperatures (40 to 60 °F) are necessary for successful incubation of the relatively temperature-sensitive eggs (Seymour 1956; Beacham and Murray 1990).

In addition to the spring and fall salmon runs, there were indications that a late-fall run possibly occurred in the San Joaquin River (Van Cleve 1945). In 1941, a run apparently of appreciable size entered the river, starting about 1 December and continuing through at least 10 December (Hatton and Clark 1942). The authors concluded that “a run of several thousand fish may enter the upper San Joaquin River during the winter months, in addition to the spring run during March, April and May” (Hatton and Clark 1942, p 123). This December run has been viewed as a possible late-fall run (Fisher 1994) because peak migration of late-fall-run fish characteristically occurs in December, at least in the Sacramento River system. A likely alternative, however, is that the migration observed by Hatton and Clark was simply the fall run, having been delayed by unfavorable conditions that evidently typified the river in the early fall months. Clark (1943) in fact stated that a “late-fall run of salmon occurs after this sand dam [the Sack Dam near Firebaugh] is washed or taken out in late November,” indicating that the fall run was usually blocked from ascending past that point any earlier. Furthermore, spawning of Central Valley fall-run stocks tend to occur progressively later in the season in the more southerly located streams, at least at the present time (F. W. Fisher unpublished data), and the spawning migration period is known to include December in the San Joaquin basin tributaries (Hatton and Clark 1942; T. Ford, personal communication, see “Notes”). Nevertheless, a distinct late-fall run (*sensu* Fisher 1994; Yoshiyama and others 1998) may have actually existed in earlier times in the San Joaquin River. Historical environmental conditions in the mainstem reach of the San Joaquin River just above the valley floor were apparently suitable for supporting late-fall-run fish, which require cool water flows during the summer juvenile-rearing period. To wit, Blake (1857, p 20) noted of the San Joaquin River (near Fort Miller) in late July 1853:

The river was not at its highest stage at the time of our visit; but a large body of water was flowing in the channel, and it was evident that a considerable quantity of snow remained in the mountains at the sources of the river. A diurnal rise and fall of the water was constantly observed, and is, without doubt, produced by the melting of the snow during the day. The water was remarkably pure and clear, and very cold; its temperature seldom rising above 64° Fahrenheit while that of the air varied from 99° to 104° in the shade.

Merced River (Merced County). Both spring and fall salmon runs, and evidently steelhead, historically occurred in the Merced River, but only the fall run has survived and is now the southernmost native chinook salmon run in existence (Reynolds and others 1993). According to a gold miner's account, Native Americans were observed harvesting salmon in the spring of 1852 at Merced Falls, where their "rancheria" (village) was located (Collins 1949). Another gold miner noted, during the first half of November 1849, "At the River Merced we saw some Indians, ...These Indians were fishing for salmon, at which business they are very expert and successful" (Woods 1851, p 83)—in obvious reference to the fall run. Boating down the lower Merced River below Hopeton on 10 November 1877, John Muir observed, "Fish abundant in deep pools—salmon, trout, and suckers" (Muir 1938, p 241). Based on the date, the salmon he saw undoubtedly were fall-run salmon and the "trout" may have been steelhead. Spring-run salmon were also reported from the vicinity of "Horse Shoe Bend" (now covered by Exchequer Reservoir), near Coulterville (Mariposa Gazette, 24 June 1882 and 25 June 1887; J.B. Snyder, personal communication, see "Notes"). Oral history obtained from local residents (Snyder unpublished memorandum, 9 May 1993) indicates that salmon occurred in the mainstem Merced River in the area between Bagby and Briceburg near the branching of the North Fork. There is a 20-foot waterfall below Briceburg (Stanley and Holbek 1984), but it probably was not steep enough to have posed a substantial obstacle to salmon (see below). Another gold miner's journal (Perlot 1985) indicates that salmon were caught in abundance on the mainstem Merced River some unspecified distance above the confluence of the South Fork—possibly approaching the vicinity of El Portal (about 2,000 ft elev.). The section of river above El Portal is of high gradient and would have presented a rigorous challenge to migrating fish; thus, it is not clear if substantial numbers of salmon, if any, were able to ascend beyond that point.

There has been disagreement on whether any salmon reached Yosemite Valley. Dr. Lafayette Bunnell, writing of his service with the Mariposa Battalion which discovered the Yosemite Valley in 1851, noted:

Below the cañon of the Yosemite, young salmon were once abundant. The Indians used to catch fish in weirs made of brush and stones; but during the extensive mining operations on the Merced and other rivers, the salmon seemed to have almost abandoned their favorite haunts, for the mud-covered spawn would not hatch. Large salmon were speared by the Indians in all the rivers,... (Bunnell 1990, p 165).

Shebley (1927, p 169) later stated: "At that time [1892] ...the steelhead and salmon ascended the Merced River to Wawona [South Fork] and into Yosemite Valley [on the mainstem] as far as the rapids below the Vernal-Nevada Falls," and there "were a few low dams in the river, but they were not high enough to prevent the steelhead and salmon passing them during the

spring floods." However, Shebley provided no evidence to support his statement, which was later discounted (Snyder 1993 unpublished memorandum). The absence of any clear reference to salmon in the early historical accounts of the Yosemite Valley (for example, Muir 1902, 1938, 1961, 1988; Hutchings 1990), and the present lack of archaeological and ethnographic evidence showing that native peoples subsisted on salmon in the higher elevation parts of the drainage (Snyder 1993 unpublished memorandum) seem to argue against the past occurrence of salmon there, at least in significant numbers. Snyder (unpublished 1993 memorandum), noted that there are no references to salmon in the native folklore of the Yosemite region, nor to terms related to the procedures of salmon fishing as there are in the cultural milieu of native inhabitants of the lower elevations. The paucity of suitable spawning gravels in Yosemite Valley (E.R. Gerstung, personal observation) also would indicate that few, if any, salmon ascended that far, although the presence of "speckled trout" (rainbow trout, *Oncorhynchus mykiss*) in Yosemite Valley was noted in some early accounts (Caton 1869; Lawrence 1884; Hutchings 1990). Yet, California Fish Commissioner B.B. Redding had noted even earlier, in 1875:

A few years since, they [salmon] spawned near the Yosemite Valley. A dam built for mining purposes, some four or five years since, prevented them from reaching this spawning ground. Last year the dam was removed and the fish have again free access to the headwaters of the Merced, but whether they have returned to their former spawning grounds on this river ...I have not learned (USFC 1876b, p 481).

It appears, therefore, that salmon at one time and in unknown numbers may have approached the vicinity of Yosemite Valley, even if they did not enter the valley proper. However, for the present, the area around El Portal or just downstream of it may be the best estimate of the historical upstream limit of salmon in the mainstem Merced River, unless supporting evidence for Shebley's (1927) statement that they ascended farther upstream can be found. Even the vicinity of El Portal may be higher than where most of the salmon historically ascended, considering the lack of archaeological evidence of salmon-fishing technology or salmon remains in excavations near El Portal (J. Snyder, personal communication, see "Notes").

Salmon most likely ascended the South Fork Merced River at least to Peach Tree Bar, about seven miles above the confluence with the mainstem, where a waterfall presents the first significant obstruction (P. Bartholomew, personal communication, see "Notes"). Hardheads are limited in their upstream distribution by the waterfall, and Sacramento suckers occur even farther upstream to the vicinity of Wawona (Toffoli 1965; P. Bartholomew, personal communication, see "Notes"). Salmon commonly spawn in the same reaches frequented by those species (Moyle 1976; E.R. Gerstung, personal observation), so they undoubtedly also reached Peach Tree Bar, if not further. It is possible

that salmon surmounted the waterfall and ranged above Peach Tree Bar, but there is no confirmatory historical information available; if they did so, their upstream limit would have been a 20-foot waterfall located near the mouth of Iron Creek, about four miles below Wawona (E.R. Gerstung, personal observation). The North Fork Merced River is a relatively low watershed (about 1,300 ft elev. at the lower end), but there are substantial falls located about one mile above the mouth (T. Ford, personal communication, see "Notes"; E. Vestal unpublished notes) which would have prevented further penetration into the drainage by salmon. Rutter (1908) also mentioned "a 12-foot fall" that separated the North Fork from the "main Merced River." This perhaps was the cascade mentioned by the gold miner J.N. Perlot which "had at all times been an insurmountable obstacle for the fish," thus accounting for his observations that the North Fork "contained no kind of fish whatsoever, not the least white-bait, not the smallest gudgeon" (Perlot 1985, p 282).

As early as 1852, a temporary barrier was erected by fishermen about ten miles below Merced Falls which blocked the spring-run salmon from their upstream spawning areas (Collins 1949). In the following decades, a succession of dams was built at Merced Falls and at locations upstream up to the Yosemite National Park boundary – including the 120-foot high Benton Mills Dam at Bagby (built in 1859) and a later (1900) dam at Kittredge, four miles below Bagby (Snyder 1993 unpublished memorandum). Those dams had already impeded the upstream migration of salmon by the 1920s, but it was the construction of Exchequer Dam that permanently barred the salmon from their former spawning grounds (CFGF 1921b). Clark (1929) stated that the existent spawning beds were on "occasional gravel bars" located between the river mouth and Exchequer Dam, with "about 12 miles" of streambed available. These are in the lower river and therefore pertain to fall-run fish. As of 1928, there were three obstructions to migrating salmon: Crocker Huffman irrigation diversion dam near Snelling; Merced Falls about three miles upriver, where there was a natural fall and the 20-foot Merced Falls Dam with a defunct fishway; and Exchequer Dam, 20 mi above Merced Falls. A decade later, Hatton (1940) considered the spawning areas to occur between "a point half a mile downstream from a line due south of Balico" and Exchequer Dam. Of this 42.2-mi stretch, only 24.1 mi was accessible to salmon due to obstructions; there were four beaver dams, passable under "usual water conditions," and four impassable rock dams lacking fishways and allowing only "seepage" to pass downstream. Above these rock dams was the Merced Falls Dam, equipped with a fishway but inaccessible to the salmon because of the downstream obstructions and low water flows. Presently, natural spawning by fall-run fish principally occurs in the stretch above Highway 59 to the Crocker-Huffman diversion dam, the upstream limit of salmon migration (Reynolds and others 1993). The Merced River Hatchery (operated by DFG) is located by this dam. Fall-run spawners ascending to this point are captured at the dam's fish ladder, for use as hatchery broodstock.

Clark (1929, p 31) reported both spring and fall salmon runs present in the Merced River and mentioned recollections by early residents of "great quantities of fish coming up the river to spawn in the summer and fall...so numerous that it looked as if one could walk across the stream on their backs." An early newspaper account (Mariposa Gazette, 26 August 1882, J.B. Snyder, personal communication, see "Notes") reported "...the water in the Merced river has become so hot that it has caused all the salmon to die. Tons upon tons of dead fish are daily drifting down the river, which is creating a terrible stench, and the like was never known before." Judging from the date, the reference was to spring-run salmon; fall-run salmon would not have entered the tributaries so early, assuming they behaved similarly to the Sacramento River fall run. By 1928, the runs were greatly depleted, with only several hundred fish reported in the Merced River during the fall (before 12 November) of that year (Clark 1929, p 31). According to Clark (1929, p 32), very low flow conditions due to irrigation diversions during the spring, summer and early fall had "just about killed off the spring and summer runs" (the "summer" run evidently was the latter part of the spring run or perhaps an early fraction of the fall run), and only fish arriving in late fall after the rains were able to enter the river. These fish were probably a late-running component of the fall run, rather than a true late-fall run (*sensu* Fisher 1994) because there was no explicit mention by Clark (1929) of early residents referring to salmon runs in December or later that would have been more characteristic of the late-fall run. Clark also referred to late fall as including November in his account for the Mokelumne River, which is a somewhat earlier run time than is characteristic of most late-fall-run fish. Even in recent years when drought conditions and extensive irrigation diversions reduced streamflows to very low levels, the salmon did not spawn in the Merced River "until after the first week of November when water temperatures [had] become tolerable" (Reynolds and others 1993, p VII.96).

Fry (1961) considered the Merced River to be "a marginal salmon stream" due to the removal of water by irrigation diversions, and he stated that there was "a poor fall run and poor spring run." Run-size estimates for the fall run were 4,000 fish for 1954 and <500 fish for every other year during the period 1953–1959 (Fry 1961). No numerical estimates were available for the spring run at that time. After 1970, fall-run spawning escapements increased to an annual average of 5,800 fish, reaching 23,000 spawners in 1985, due to increased streamflows released by the Merced Irrigation District and operation of the Merced River Hatchery (Reynolds and others 1993). As in other San Joaquin basin tributaries, spawning escapements in the Merced River, including returns to the Merced River Hatchery, dropped to "seriously low levels" during the early 1990s – numbering <100 fish in 1990 and <200 in 1991 (DFG 1996 unpublished data). The fall run increased from about 1,000 to 2,000 spawners in 1992–1993 to 4,000 to 6,000 spawners in 1996–1998 (DFG 1996 unpublished data), perhaps auguring a partial recovery of the stock. The Merced River

Hatchery, operated since 1971 by DFG, has received a major fraction of the spawning run in this stream, accounting for 5% to 39% of the annual runs during the 1980s, 19% to 67% in 1990–1994, and 17% to 30% in 1995–1998 (DFG unpublished data). Late-fall-run salmon are said to occur occasionally (Reynolds and others 1993), but the spring run no longer exists in the Merced River.

Tuolumne River (Stanislaus and Tuolumne counties). At least spring and fall salmon runs historically used the Tuolumne River. Clavey Falls (10 to 15 ft high), at the confluence of the Clavey River, may have obstructed the salmon at certain flows, but spring-run salmon in some numbers undoubtedly ascended the mainstem a considerable distance. The spring-run salmon were most likely stopped by the formidable Preston Falls four miles above Early Intake Dam near the boundary of Yosemite National Park (about 50 mi upstream of present New Don Pedro Dam), which is the upstream limit of native fish distribution (DFG unpublished data). Sacramento suckers (*Catostomus occidentalis*), riffle sculpins (*Cottus gulosus*) and California roach (*Lavinia symmetricus*) were observed during stream surveys between Early Intake and Preston Falls (DFG unpublished data; P. B. Moyle unpublished data), and spring-run salmon probably formerly occurred throughout that reach as well. If they were present in the Tuolumne drainage, steelhead probably ascended several miles into Cherry Creek, a tributary to the mainstem about one mile below Early Intake, and perhaps spring-run salmon also entered that stream. Steep sections of stream in the Clavey River and the South and Middle forks of the Tuolumne shortly above their mouths most likely obstructed the salmon (T. Ford, personal communication, see “Notes”), although Sacramento pikeminnow are found within the first mile of the Clavey River and suckers and roach occur up to 10 to 15 miles upstream (EA Engineering, Science and Technology 1990). In the lower South Fork, a large waterfall (25 to 30 ft high, Stanley and Holbek 1984) probably prevented further access up that fork. The North Fork, with a 12-foot waterfall about one mile above the mouth, likewise offered limited access. Probably few, if any, salmon entered those upper reaches of the Tuolumne drainage (T. Ford, personal communication, see “Notes”). The waterfalls just below present Hetch Hetchy Dam on the mainstem, about ten miles above Preston Falls, evidently stopped all fish that might have ascended that far, and John Muir wrote that the river was barren of fish above the falls (Muir 1902). There are no indications that salmon ever reached Hetch Hetchy Valley, or Poopenaut Valley farther downstream (Snyder 1993 unpublished memorandum). Just as with the Merced River, there is no archaeological or ethnographic evidence indicating that salmon were part of the subsistence economics of the native inhabitants of the higher elevations along the upper Tuolumne River (Snyder 1993 unpublished memorandum).

The first written record of salmon in the Tuolumne River is that of the Frémont Expedition of 1845–1846. Frémont’s (1848, p 18) journal entry for 4 Feb-

ruary 1846 reads: "Salmon was first obtained on the 4th February in the Towal-um-né river, which, according to the Indians, is the most southerly stream in the valley in which this fish is found." It is not clear whether Frémont's party caught the salmon or obtained them from the local native inhabitants, but in any case, it is likely that the fish were early arrivals of the spring run. Although the bulk of the spring-run salmon migration occurs during April through June, at least in the Sacramento drainage (Fisher 1994), spring-run fish have occasionally appeared in their spawning streams in early February, as in Butte Creek during 1995 (F. W. Fisher unpublished data), and sometime during February in the American River (in 1946) (Gerstung 1971 unpublished report). The occurrence of salmon in the Tuolumne River in those early years was also noted by John Marsh, who had arrived in California in the mid-1830s. Quoting Marsh, Edwin Bryant wrote, "...the river of the Towalomes; it is about the size of the Stanislaus, which it greatly resembles,...and it particularly abounds with salmon" (Bryant 1849, p 277). Furthermore, in his memoirs of the Gold Rush, the entrepreneur Samuel Ward recollected enjoying "a plentiful fish supper" of fresh salmon, caught by rifle shot in the lower Tuolumne River at Dickensons Ferry (located roughly halfway between the river mouth and the Sierra foothills (Collins 1949, p 104). That occasion was "late in the autumn [1851], just after winter's first premonitory showers" (Collins 1949, p 100) – coincident with the timing of the fall run. A later historical account also noted of the local native people: "Every spring, when the salmon were running up the river, enough were caught and dried to last nearly all the year"; "The waters of the Tuolumne, Stanislaus, Merced and San Joaquin generally furnish them with good fishing. They spear the salmon with spears made of some kind of tough wood,..." (Elliott 1882, p 162, 166).

Significant blockage of salmon runs in the Tuolumne River began in the 1870s when various dams and irrigation diversion projects were constructed, although dams and water diversions associated with mining had been present as early as 1852 (Snyder 1993 unpublished memorandum) and undoubtedly had some effect. Wheaton Dam, built in 1871 at the site of present-day La Grange Dam, may have blocked the salmon to some degree (T. Ford, personal communication, see "Notes"). By 1884, the Tuolumne and Stanislaus rivers were "dammed in such a way to prevent the fish from ascending" (CFC 1884, p 16). La Grange Dam, a 120-foot-high engineering marvel when completed in 1894, permanently cut off the former spring-run spawning areas. In 1896, the California Fish Commission stated, "The number of salmon that enter this stream [Tuolumne River] to spawn is small, and after its waters are taken out for irrigating purposes, will probably decrease," and the proposed fish ladder for La Grange Dam was viewed by the Fish Commission to be "not warranted, and would be of little or no benefit to the people or the fish" (CFC 1896, p 18). However, mining and other activities that degraded the river habitat undoubtedly also affected the salmon runs even before the early period of dam construction on the Tuolumne River. John Muir recorded in his journal in

November, 1877: "Passed the mouth of the Tuolumne.... It is not wide but has a rapid current. The waters are brown with mining mud. Above the confluence the San Joaquin is clear..." (Muir 1838, p 244).

Clark (1929) stated that the spawning grounds in 1928 extended from the town of Waterford to La Grange, over 20 miles of "good gravel river." At the time, there were two dams of major significance: La Grange Dam and Don Pedro Dam (built in 1923) 13 miles upriver; the latter was 300 ft high and formed a large irrigation reservoir (Clark 1929). Hatton (1940) later stated that the spawning beds in the Tuolumne River lay between a point 2.2 miles below the Waterford railroad bridge and the La Grange Power House. As of 1939, the Modesto Weir (a low structure) had no water diversion and was passable to salmon because the flash boards were removed "several weeks in advance of the fall run" (Hatton 1940). The rest of the Tuolumne River was clear of obstructions up to the impassable La Grange Dam. Spawning now occurs in the approximately 20-mile stretch from the town of Waterford (rm 31) upstream to La Grange Dam (EA Engineering, Science and Technology 1992). La Grange Dam remains a complete barrier to salmon and thus defines the present upstream limit of their spawning distribution (Reynolds and others 1993). The total area of spawning gravel presently considered available to salmon in the lower Tuolumne River (below La Grange Dam) is 2.9 million square feet (EA Engineering, Science and Technology 1992).

The California Fish Commission (CFC 1886, p 20) noted of the Tuolumne River: "[it] at one time was one of the best salmon streams in the State; Salmon have not ascended the stream for some years." Clark (1929) also reported that salmon generally were "scarce" in the Tuolumne River; at that time, both spring and fall runs still occurred at low levels, but the spring run was inconsequential, amounting "to almost nothing," and the fall run comprised "some fish" (Clark 1929, p 32). Clark noted, however, that "a good run" (evidently the fall run) had been reported in 1925 which "surpassed anything that had appeared in several years." Two decades later, only "a bare remnant of a spring run" was reported to exist during 1944-1946 (DFG 1946).

Only the fall run presently occurs in appreciable numbers in the Tuolumne River. In the past, fall-run spawning escapements in the Tuolumne River during some years were larger than in any other Central Valley streams except for the mainstem Sacramento River, reaching as high as 122,000 spawners in 1940 and 130,000 in 1944 (DFG 1946; Fry 1961). In fact, over the past half-century the Tuolumne River has supported one of the largest natural populations of salmon in the Central Valley tributaries (DFG unpublished data; USFWS 1995). Tuolumne River fall-run salmon at times comprised up to 12% of the total fall-run spawning escapement for the Central Valley (Reynolds and others 1993), but run sizes during the early 1990s fell to extremely low levels—specifically, fewer than about 130 spawners in each of the years 1990-1992 and

about 400 to 500 fish in 1993 and 1994 (DFG 1996 unpublished data). The fall run recently rebounded to at least 3,600 to 5,500 spawners in 1996–1997 and 7,900 spawners in 1998 (DFG unpublished data). The fall run historically has been a naturally sustained population because there is no hatchery on the Tuolumne River, unlike most other major salmon streams in the Central Valley (Reynolds and others 1993). However, increasing numbers of hatchery-derived spawners have ascended the Tuolumne River in recent years, mainly due to large releases of hatchery juveniles (from Merced River Hatchery) for study purposes into this stream and elsewhere in the San Joaquin River basin and Sacramento-San Joaquin Delta (DFG unpublished data; FERC 1999).

It has been stated that “a small population” of late-fall-run fish exists in the Tuolumne River (Reynolds and others 1993), but the existence of such a run appears to be based mainly on the occurrence of juveniles in the river during the summer and on observations of occasional spawning in later months (January through March) than is typical for fall-run fish (T. Ford, personal communication, see “Notes”). However, hydrological conditions in the Tuolumne River during the past few decades have not been conducive to the maintenance of a late-fall run – notably the lack of consistent, cool streamflows during the summer to support the juveniles (Reynolds and others 1993). It is possible that the infrequent observations of fish with late-fall-run timing characteristics have been strays from the Sacramento River system and their progeny. Late-emerging or slow-growing fry produced by fall-run fish, perhaps of hatchery origin, also could account for some of the juveniles observed over-summering in the river.

Stanislaus River (Stanislaus, Calaveras counties). Both spring and fall runs historically occurred in the Stanislaus River. The forty-niner Alfred Doten wrote in his journal for 4 November 1850: “At sunset we crossed the Stanislaw river and camped on the opposite side – Beautiful river – forded it at a shallow place where the natives were shooting and spearing salmon” (Clark 1973, p 59) – obviously the fall run. Another gold miner, Howard C. Gardiner, made note of salmon in the Stanislaus River at Knights Ferry, in mid-December 1848 (the exact date unknown, but probably soon after December 19): “...we reached the ferry...the others went over, leaving me to dicker with an Indian for the purchase of a salmon which we had seen him capture a few minutes previous. The native soon came with the fish which must have weighed twenty-five pounds.... I bought the salmon for eight dollars...” (Morgan 1970, p 109). The approximate date is consistent with the peak migration period of the late-fall run, but also with the end of the fall run (Fisher 1994). The California Department of Fish and Game reported that besides the spring salmon run, “lesser runs occurred in fall and winter due to the natural, unaltered regime of the river” (DFG 1972, p 2–3), but the later-running fish were most likely late-fall-run salmon or perhaps a segment of the fall run.

Steelhead evidently also were seen by the gold miners, as attested by Alfred Doten:

The Salmon Trout of the mountain streams is a most beautiful and delicious fish, and not to be beaten for good eating by any other freshwater fish; at least I used to think so when I was a gold digger. They generally weigh from two to four pounds, and are abundant in most of the upper streams and rivers of the Sierra Nevada (Clark 1973, p 311).

The native Central Sierra Miwok people, located near the Tuolumne and Stanislaus rivers, were said to have “fished in the Le Grange [sic] and Knights Ferry Area for two kinds of salmon: The summer salmon which were small and also called ‘red salmon,’ and winter salmon or ‘dog salmon’ which were larger, ‘they were all the big ones’” (Theodoratus 1976, p 486) – the two kinds apparently corresponding to spring-run (summer or red) and fall-run (winter or dog) salmon. In an interview conducted in 1975, an elder (90+ years old) Miwok informant stated that the “red salmon” (spring run) were speared in the Stanislaus River above a bridge near Knights Ferry, and some numbers also were taken at “Burns Ferry” (now covered by Tulloch Reservoir) and farther upstream at a “dam” near Columbia (perhaps at a mining diversion) (Theodoratus 1976). The “winter salmon” (fall-run) fishing spots were at Knights Ferry and, when the water was high, at “Wild Cat Canyon.” Other Miwok and non-Indian informants reported that salmon were taken below the “old Camp Nine bridge” (near the town of Stanislaus), “under the bridge at Parrotts Ferry” and “in the Melones area...in the early 1900s” (Theodoratus 1976, p 487; Maniery 1983). The latter two sites are now covered by upper New Melones Reservoir. According to one Miwok informant, his father caught salmon in six-foot long basketry fish traps: “...he use[d] to haul fish out of the canyon with ten of his mules up from Camp Nine [Stanislaus] to Tablerock Mountain up to Murphys...to sell the salmon for 50¢ a piece” – some of which “weighed up to twenty-five pounds or so” (Theodoratus 1976, p 398). The large size of those fish suggests they were of the fall run. Salmon also were taken near Duck Bar (4.5 mi below Stanislaus, now inundated), where a long-time Miwok resident named Indian Walker caught them in fish traps to sell to the white community (Cassidy and others 1981). Barrett and Gifford (1933, p 189) reported that “salmon were caught in the late spring” – in obvious reference to the spring run.

Spring-run and perhaps some fall-run salmon probably went considerable distances up the forks because there were few natural obstacles (W. Loudermilk, personal communication, see “Notes”). Before the filling of New Melones Reservoir, there were no natural barriers to salmon in the reach from Old Melones Reservoir upstream to the mouth of the Middle Fork Stanislaus River (which was a popular rafting reach; E.R. Gerstung, personal observation), or on the Middle Fork from its mouth up to Sand Bar Flat located just below the

Spring Gap Powerhouse (E. Vestal, personal communication, see "Notes"). One ethnographic account stated, "On the Stanislaus river, salmon (*kosimo*) went as far as Baker's bridge where there is a waterfall" (Barrett and Gifford 1933, p 189). Baker's Bridge was located near Spring Gap Powerhouse on the Middle Fork, about two miles below present-day Beardsley Reservoir, according to an old-time rancher in that area (personal communication to E.R. Gerstung, see "Notes"). That same location was designated as "Baker's Crossing" on an old US Geological Survey map, drawn in 1901 by Thomas R. Hanna (Map of Stanislaus Forest Reserve, Alpine Count Library Archives, Markleyville). Apparently, there were no impassable natural obstacles on the Middle Fork to just above present-day Beardsley Reservoir (3,400 ft elev.) (E. Vestal, personal communication, see "Notes"), although the increasingly steep gradient up to that point may have deterred most salmon.

In the North Fork Stanislaus River, suckers and hardhead occurred in the first several miles up to the confluence of Griswold Creek (Northern California Power Authority 1993 unpublished report), so salmon undoubtedly would have ascended at least to that point. The North Fork was probably accessible to salmon as far as McKay's Point (about eight miles above the confluence with the Middle Fork), where the gradient steepens and which we take as the practical upstream limit. Presumably few, if any, salmon passed that point and they probably were blocked five miles farther upstream by a 15-foot waterfall above Board's Crossing. The South Fork Stanislaus River is a small drainage and is unlikely to have supported more than a few, if any, salmon because of the paucity of habitat. We have seen no suggestions of salmon having occurred in the South Fork, and for the present we do not include it as a former salmon stream.

Damming and diversion of water on the Stanislaus River, for both mining and irrigation, began soon after the Gold Rush. The earliest "permanent" dam on the river was the original Tulloch Dam, constructed in 1858 just downstream of the present Tulloch Dam (Tudor-Goodenough Engineers 1959). The original Tulloch Dam was a relatively low structure and evidently had an opening at one end (photograph in Tudor-Goodenough Engineers 1959), and its impact on the salmon runs, therefore, may not necessarily have been significant. Clark (1929) stated that the salmon spawning beds were distributed over ten miles of stream, from the marshlands above Oakdale to Knight's Ferry. Dams on the river by that time included 20-foot Goodwin Dam (completed in 1913) 18 mi above Oakdale, which had a fishway and was at times negotiable to salmon, and the 210-ft impassable Melones Dam (completed in 1926) above the town of Melones. The spawning beds in 1939 were reported by Hatton (1940) to extend from Riverbank Bridge to the Malone Power House, although of this 32.7-mile distance, the 9.3 miles between Goodwin Dam and the Power House was "only rarely accessible to salmon." Hatton (1940, p 355) stated that the fishway over Goodwin Dam was "seldom passable" and that the fluctuat-

ing water level caused by hydroelectric operations above Goodwin Dam and the “almost complete diversion of water at the dam” made it “very nearly an impassable barrier.” Fry (1961) also mentioned the blockage of migration by Goodwin Dam, the operation of which also caused low and warm flows downstream during the summer and “violent” water fluctuations (due to power-generation releases) during the fall and winter. Presently, the salmon do not ascend the Stanislaus River farther than Goodwin Dam, which regulates streamflows from Tulloch Reservoir and diverts water for irrigation and power generation (Reynolds and others 1993). Much of the spawning occurs on the extensive gravel beds in the 23-mile stretch from Riverbank upstream to Knights Ferry, which are essentially on the valley floor (T. Ford, personal communication, see “Notes”). Upstream of Knights Ferry, where the river flows through a canyon, spawning is concentrated at Two Mile Bar (about one mile above Knights Ferry) but also occurs in scattered pockets of gravel (T. Ford, personal communication, see “Notes”).

The California Fish Commission reported that while the Stanislaus River had once mirrored the Tuolumne River as a preeminent salmon stream, by 1886 only an occasional salmon was seen “trying to get over one of its numerous dams” (CFC 1886, p 20) Much later, Clark (1929, p 32) reported that the Stanislaus River “has a good spring and fall run of salmon,” but he also stated that their abundance was “about the same as in the Tuolumne” where he had described them to be “scarce.” Given Clark’s contradictory statements, it is not clear how abundant, even qualitatively, the salmon were in the Stanislaus at the time of Clark’s survey (late 1920s). Historically, the spring run was said to have been the primary salmon run in the Stanislaus River, but after the construction of dams which regulated the streamflows (namely, Goodwin Dam and, later, Melones and Tulloch dams), the fall run became predominant (DFG 1972). Fry (1961, p 64) described the Stanislaus River as “a good fall run stream for its size” but it had “almost no remaining spring run.”

The Stanislaus River fall run, in recent historical times, has contributed up to 7% of the total salmon spawning escapement in the Central Valley (Reynolds and others 1993). Annual escapements for the fall run were minimally estimated at 4,000 to 35,000 spawners (average about 11,100) during 1946–1959 (Fry 1961), before the construction of Tulloch Dam (in 1959). In the following 12-year period (1960–1971), the average run size was about 6,000 fish (DFG 1972). Fall-run abundances during the 1970s and 1980s ranged up to 13,600 (average about 4,300) spawners annually (DFG unpublished data). The numbers of spawners returning to the Stanislaus River have been especially low during most of the 1990s – <500 fish annually in 1990–1993, 600 to 800 fish in 1994–1995, and <200 fish in 1996 – but there was a modest increase to 1,500 spawners in 1997 and 2,200 spawners in 1998 (DFG unpublished data).

Presently (1999) only the fall run has sustained itself in the Stanislaus River, although small numbers of late-fall-run fish have been reported to occur (Reynolds and others 1993). As in the Tuolumne River, the recent occurrence of late-fall-run salmon in the Stanislaus River could be due to strays from the Sacramento River system.

Calaveras River (Calaveras County). The Calaveras River is a relatively small, low-elevation drainage that receives runoff mainly from rainfall during November through April (Reynolds and others 1993), and its lower reaches historically were dry during part of the year (Carson 1852). This river was probably always marginal for salmon, and it lacks suitable habitat for spring-run fish (E.R. Gerstung, personal observation). Chinook salmon runs reportedly occurred on an "irregular basis" (Reynolds and others 1993), although Clark (1929, p 235) had stated that the Calaveras River was "dry most of the summer and fall and so it has no run of salmon." Yet, the name of the river itself represents, in a way, a salmon legacy. Quoting the historian Sanchez (1932, p 291):

In his diary Moraga says that the river tribes fought against those of the Sierra for possession of the salmon in the stream, and that in one battle many were said to have been killed and left on the field. A great number of skulls, relics of this bloody conflict, were found by Moraga scattered along the creek bed, and for that reason he called it Las Calaveras [The Skulls].

O'Brien (1951, p 33) further elaborated:

Moraga followed them...and there halted in amazement. Skulls and bones littered an acre and more. An Indian of a nearby rancharía explained that the field was an ancient battleground. A long time before, he said, invading warriors swarmed down from the Sierra to drive the tribes of the Sacramento and San Joaquin Valleys from their river fishing preserves...and these skulls and bones were the remains of those who had fallen.

The Calaveras River had, in recent times, an unusual "winter" salmon run which spawned during late-winter and spring, but it is unknown if the run had existed before the dams were built on the river. This run has been referred to as a "winter run," but perhaps it was more like a late-fall run, given that the spawning period was relatively early compared to the Sacramento winter run. The presence of this run was documented for six years within the period 1972-1984 and it numbered 100 to 1,000 fish annually (Reynolds and others 1993). The fish ascended to New Hogan Dam, and they held and spawned in the reach just below the dam (T. Ford, personal communication, see "Notes"). Management of streamflows by the US Army Corps of Engineers entailed high-flow releases from New Hogan Dam interspersed with periods of very low flow, which undoubtedly contributed to the apparent demise of this run since 1987 (T. Ford, personal communication, see "Notes"; USFWS 1995). Bel-

lota Dam, 15 mi below New Hogan Dam, and at least two other diversion dams are known to have blocked upstream salmon migration during periods of low streamflow (Reynolds and others 1993). The run's extirpation may also have been hastened, if not guaranteed, by persistently low streamflows due to the 1987–1992 drought and to irrigation diversions.

It is possible that the existence of salmon—particularly the supposed “winter run”—in this river during recent decades has been mainly the result of suitable conditions created by the dams. Historically, the natural occurrence of salmon there was most likely limited to wet years. Currently, fall-run salmon—perhaps those destined for other San Joaquin River tributaries—occasionally enter the Calaveras River when suitable fall streamflows occur. For example, several hundred fall-run fish were observed during the fall of 1995 at Bellota Dam, where they were temporarily blocked (DFG unpublished data). We have no information on the historical upstream range of salmon in the Calaveras River, so we consider the site of New Hogan Dam (the upper limit in recent times) as a minimal approximation of the historical limit.

Mokelumne River (San Joaquin, Amador counties). The Mokelumne River, in its original state, apparently supported at least fall and spring salmon runs. Some evidence suggests that a late-fall run also occurred at one time. In what is probably the earliest record of salmon in the Mokelumne River, the fur trapper Jedediah Smith, having encamped on “Rock River” (Mokelumne River), wrote in his journal for 22 January 1828: “Several indians came to camp and I gave them some tobacco. They brought with them some fine salmon some of which would weigh 15 or 20 lbs. I bought three of them and one of the men killed a deer...” (Sullivan 1934, p 56). The salmon that would have been present during that part of January in “fine” condition most likely were late-fall-run or perhaps spring-run, although the timing is extraordinarily early for the latter. Smith’s party evidently was on the lower Mokelumne River on the marshy valley floor, for “...although the ground was rolling the horses sank at every step nearly to the nees [sic].” Two decades later, Alfred Doten similarly recorded (for 22 December 1851): “Saw three fine salmon, which were brought from the Moqueleme—they averaged about 20 lbs a piece” (Clark 1973, p 80). That date is consistent with the peak migration time of the late-fall run, and although later-arriving spawners of the fall run cannot be completely discounted, it is more likely that late-fall run fish would have been present in “fine” physical condition. Ethnographic information attests that native Northern Sierra Miwok people on the Mokelumne River in the past had at least a simplified “first-salmon” rite (Aginsky 1943)—suggesting the historical presence of the spring salmon run, given that such rites characteristically were associated with the onset of the spring-run harvest in other Central Valley streams (for example, Gayton 1946 [p 256], 1948b [p 166]; Voegelin 1942, [p 57, 175]) and on the northern California coast (Swezey and Heizer 1977).

Salmon ascended the river at least as far as the vicinity of present-day Pardee Dam (rm 73). Reportedly, a large waterfall (30+ ft high) was present at Arkansas Ferry Crossing, one mile downstream of the Pardee Dam site in a narrow rocky gorge (R. Nuzum, personal communication, see "Notes"), and it may have posed a significant barrier to the fall run. The site of the waterfall was inundated by Camanche Reservoir, and no natural obstructions presently exist between Camanche Reservoir and Pardee Dam (S. Boyd, personal communication, see "Notes"). Spring-run salmon undoubtedly would have ascended past that former waterfall to reach higher elevations where water temperatures were suitable for over-summering. It has been stated that, "An unknown number of chinook salmon" spawned upstream of the Pardee Dam site in earlier times (FERC 1993). Steelhead were believed to have spawned mostly in the reaches above Pardee Dam (Dunham 1961 unpublished report). Because there are no impassable falls between Pardee and the Electra powerhouse 12 mi upstream, spring-run salmon undoubtedly also reached the latter point. Bald Rock Falls (30 ft high), seven miles beyond Electra, is a complete fish barrier (Woodhull 1946). Native fish species such as hardhead and pikeminnow are known to have reached the falls (Woodhull 1946), so Bald Rock Falls can be reasonably taken as a likely upstream limit for both salmon and steelhead.

The California Fish Commission reported in 1884 that the Mokelumne River was the "only stream emptying into the San Joaquin not dammed" (CFC 1884, p 16). Collins (1892, p 163) also asserted: "Salmon do not run into the San Joaquin in large numbers. In the fall, when the fishery is at its best, fishermen go a few miles up the Mokolumne ...[sic]" Yet, the salmon runs into the Mokelumne River already had been largely eradicated by 1877 due to gold mining activities (CFC 1877, p 5). However much the salmon runs subsequently recovered from the habitat degradation of the gold mining era, the runs were believed to have started another decline after the construction of Woodbridge Dam (15 ft high) in 1910, at the town of Woodbridge (rm 39) (Dunham 1961 unpublished report). Fry (1961, p 64) cited Woodbridge Dam as having been "a serious fish block" for many years, as well as providing "often too little water for the passage of salmon," and he mentioned industrial and mining pollution as having been "very serious" at times. As of 1928 the salmon spawning grounds reportedly extended from the river mouth above tidewater for about 15 mi to above Woodbridge Dam (Clark 1929). There was a small fishway at this dam which had very little water flowing down it during summer and fall (Clark 1929). Clark reported that the Mokelumne River at that time had "only a fall run," "usually quite late." He stated that a "considerable run" migrated upriver each year, although not as large as in former years, and that the flashboards in Woodbridge Dam were taken out in late fall (November) to allow passage of the salmon. Although this is possibly an indication of a late-fall run, it seems more likely that the fish for the most part were a late-running fall run, delayed by the lack of water. The true late-fall

run, as currently recognized (Fisher 1994; Yoshiyama and others 1998), probably would not have been present in the Mokelumne River or other tributaries in significant numbers until December at the earliest. However, the earliest historical references to salmon (noted above) seem to indicate that late-fall run salmon actually occurred in the Mokelumne River at least until the mid-19th century.

Despite Clark's (1929) statement to the contrary, spring-run salmon evidently still entered the lower Mokelumne River during the early 1930s. Salmon and other fish were landed in the small fishing port of Lockeford, about nine miles upstream of Woodbridge. Scofield (1954, p 78) reported that in the period 1931-1935, "an average of 2,000 pounds per year of mixed fish were credited to this town" and that "During May, June and July salmon predominated." The salmon in that season almost certainly would have been spring-run fish. Scofield (1954, p 78) also reported "only the record of 3,800 pounds of salmon in August and September of 1931" associated with the town of Acampo three miles north of Lodi on the east side of the Mokelumne River. If the fall run in this river usually ran late, as Clark (1929) stated for that historical period, then perhaps those salmon recorded in August-September at Acampo were a component of the spring run that had been blocked from ascending farther upstream, presumably by Woodbridge Dam.

The construction of Pardee Dam in 1928 presented an insurmountable obstacle, cutting off the upper spawning areas (Dunham 1961 unpublished report). Hatton (1940) stated that spawning beds on the Mokelumne River occurred in the 22.5 mi between Lockeford Bridge and Pardee Dam. At that time (1939), the irrigation dam at Woodbridge had a fishway but was impassable at times due to "fluctuating water levels," and Hatton was of the opinion that probably most of the migrating spawners did not ascend to the spawning beds until the dam's weir boards were removed, usually "around the first week in November."

Fall-run salmon are now stopped at the lower end of Camanche Reservoir, about nine miles below Pardee Dam. They spawn in the reach from Camanche Dam (rm 64) downstream to Elliott Road (rm 54) (J. Nelson, personal communication, see "Notes"), and 95% of the suitable spawning habitat is within 3.5 miles of Camanche Dam (Reynolds and others 1993). Before the completion of Camanche Reservoir (1964), the fall run also spawned upstream from Camanche Dam to the canyon about three miles below Pardee Dam (Reynolds and others 1993). The Mokelumne River Hatchery, operated by DFG, was built in 1965 as mitigation specifically for that spawning stock component (Reynolds and others 1993; J. Nelson, personal communication, see "Notes").

Fry (1961) reported that counts of fall-run spawners passing Woodbridge Dam ranged from <500 (in two separate years) to 7,000 fish during the period

1945–1958, and there were partial counts of 12,000 fish each in 1941 and 1942 (DFG 1944; Fry 1961). Fry also stated that the spring run appeared to be “practically extinct.” During the period 1940–1990, total annual run sizes ranged between 100 and 15,900 fish (Reynolds and others 1993); the runs averaged 3,300 spawners during 1940–1963 (before impoundment of Camanche Reservoir) and 3,200 spawners during 1964–1990 (post-impoundment) (Reynolds and others 1993). More recent annual run-size estimates for the fall run have been 400 to 3,200 (average about 1,800) total spawners during 1990–1994, increasing to 5,400 to 7,800 fish in 1995–1996 and perhaps 16,700 fish in 1997 (DFG unpublished data). The latter DFG estimate for 1997 may be inflated; a lower escapement of about 10,180 spawners was reported by the East Bay Municipal Utility District (J. Miyamoto, personal communication, see “Notes”). Hatchery returns have composed 14% to 69% of the fall run during the 1990s. Estimated numbers of natural spawners during this period ranged from 180 (in 1991) to 10,160 fish (in 1997), averaging 2,500 fish (DFG unpublished data).

Cosumnes River (El Dorado County). The Cosumnes River, a branch of the Mokelumne River, historically has been an intermittent stream and therefore offered limited access to salmon. Yet, the river derives its name from the Cosumne triblet of the Valley Yokuts – the “People of the Salmon Place” in the language of the neighboring Miwok people (Latta 1977, p 99) – or, alternatively, from Southern-Central Miwok words for salmon (*kos'-sum*, *kos'-sum-mi*) (Powers 1877, p 347; Bennyhoff 1977, p 101). Latta (1977, p 100) noted that the Cosumne village of “*Musu* (moo-soo, probably a variant of *Cosu* and meaning Salmon Place) was...located two miles northeast of present Bruceville” – about nine miles above the mouth of the Cosumnes River.

Only a fall salmon run is definitely known to have occurred in this river. Hallock and Van Woert (1959) reported that the Cosumnes River had a “notoriously late” fall run, probably due to insufficient streamflows until well into the fall rainy season. There is no indication that a spring run ever existed here (J. Nelson, personal communication, see “Notes”) and the atypical streamflow regime and low elevation of the drainage make it unlikely that there was one. There is a 30-foot falls a half mile below Latrobe Highway Bridge which has been viewed as a barrier, and which we take as the historical upstream limit. However, salmon probably did not usually reach that far upriver because of the limited time available for migration in this stream, and most likely only a few fish ascended past Michigan Bar (rm 31). If any fish were able to surmount that obstacle, they undoubtedly were stopped by a second waterfall (50 ft high) 8.5 mi farther upstream at the Highway 49 crossing.

Clark (1929) reported the presence of “a considerable run” (fall run), which he stated to be equal in abundance to that in the Mokelumne River. At that time the spawning grounds extended from the river mouth above tidewater to the

irrigation diversion dam near the town of Sloughhouse, which was a barrier to the salmon. In 1939, the spawning grounds on the Cosumnes River extended along the 15.2 mi stretch from Sloughhouse Bridge up to the falls below Latrobe Highway Bridge (Hatton 1940). Hatton (1940) reported that the best spawning areas were between the Sloughhouse and Bridgehouse bridges; just above Bridgehouse the river passed through a canyon where bedrock largely replaced the gravel beds. At that time (1939), the 18-foot high Bridgehouse Dam was the only permanent dam on the river, having two “apparently satisfactory fishways” but an unscreened diversion. The lower end of the stream was dry during the months when irrigation diversions were taken, but in late fall “a run of undetermined size” took place (Hatton 1940). The fall run presently spawns in the reach from downstream of the Highway 16 crossing (Bridgehouse Bridge) up to the falls below Latrobe Road (J. Nelson, personal communication, see “Notes”). Additional spawning habitat occurs downstream of the Highway 16 crossing to Sloughhouse Bridge, but below that point the substrate is largely sand and unsuitable for spawning (E.R. Gerstung, personal observation). The sole dam in the river—Granlees Diversion Dam (located one mile upstream of the Highway 16 crossing)—presently may pose an obstacle to salmon migration because its fish ladders are sometimes inoperative. The salmon generally cannot ascend the river until late October to November, when adequate flows from rainfall occur (Reynolds and others 1993).

Fry (1961) reported run-size estimates for the fall run of <500 to 5,000 fish for the period 1953–1959. Historically, the run size has averaged about 1,000 fish, but more recent runs, when there was water in the streambed, numbered no more than 100 individuals (Reynolds and others 1993). In many years there has been insufficient streamflow to maintain connection with the San Joaquin River. No salmon have been observed in the Cosumnes River since 1988 (DFG unpublished data).

American River (Sacramento, Placer counties). Spring, fall and possibly late-fall runs of salmon, as well as steelhead, ascended the American River and its branches and were impeded to varying degrees by a number of natural obstacles, at least one which no longer exists. According to a Native American (Nisenan) informant, salmon and steelhead were said to have formerly entered all the small, lower-elevation streams around Auburn (at the juncture of the North and Middle forks) and Colfax (about 16 mi farther up the North Fork) (Wilson 1972). In the North Fork American River, steelhead were observed during DFG surveys in the 1930s at Humbug Bar, above where the North Fork of the North Fork enters (DFG unpublished data); because there are no substantial falls below that point, spring-run salmon no doubt also easily ascended that far. Mumford Bar, about seven miles above Humbug Bar, was one of several salmon fishing spots for the native Nisenan people, at which “salmon [were] taken with bare hands during heavy runs” (Beals 1933, p 347). For the present,

given the lack of more definite information, we take Mumford Bar as the minimal upstream point reached by salmon. However, if the salmon, like steelhead, were able to surmount the waterfall at Mumford Bar, they would have had clear passage about four miles farther upstream to a 10-foot waterfall at Tadpole Creek (2,800 ft elev.), which is too steep for kayakers to boat over (Stanley and Holbek 1984). And if salmon were able to jump that waterfall, their upper limit would have been another seven miles upstream at the 60-foot falls at Royal Gorge (4,000 ft elev.), which likely was the uppermost barrier to steelhead (DFG unpublished data). That uppermost limit would accord with Beals' (1933) general statement that salmon reportedly ranged above the elevational limit of permanent habitation (3,000 to 4,000 ft) of the Nisenan people of the area.

On the Middle Fork American River, falls that had existed before the gold mining era at Murderer's Bar, about three miles above the confluence with the North Fork, obstructed the salmon at least to some degree. The pioneer Myron Angel wrote:

Before the falls at Murderer's Bar was cut down, during spawning time, the salmon would accumulate so thickly in a large pool just below, that they were taken in great numbers by merely attaching large iron hooks to a pole, running it down in the water, and suddenly jerking it up through the mass. And that place was not an exceptional one; it was so at all places where there was any obstruction to free running. During these times, the Indians supplied themselves with fish, which they dried in the sun. (Angel 1882, p 402)

It is likely that the dense aggregations of salmon harvested by the native people below the natural obstacles were more often fall-run fish, impeded by the low fall-season streamflows. The earlier-migrating spring run, ascending mainly during the spring flood flows, would have been able to transcend some of those same obstacles (CFC 1900a, p 25, 1900b, p 13). Spring-run salmon probably were able to ascend the Middle Fork a fair distance due to the absence of natural barriers above Murderer's Bar. In 1938, the spawning area for salmon was reported to extend up the Middle Fork to below the mouth of Volcano Creek (1,300 ft elev.) (Sumner and Smith 1940); salmon likely reached the confluence with the Rubicon River (1,640 ft elev.), which we view as the historical upstream limit. Steelhead were observed in the Rubicon River during the early DFG surveys, but a 15-foot waterfall about four to five miles upstream from the mouth was a likely barrier to them and to any salmon that ascended that far.

In the South Fork American River, a major part of the salmon runs went at least as far as Salmon Falls, and "large quantities" were harvested there in 1850 and 1851 by gold miners and Native Americans (CFC 1875, p 14). As recounted by Special Indian Agent E.A. Stevenson: "...saw them at Salmon

Falls on the American river in the year 1851, and also the Indians taking barrels of these beautiful fish and drying them for winter" (31 December 1853 letter to Superintendent of Indian Affairs T. J. Henley, as cited in Heizer 1993, p 16). The forty-niner Daniel Woods also noted in his journal entry for 4 July 1849, at Salmon Falls: "They [the "Indians"] have brought us in some salmon, one of which weighs twenty-nine pounds. These they spear with great dexterity, and exchange for provisions, or clothing, and ornaments of bright colors" (Woods 1851, p 49). The site of Salmon Falls is now covered by Folsom Reservoir, and there has been disagreement on whether the 20-foot falls originally were a complete barrier to migrating salmon. It seems likely that it was the fall run—egg-laden and migrating during low streamflows—that would have been largely blocked, especially before the major fall rains had swelled the streams (CFC 1900a, p 25). But even the fall run may not have been completely barred by the falls—their dense concentration there and at other places perhaps being bottlenecks where some fraction of the run rested or was stalled until streamflows increased before ascending further. Salmon Falls was blasted sometime near the turn of the century, by one account to create passage for log drives down the river (DFG unpublished notes) and by another to allow the salmon to go farther upstream, but the latter attempt was said to have ended in failure (Cassidy and others 1981). The California Fish Commission reported "the removal of obstructions at Salmon Falls, in the American River" sometime during 1888–1890, for which the State Legislature appropriated \$500 (CFC 1890, p 4). The falls were also later blasted in 1935 by the California Division of Fish and Game "to make them more passable for steelhead trout and salmon" (DFG unpublished notes). However, there is evidence that salmon did in fact ascend the South Fork past Salmon Falls in earlier times, before the attempts to modify the falls. Henry W. Bigler, one of the Mormon workmen at Sutter's Sawmill at Coloma during the fateful winter of 1847–1848, wrote in his diary, "Our grub was mainly unbolted flour, pork, mutton, salmon, peas, tea, coffee and sugar" (Gudde 1962, p 84). Based on a review of that and other documents, Gay (1967, p 138) added: "Beef and beans also formed part of the diet...the pork, mutton and beef was freshly killed on the spot; while the river rewarded anyone who had piscatorial inclinations with a nice catch of salmon." A gold miner's account (Steele 1901, p 275) stated: "In the latter part of August [1852] a band of forty or fifty Indians camped on the opposite bank of the river, spending about two weeks mining and fishing....Here, with long spears, they caught many fine salmon"; the location was "Texas Bar on the south fork of the American River," one-half mile upstream of Chili Bar and "about two miles from Placerville." Also, Voegelin (1942, p 174) reported the following ethnographic information given in 1936 by a 65-year-old Nisenan informant who had lived all her life in the vicinity of Camino (about five miles east of Placerville and due south of present Slab Creek Reservoir on the South Fork): "Salmon obtainable within area, in American River. No salmon caught until certain time in summer; first fish cooked, divided and eaten by all members of community, for 'good luck'." The impli-

cation of the last statement is that those were spring-run salmon which became obtainable as streamflows dropped during the summer; also, there was an annual first salmon ceremony of sorts, indicating that a regular run of salmon in the South Fork American River. Beals (1933, p 347), based upon his ethnographic survey of elder Nisenan informants in 1929, reported that salmon “Ascended S. fork American r. to Strawberry near summit.” However, we view Beals’ statement broadly – that is, that salmon went up to the general area approaching the present town of Strawberry – because it is less specific than other ethnographic references to salmon that we have included. There is a 30-foot waterfall with an incline of 45° (E.R. Gerstung, personal observation) at Eagle Rock, about eight miles downstream of Strawberry, which kayakers portage around (Stanley and Holbek 1984). There are also several steep stretches above Eagle Rock up to Strawberry, and very little suitable habitat (pools and gravel beds), so salmon probably did not ascend past Eagle Rock in significant numbers, if at all. We take the vicinity of Eagle Rock (4,300 ft elev.), therefore, as the most likely upper limit for salmon in the South Fork.

Hydraulic mining during the 1850–1885 period caused the deposition of large quantities of sediments into the American River, as was true for many other Sierra streams. By one estimate, about 257 million cubic yards of gravel, silt, and debris from mining operations were washed into the American River (Gilbert 1917). Again quoting Indian Agent Stevenson (31 December 1853 letter, in Heizer 1993, p 16):

The rivers or tributaries of the Sacramento formerly were clear as crystal and abounded with the finest salmon and other fish.... But the miners have turned the streams from their beds and conveyed the water to the dry diggings and after being used until it is so thick with mud that it will scarcely run it returns to its natural channel and with it the soil from a thousand hills, which has driven almost every kind of fish to seek new places of resort where they can enjoy a purer and more natural element.

According to one gold miner’s account, in the summer of 1851, “Salmon were then caught in the river” at Horseshoe Bar on the North Fork American River about seven miles above the confluence with the South Fork, “and fried salmon was no uncommon dish” (Morgan 1970, p 165). By 1860 a sand bar had formed across the mouth of the American River on the Sacramento River (Reynolds and others 1993). The silting over of the spawning beds in the mainstem and forks due to mining activities nearly exterminated the salmon runs in the American River (Gerstung 1989). Stone (1874, p 176) wrote, “The American Fork was formerly a prolific salmon river, but the mining operations on its banks have rendered it so muddy that the salmon have abandoned it altogether, and none ascend it now.” Similarly, the California Fish Commission reported: “The American is a shallow, muddy stream.... But few fish are found in the lower part of the stream.... This river, prior to placer mining, was

one of the best salmon streams in the State. Of late years no salmon have ascended it" (CFC 1886, p 20).

Somewhat later, the construction of dams that lacked adequate fish passage facilities caused the further diminishment of the runs (Gerstung 1989). The 68-foot high Old Folsom Dam (completed in 1895), 27 mi upstream from the mouth, initially was an impassable barrier to salmon and blocked them from reaching the forks of the American River for about 36 years (Sumner and Smith 1940). A fish ladder was built for Old Folsom Dam in 1919, but Clark (1929) stated that salmon were never known to have passed above it, although steelhead probably did; an effective fish ladder for salmon was later constructed in 1931 (Sumner and Smith 1940). Another potential barrier to salmon was a 16-foot high dam built in 1899 by the North Fork Ditch Company on the North Fork American River near Auburn, a few miles downstream of the confluence with the Middle Fork; a rock chute fishway was provided in 1912, but it allowed difficult passage and few salmon used it (Sumner and Smith 1940). The 140-foot high North Fork Debris Dam (completed in 1939), two miles above the confluence with the Middle Fork, posed yet another impassable barrier and assured the extirpation of the salmon run in the North Fork (Sumner and Smith 1940).

Clark (1929, p 36) stated that the salmon run in the American River had "always been a late-fall migration," although he provided no further details, and also that this river "[had] known great runs." An early gold miner noted salmon migrating up the American River about seven miles east of Sutter's Fort on 1 December 1848, of which "thirty-five splendid salmon" were procured by "well-directed rifle-ball" (Buffum 1959, p 41). Early December coincides with the upriver migration periods of both fall and late-fall runs; however, it is appreciably later than the peak migration presently observed for the Sacramento Valley fall run (September through October) but within the peak migration period for the late-fall run (December) (Fisher 1994). The implication seems to be that a late-fall run occurred in the American River, possibly in substantial numbers. However, it is more likely that the run was a fall run that had a relatively late or extended migration season, combined perhaps with some unknown numbers of true late-fall-run fish. The spring run is known to have entered the American River as early as February, as occurred in 1946 (Gerstung 1971 unpublished report).

Clark (1929) described the 1927-1928 salmon run as "very good" and noted that residents on the river had seen no noticeable decrease in the run size over the previous 20 years, although the run reportedly had been devastated by early mining operations. Spawning occurred from the river mouth to Old Folsom Dam about one mile above the town of Folsom, "a distance of 30 mi of good gravel river." In the 1940s, both the spring and fall runs began to re-establish themselves in the American River above Old Folsom Dam. Counts at

the fishway at Old Folsom Dam showed that the spring run reached a maximum of 1,138 fish in 1944 and the fall run reached 2,246 fish in 1945 (Gerstung 1971 unpublished report). The spring-run count dropped to 42 fish in 1945, 16 in 1946, and three fish in 1947; both the spring and fall runs reportedly were decimated after the fish ladder on Old Folsom Dam was destroyed by flood waters in 1950 (Gerstung 1971 unpublished report). The spring run was finally extirpated during the period of construction of present-day Folsom Dam and Nimbus Dam (the latter completed in 1955) (Gerstung 1971 unpublished report).

Fry (1961, p 64) noted the presence of "a small spring run," at least through 1951, which became mixed with the "much larger fall run" during spawning. Combined run sizes were 6,000 to 39,000 spawners annually during the period 1944–1959, with estimates exceeding 30,000 fish during 1944–1946; these fish comprised mainly the fall run but included "a small but unknown proportion of spring run fish" in the first three years of the period (Fry 1961). During 1944–1955, an estimated average of 26,500 salmon (range 12,000 to 38,652) spawned annually in the mainstem American River below the town of Folsom; about 73% of the spawners used the five-mile stretch between Old Folsom Dam and the present site of Nimbus Dam, and the remainder spawned farther downstream (Gerstung 1971 unpublished report). In recent decades, spawning escapements of the fall run have ranged from about 10,000 to 95,000 fish annually (Gerstung 1989, DFG unpublished data). Spawning escapements were about 10,200 to 75,000 fish (average: 41,000) during 1990–1997, with Nimbus Hatchery accounting for an estimated 9% to 59% of the spawning runs during this period (DFG unpublished data). The fall run formerly spawned not only above the site of Nimbus Dam but above Folsom Dam as well (J. Nelson, personal communication, see "Notes"). Completion of Nimbus Dam is said to have inundated half of the then-existent spawning gravels in the American River (Holmberg 1972). Fall-run salmon presently are limited in their upstream migration by Nimbus Dam and spawn mainly downstream from the dam to just above the Watt Avenue crossing (J. Nelson, personal communication, see "Notes"); the habitat downstream of Watt Avenue presently consists mainly of pools unsuitable for spawning (E.R. Gerstung, personal observation).

Bear River (Placer County). The Bear River, the second largest tributary to the Feather River, historically contained salmon, but evidently only a fall run. The run reportedly was "substantial" (Reynolds and others 1993) but has not occurred in its former numbers for decades (J. Nelson, personal communication, see "Notes"). Adult salmon ascended as far as present day Camp Far West Reservoir, where a waterfall in that vicinity probably barred their further passage. No waterfall exists there now, so it evidently was submerged or built upon during the construction of Camp Far West Reservoir and Dam (J. Hiskox, personal communication, see "Notes"). There are no natural barriers above Camp

Far West Reservoir at least to Rollins Reservoir 24 mi upstream, next to present-day Chicago Park (J. Hiskox, personal communication, see "Notes"). According to one native Nisenan informant who had resided most of her life around Chicago Park, there were no salmon in that area (Voegelin 1942), so the salmon evidently were completely blocked by the waterfall near Camp Far West.

Clark (1929, p 36) stated, erroneously, that the Bear River "has never been known to be a salmon stream," with only an occasional salmon observed there. Clark reported the presence of an impassable dam near the town of Lincoln (which is not on the river but lies about nine miles south of Camp Far West Reservoir). As with other Sierra streams, hydraulic mining activities caused substantial sedimentation problems in the Bear River such that by 1876 its channel had become completely filled (Reynolds and others 1993). According to early historians,

Near Wheatland the river has altered its course for several miles, making a new channel half a mile south of the old bed. The banks of this stream were once twenty-five to thirty feet high. Its channel has been filled up, and the water is so thick and heavy with sediment that in summer there is scarcely any stream at all. From 1866 to 1869, the stream almost ceased to run except on Sundays, the water on other days being used by the miners (Chamberlain and Wells 1879, p 86).

The effect on the salmon runs at that time would have been catastrophic and undoubtedly accounts for the apparent historical scarcity of salmon immediately before Clark's (1929) assessment. Indeed, it was written by early historians:

Bear, Yuba and Feather rivers were full of salmon, and the Indians speared them by the hundred in the clear water. When the river began to be muddy, the fish became scarce. The Indians even then speared them, and although unable to see the fish, they could tell their position with unerring precision by the ripples made in their passage through the water (Chamberlain and Wells 1879, p 15).

The abundance of salmon in the Bear River long ago was also attested in an old newspaper account (Marysville Daily Appeal, 24 July 1889):

J. M. C. Jasper, of Wheatland, says that the generation now growing up in that vicinity are altogether too incredulous, because they wont [sic] believe that thirty years ago he used to stand on the banks of Bear river and with a pitchfork catch salmon weighing thirty pounds and over, to feed to the hogs. Many other old-timers tell the same thing.

And, according to the California Fish Commission, "It is the testimony of all the pioneer miners that every tributary of the Sacramento, at the commencement of mining, was, in the season, filled with this fish, ...A few salmon continued to enter the Feather, Yuba, Bear, and American Rivers until the floods of the Winter of 1860-1, which covered the gravel bottoms of all those streams with mining sediment..." (CFC 1880, p 3). The change in the Bear River was so profound that the Commission would later write, "Bear has lost all claim to the name of river... It never was noted as a fish stream, although a few salmon and perch were taken from its waters in early days" (CFC 1886, p 20).

Within the present decade or so, the fall run has occurred only occasionally, when heavy rains and dam spillage provide adequate flows (Reynolds and others 1993). At those times, the run may number in the "hundreds" (Reynolds and others 1993). The spawning distribution has its upper limit at the South Sutter Irrigation District (SSID) diversion dam, 15 mi above the confluence with the Feather River and 0.5 mi below Camp Far West Reservoir. The spawning areas extend from the SSID dam downstream about six miles to a point near Highway 65, although there are additional spawning gravels extending four to five miles farther downstream to Pleasant Grove Road (J. Nelson, personal communication, see "Notes"). There is no suitable upstream holding habitat for spring-run salmon in the Bear River (J. Nelson, personal communication, see "Notes").

Yuba River (Yuba County). Both spring and fall runs originally occurred in the Yuba River. A pioneer missionary's wife, writing of the Marysville area in 1851, noted:

The rivers abound in excellent salmon, which the Indians spear in great numbers, and dispose of in the towns. They are the finest I ever tasted. Some of them are three and four feet long, and weigh fifty pounds or more. It is amusing to see the Indians spearing them.... Their aim is unerring (Bates 1857, p 156).

In the North Fork Yuba River, salmon were caught by PG&E workers in the Bullards Bar area during the 1898-1911 period of operation of the Yuba Powerhouse Project; the ditch tenders at the diversion dam "would nail two or three salmon on boards, place them body down in the ice-cold ditch stream, and ten hours later the night's dinner would come floating down" to the powerhouse on the valley floor (Coleman 1952, p 139). In later years, the salmon ascended in "considerable numbers" up to Bullards Bar Dam during its period of construction (1921-1924) - "so many salmon congregated and died below it that they had to be burned" (Sumner and Smith 1940, p 8). There are no natural barriers above the Bullards Bar Dam site, so salmon presumably had been able to ascend a considerable distance up the North Fork. There is photographic evidence of steelhead (called "salmon-trout" in early writings)

occurring farther upstream at Downieville at the mouth of the Downie River (DFG file records). In their historical account of Sierra County, Fariss and Smith (1882, p 422) related the following episode from 1849: "While encamped on Jersey flat Jim Crow one day killed with a small crow bar a salmon-trout which weighed fourteen pounds. It was boiled in the camp kettle ... afterwards gold was found in the bottom of the kettle." Jersey Flat (formerly Mur-raysville) was located across the river from Downieville (Fariss and Smith 1882). That incident may have been a reference to salmon because the latest spring-run spawners possibly were present at that date (shortly after October 5). Also, native Central Valley steelhead typically weighed three to eight pounds and rarely exceeded 13 lbs (Eigenmann 1890; Hallock and others 1957, 1961), at least in the present century, although steelhead in coastal streams may reach about 20 lbs (Hubbs 1946; Barnhart 1986). On the other hand, the term "salmon-trout" suggests the fish was distinguished from salmon so it could have been an uncommonly large steelhead, possibly of a now extinct summer run. In fact, there is evidence that "summer" steelhead formerly occurred in parts of the Sacramento River system as late as the 1930s and 1940s (Needham and others 1941; McEwan and Jackson 1996), and a few large steelhead (for example, up to 15.5 lbs) were observed in a DFG study of Sacramento River steelhead during the 1950s (Hallock and others 1961). Referring to the salmon runs in 1850 and 1851, the California Fish Commission (CFC 1875, p 14) stated that "large quantities were taken by the miners and by Indians ... as far up as Downieville on the Yuba," and at other points on the American and Feather rivers. There are no natural obstructions from Downieville upstream to Sierra City, where Salmon Creek enters, so spring-run salmon and steelhead most likely were able to traverse that distance. Deep pools are present throughout the North Fork Yuba River from its mouth up to Sierra City (E.R. Gerstung, personal observation) and would have provided prime holding habitat for spring-run salmon. Spring-run salmon and steelhead probably ascended the higher-gradient reaches up to about two miles above the juncture of Salmon Creek and their absolute upstream limit on the North Fork would have been Loves Falls.

In the Middle Fork Yuba River, there are no significant natural obstructions except for a 10-foot falls in the lower reach, and salmon possibly had access to a considerable portion of the Middle Fork. Both salmon and steelhead were observed in the lower part of the Middle Fork, near where the North Fork joins, during a DFG survey in 1938 (DFG unpublished data). Steelhead were found as far upstream as the mouth of Bloody Run Creek (DFG unpublished data). Whether salmon also reached that far remains conjectural, although it is likely that salmon ascended some unknown distance up the Middle Fork because other native fishes such as pikeminnow have been observed as far upstream as Box Canyon, several miles below Milton Reservoir (R. Cutter, personal communication to E.R. Gerstung, see "Notes"). However, direct information is lacking and it is uncertain if many salmon were able to sur-

mount the 10-foot falls on the lower river; therefore, we conservatively consider the falls 1.5 mi above the mouth as the effective upstream limit of salmon in the Middle Fork. Similarly, little is known of the original distribution of salmon in the South Fork Yuba River—the salmon population was severely depressed and access up the stream long since obstructed by dams by the time the DFG surveys were conducted in the 1930s. There are records of salmon occurring within one to two miles upstream of the mouth of the South Fork Yuba River (DFG unpublished data). A substantial cascade with at least a 12-foot drop, located one-half mile below the juncture of Humbug Creek (CRA 1972; Stanley and Holbek 1984), may have posed a significant obstruction to salmon migration, but it was not necessarily a complete barrier. This cascade, or “step-falls,” is similar in dimensions and conformation to cascades on other streams, which salmon are known to have surmounted (P. Lickwar, personal communication, see “Notes”). However, we presently take that cascade below Humbug Creek as essentially the historical upstream limit of salmon during most years of natural streamflows. Steelhead are known to have ascended the South Fork as far as the juncture of Poorman Creek near the present town of Washington (DFG unpublished data), and perhaps some spring-run salmon historically also reached that point. Among the tributary streams of the lower Yuba River, salmon and steelhead were observed to ascend Dry Creek at least five to six miles in past decades (for example, in the 1960s; E.R. Gerstung, personal observation), and they occasionally still do when streamflows are high. Steelhead also went up Deer Creek a quarter of a mile where they were stopped by impassable falls (E.R. Gerstung, personal observation), but we have no records of salmon in that stream.

The Yuba River, along with the Feather and Bear rivers, sustained some of the most intensive hydraulic mining carried out during the gold mining years (1853–1885) (Kelley 1989; Reynolds and others 1993), and the effects on the salmon runs were undoubtedly severe. The Yuba in its pristine state, in 1849, was described by a forty-niner thusly:

Juba River is a fine stream, deep enough for navigable purposes for a considerable distance up its course to where it widens out at the ford, passing over a broad, level, gravell bed. Its waters in the stream appear of a greenish hue, but when taken into a glass are perfectly colourless, clear, and well-tasted (Kelly 1950, p 50).

With banks rising about fifteen to twenty feet above the original channel at low water, the Yuba River was rapidly degraded by the immense influx of hydraulic mining debris. In March 1860, the Marysville Appeal remarked that the “yellow Yuba...that turgid vehicle of sediment takes a vulgar pride in spreading out its dirty face” (Kelley 1989, p 69). The great flood of 1861–1862 buried much of the “lower” bottomlands along the Yuba under sand deposits averaging two to seven feet deep (Kelley 1989). By 1876 the channel of the

Yuba River reportedly had become completely filled, and what remained of the adjoining agricultural lands was covered with sand and gravel (Kelley 1989; Reynolds and others 1993)—a marked deterioration of the river as salmon habitat. Chamberlain and Wells (1879, p 86) wrote:

At Timbuctoo ravine it is claimed that the Yuba river has been filled with a deposit, eighty feet in depth.... At Marysville, the depth of the deposit is about twenty-two feet. At a point, in front of the city, the river was considerably deeper than at any point above or below; this has been filled up to the regular line of the bottom, the deposit being over thirty feet in thickness. The bottomlands along the Yuba and Bear rivers have been covered to a depth of five to ten feet, extending, in some places, one and one-half miles back from the streams.

It was estimated that during the period 1849–1909, 684 million cubic yards of gravel and debris due to hydraulic mining were washed into the Yuba River system (Gilbert 1917)—more than triple the volume of earth excavated during construction of the Panama Canal. The California Fish Commission described the Yuba River as “a shallow stream, except during the rainy season ... and its water is muddy” due to the mining that was still being carried on along the river (CFC 1886, p 20).

Clark (1929) reported that the salmon spawning grounds extended from the river mouth up to the town of Smartsville, but that very few salmon (evidently spring run) went past that point farther upstream. As of 1928, there was the “Government barrier” dam (Daguerre Point Dam) near the town of Hammond below Smartsville which served to catch sediments washed down the river from mining and dredging operations farther upriver. Although fishways had been provided at this dam, they were destroyed by floods in winter 1927–1928, but in any event few salmon reportedly went farther upriver to spawn (Clark 1929). Daguerre Point Dam (15 ft high), located about 11 mi east of Marysville on the valley floor (at 120 ft elev.), was said to have “almost completely blocked king salmon runs since its construction in 1910” (Sumner and Smith 1940, p 7); but salmon did surmount that dam in occasional years because they were observed in large numbers in the North Fork Yuba River during the early 1920s at Bullards Bar. Before the construction of Daguerre Point Dam, “heavy runs of salmon” reportedly occurred in Dry Creek and Deer Creek upstream of the dam site, but “few, if any,” were present in 1938 (Sumner and Smith 1940, p 8). An even earlier structure, Barrier No. 1 (built in 1904–1905), was 4.5 mi above the later site of Daguerre Point Dam and probably hindered salmon until floods destroyed it in 1907 (Sumner and Smith 1940). Clark (1929) also reported that located on the South Fork Yuba north of Nevada City was Edison Dam, a power project dam that had a “good fish ladder and screens.” There evidently were other dams on the Yuba River which were washed out or damaged during the winter of 1927–1928. Fry (1961, p 63)

later stated that the Yuba River “was seriously handicapped” for many years by a diversion dam (evidently Daguerre Point Dam) which lacked a functional fish ladder and below which there “was often very little water.” Although adequate fish ladders were later provided about 1950–1952 (DFG 1953), the low-water conditions remained as of 1959 (Fry 1961). Construction of Englebright Dam 12.5 mi farther upstream (282 ft elev.) in the late 1930s eliminated much spring-run salmon habitat and “severely reduced the spring run” (DFG 1990). Englebright Dam presently is the upstream limit of salmon distribution. Although most of the salmon spawning habitat occurs in the 7.8 miles of river on the open valley floodplain downstream of Daguerre Point Dam (Reynolds and others 1993), the greater part of the run now generally spawns above Daguerre Point (J. Nelson, personal communication, see “Notes”). The fall run previously spawned in the entire stretch from Englebright Dam downstream to Simpson Lane (Marysville), below which the substrate is too sandy (J. Nelson, personal communication, see “Notes”). The spring run, when the fish were common in the recent past, spawned in the area between Englebright Dam and Highway 20 (J. Nelson, personal communication, see “Notes”).

Salmon originally migrated into the Yuba River in large numbers to spawn. The California Fish Commission reported that in 1850 “the salmon resorted in vast numbers to the Feather, Yuba, American, Mokolumne [sic], and Tuolumne Rivers,” and on the Yuba River as late as 1853 “the miners obtained a large supply of food from this source”; however, by 1876 the salmon no longer entered those streams (CFC 1877, p 5). At the time of Clark’s survey in 1927–1928, a fall run occurred in late fall and there was an occasional, “slight” spring run. Clark (1929, p 37) stated that “very little could be learned” about past salmon abundances in this river, but at that time (1928) the salmon (essentially the fall run) were “holding their own and not decreasing.” By the late 1950s, Fry (1961, p 63) noted that the spring salmon run had “virtually disappeared.” A remnant spring run managed to persist at least up to 1995 in “minimal numbers” (J. Nelson, personal communication, see “Notes”), but the run has been genetically mixed with the fall run due to spatial overlap of their spawning areas, as is the case also in the Feather and American rivers (J. Nelson, personal communication, see “Notes”). Fry (1961) reported fall-run spawning escapements of 1,000 to 10,000 fish during 1953–1959. The assessment by the California Department of Fish and Game (Reynolds and others 1993) was that the Yuba River “historically supported up to 15% of the annual run of fall-run chinook salmon in the Sacramento River system.” Fall-run escapements during the period 1953–1989 ranged within 1,000 to 39,000 fish and averaged 13,050 annually (Reynolds and others 1993). More recently (1990–1997), fall-run estimates have varied from 5,900 to 25,800 spawners annually (DFG unpublished data).

Feather River (Yuba, Butte, Plumas counties). The Feather River, noted by one early traveler in 1843 as "tributary to the Sacramento and still richer in salmon" (Van Sicklen 1945), was renowned as one of the major salmon-producing streams of the Sacramento Valley. California Fish Commissioner R.H. Buckingham wrote in the *Sacramento Bee* (31 December 1885), "In years gone by, some of the fishermen of Sacramento would ascend the Feather river as far as Yuba City, to fish for salmon, which were very plentiful at times, Indians catching as many as two hundred in a single night with spears." Regarding the native fishing for salmon, an early historical account stated,

The Feather River was partially closed by piles extending nearly to the middle of the stream. These piles were interwoven with brush so as to prevent the passage of the fish. They were thus compelled to pass through the opening, where the Indians on platforms, captured them with their spears in their ascent of the stream (Chamberlain and Wells 1879, p 15).

Salmon originally ascended a considerable distance into the Feather River system, particularly the spring run which spawned in the higher streams and headwaters. They went up the West Branch at least to the site of Stirling City (F. Meyer, personal communication, see "Notes"), and also up along the entire length of the North Fork Feather River through the area now covered by Lake Almanor and into the surrounding tributary streams (>4,200 ft elev.). Early correspondence sent to the DFG state that large numbers of spring-run fish ("in the thousands") entered the North Fork, most of which were stopped by Salmon Falls (about ten feet high) approximately 2 to 2.5 miles above the town of Seneca (DFG letters no. 1, no. 2). One writer stated, "There was an old indian couple known as Caribou Bill and his wife who used to net them at the Falls, smoking and drying them for use during the winter.... The spring run usually reached the Falls about the first of July" (DFG letter no. 1). A few fish were able to surmount the falls and proceed farther upstream to the area of present Lake Almanor (DFG letter no. 1). Flows from the many springs that fed the Lake Almanor area (formerly "Big Meadows"), together with streamflows from farther up the North Fork, undoubtedly were sufficient for salmon to have ascended through the lakebed area and up the North Fork another six miles or more (J. Nelson, personal communication, see "Notes"). In a newspaper article more than a century ago, a Dr. J.H.C. Bonte wrote of salmon angling: "They are caught with hook and bait now along the Sacramento river above Knight's Landing, and in the Feather river not far below Lassen's peak.... Young salmon are frequently caught in Big Meadows, Plumas county, and older ones weighing eight and ten pounds, are also taken though not very often" (*Sacramento Union*, 24 December 1881).

Judging from streamflows that occur in the Hamilton Branch of the North Fork above Lake Almanor, salmon most likely ascended that branch for several miles, possibly to within a very short distance of present-day Mountain

Meadows Reservoir (J. Nelson, personal communication, see "Notes"). Spring-run salmon are also said to have ascended Indian Creek, a tributary of the East Branch of the North Fork (DFG letter no. 2), at least as far as Indian Falls (near the junction of Highways 89 and 70). They concentrated and were harvested there by Native Americans, although the falls were not necessarily their upper limit in that stream (J. Nelson, personal communication, see "Notes"). In reference to two North Fork tributaries, Hanson and others (1940) stated that the quality of spawning habitat was good in Yellow Creek and excellent in Spanish Creek (a tributary of the East Branch of the North Fork), although by that time salmon reportedly were blocked farther downstream by a diversion dam. The previous distribution of salmon in those two streams is unknown, but Yellow Creek probably was used at least to some extent. A substantial waterfall occurs above the mouth of Spanish Creek (R. Flint, personal communication, see "Notes") and possibly barred salmon from ascending any appreciable distance, although DFG correspondence indicates salmon may have entered "Clear Creek" (a tributary of Spanish Creek) for spawning (DFG letter no. 2).

In the Middle Fork Feather River, the salmon were stopped near Bald Rock Dome shortly above Lake Oroville by Bald Rock Falls (18 ft high) and Curtain Falls (30 ft) immediately upstream. Spring-run salmon were observed spawning below Bald Rock Falls in the 1960s before Oroville Dam was built, and sport fishermen often caught large numbers of salmon from the pool below the falls (E.R. Gerstung, personal observation). Testimonies of Native American (Concow Maidu) residents also identify the waterfall below Bald Rock Dome as having "marked the upper limits of salmon migration" which "made it a desirable fishing spot for the Indians" during earlier times (Jewell 1987, p 19). In Fall River, a tributary of the Middle Fork, the 640-foot Feather Falls about one mile above the mouth certainly was a barrier.

The South Fork Feather River, according to Hanson and others (1940), had "much more spawning gravel per mile of stream than either the Middle or North Fork," but at that time nearly all of the streamflow was diverted for irrigation into the Forbestown and Palermo canals. Before the diversion of the stream, spring-run salmon may have ascended to the vicinity of Forbestown, near the present upper limit of the South Fork arm of Lake Oroville.

Clark (1929) reported both spring and fall runs present in the Feather River. The main spawning beds extended for 30 mi from the river mouth up to Oroville. At that time (1928), the spring-run fish evidently still went up all four branches above Oroville, which were all suitable as spawning habitat, up to points where they were blocked by dams. Several dams in the Feather River drainage presented obstacles to salmon in 1928. The Sutter-Butte Dam six miles below Oroville was a five-foot high irrigation diversion dam with a reportedly ineffective fishway and lacking fish screens on the intake ditches,

although the salmon nonetheless surmounted it (Clark 1929). Miocene Dam near the town of Magalia on the West Fork was 12.5 ft high power project with no fishway or fish screens. Stirling City Dam, also on the West Fork, was eight feet high and supplied a powerhouse; it had a fish ladder but Clark stated that salmon never reached this far upriver. On the North Fork was the Great Western Power Company dam equipped with a fish ladder, although water diversions to the powerhouse dried up the river for "a number of miles" when streamflow was low (Clark 1929). Clark was not aware of any barriers to salmon on the Middle Fork Feather River, but he noted that the South Fork had two irrigation diversion dams: Dam No. 1 on Lost Creek, which took "nearly all the water from the South Fork during the summer months," and Dam No. 2 located on the main fork and lacking a fishway.

Clark (1929, p 38) stated: "The runs of salmon, both spring and fall, used to be very heavy in the Feather River previous to the building of obstructions. It is true that the mining operations in the early years may have reduced the amount of fish somewhat, but the building of dams has almost destroyed the spring run." However, the effect of early mining operations on salmon habitat, while not quantifiable, nonetheless was undeniably substantial during their heyday. The California Fish Commission noted that mining sediments which washed into the Feather, Yuba and American rivers during the winter floods of 1860-1861 smothered the spawning grounds of the few salmon returning to those streams up to that time (CFC 1880). John Muir (1938, p 244), referring to the turbidity of the Sacramento River in October 1877, stated, "...the Sacramento is clear above the confluence of the Feather." Somewhat earlier, Stone (1874) noted that poor water quality resulting from intense mining activity was the reason for the absence of salmon from the Feather, Yuba, and American rivers. A decade later, Stone (1883a, p 221) again observed:

...the Feather River, the Yuba, the American Fork, have long ago been completely ruined as spawning grounds, in consequence of the immense deposit of mud in them, caused by the hydraulic mining operations on these rivers. Not a salmon ever enters these streams now. Except possibly at a time of very high water, these streams are so thick with mud that it would kill any fish attempting to ascend them.

A graphic account was given by Chamberlain and Wells (1879, p 85):

A detailed statement of the loss by mining debris it is impossible to make, but its ravages can be seen on every hand. The surface of the country has undergone a change; the streams diverted from their obstructed channels, have been compelled to seek new courses and outlets for their mud-burdened waters. The banks of Feather, Yuba, and Bear rivers, were, formerly, several feet above the ordinary level of the water, and the steamers and sailing vessels were enabled to make easy and convenient landings. The streams were as clear as crystal, at

all seasons of the year, and thousands of salmon and other fishes sported in the rippling waters, their capture being a favorite amusement of both the white man and the native. But now the channels have become choked with sediment, the waters heavy and black with its burden of mud, and the fish been compelled to seek other localities... The bed of the Feather river, from Oroville to the mouth of Yuba river has been raised six or eight feet.

Even two decades later Rutter (1904, p 71) would write: "The water of the upper part of the Sacramento River and the upper tributaries is quite clear, and continues so until the mouth of the Feather River is reached, from which point to the mouth it is very muddy. It is in the muddy water between the mouth of Feather River and Vallejo that the salmon for the markets are taken." An estimated minimum of 40 million cubic yards of mining debris from the lower river and up to 186 million cubic yards from the entire watershed were produced in the Feather River basin during the period of hydraulic mining before 1909 (Gilbert 1917).

Clark (1929, p 38) described the fall salmon run as "large, although not extremely abundant" and having "fallen off in the last few years" and suggested that the populations showed a three- or four-year cycle, based on statements by river residents. Fry (1961) reported run-size estimates for the fall run of 10,000 to 86,000 fish during the period 1940–1959, and about 1,000 to 4,000 fish for the spring run. The fall run spawned mainly in the mainstem, while most of the spring run spawned in the Middle Fork, with a few spring run entering the North Fork, South Fork and West Branch (Fry 1961). Just before the completion of Oroville Dam (in 1967), a small naturally-spawning spring run still existed in the Feather River, but the Oroville project cut off all the original spring-run habitat (Reynolds and others 1993). Currently, the fall run has its upstream limit at Oroville Dam fish barrier, spawning from there downstream to a point about two miles above the Gridley Road crossing (J. Nelson, personal communication, see "Notes"). There is also a hatchery-sustained population of "spring-run" fish that has been genetically mixed with the fall run (Fisher 1994; DFG 1998) and which spawns in the one-half-mile stretch between the fish barrier immediately below Oroville Dam and downstream to Highway 7 (J. Nelson, personal communication, see "Notes"). The hybrid spring-run fish hold over the summer in deep pools within the so-called "low-flow" section of the river between Thermalito Diversion Dam (five miles below Oroville Dam) and the downstream Thermalito Afterbay Outlet (Reynolds and others 1993). They are spawned artificially in the Feather River Hatchery and also spawn naturally in the river during late September to late October (Reynolds and others 1993). The "spring run" thus overlaps temporally as well as spatially with the fall run—which is the cause of the hybridization between the runs. The hybrids consistently enter the hatchery as the early component of the spawning run, but infusion of fall-run genetic material into the hybrid population by artificial hatchery selection

continues to dilute the genetic integrity of the putative (hybrid) spring-run fish (F.W. Fisher unpublished data).

The Feather River Hatchery, located at the town of Oroville, was built by the California Department of Water Resources to mitigate for the loss of upstream spawning habitat of salmon and steelhead due to the building of Oroville Dam (Reynolds and others 1993). The California Department of Fish and Game began operating the hatchery in 1967 (Reynolds and others 1993). The Feather River Hatchery presently is the only source of eggs from "spring-run" chinook salmon in the Central Valley and is viewed as a key component in plans for restoration of spring-run populations (Reynolds and others 1993). Population estimates for the period 1982-1991 indicated an average of 2,800 "spring-run" fish, compared to the average of 1,700 fish before the construction of Oroville Dam (Reynolds and others 1993). The hybrid spring-run stock increased since the early 1980s and numbered >5,000 fish in 1989 (Campbell and Moyle 1991; DFG 1998). More recently (1990-1996), the spring run has ranged between 1,500 and 6,000 fish (average: 3,800; DFG 1998). The increase in numbers is attributed to the consistent supply of cold water to both the hatchery and "low-flow" section of the river (Reynolds and others 1993) but probably also reflects the extension of the seasonal period ("perhaps arbitrarily") in which spawners entering the Feather River Hatchery are defined as spring-run fish (DFG 1998, p VII-6). See Hedgcock and others (this volume) for a discussion of the genetic attributes of Feather River spring run.

Fall-run salmon also increased after completion of the Oroville Dam complex in 1968, averaging 39,100 spawners before the project and 51,400 fish afterwards (Reynolds and others 1993). In addition, anglers are estimated to have harvested 10,000 fish (spring and fall runs combined) each year in the ten-year period before 1993 (Reynolds and others 1993). Fall-run escapements more recently (1991-1997) have averaged 53,600 fish annually (range: 32,200 to 71,800), including both hatchery and natural spawners, compared to an annual average of 51,200 fish (range: 30,500 to 77,800) during the 1980s (DFG unpublished data). The hatchery component of the fall spawning escapements composed 13% to 41% of the annual runs during 1991-1997 (DFG unpublished data). The fall run may be considered to be genetically introgressed by hybridization with the spring run due to hatchery practices (DFG 1998).

The DFG attempted to introduce a late-fall run into the Feather River in the fall of 1970 by planting over one million eyed eggs from Coleman National Fish Hatchery (DFG 1974). The Feather River Hatchery received returning age-3 and age-4 adults for two generations following the plant, during 1973-1978, but this introduced run failed to persist.

Butte Creek (Butte County). Butte Creek, described by John C. Frémont (1848, p 21) as "a beautiful stream of clear water about fifty yards wide, with a bold current

running all the year," historically supported spring and fall salmon runs and evidently a late-fall run (Hallock and Van Woert 1959). The spring run probably ascended at least as far as the present vicinity of Centerville Head Dam near DeSabra, which we consider here as the upstream limit. Pacific Gas & Electric Company employees at one time had reported salmonids migrating past the site to areas upstream (J. Nelson, personal communication, see "Notes"), but it is not known how much farther upstream they went, or whether they were salmon or steelhead. A waterfall (25+ ft high) about one-half to one mile below Centerville Head Dam previously had been viewed as a barrier to salmon migration, but the presence of one salmon carcass above the waterfall during a DFG spawning survey in early 1995 (J. Nelson, personal communication, see "Notes") indicates that some portion of the spring run historically ascended above the waterfall. Steelhead are believed to have ascended as far upstream as Butte Meadows (Flint and Meyer, 1977 unpublished report), but salmon most likely did not reach that far (J. Nelson, personal communication, see "Notes").

Clark (1929, p 38) described Butte Creek as having been known as "a very fine salmon stream" and "a good spawning ground." He stated that there was only a fall run present, "as the water is very low and warm in the summer." At that time (1928) so much water was being diverted from the stream during most of the summer and fall that the fall run was stated by Clark to have been "almost destroyed." However, it appears that Clark did not fully recognize that the flow conditions he observed in the summer and fall, while detrimental to the fall run or to any salmon that might be present in the lower creek, did not preclude the existence of the spring run. Spring-run fish, migrating during the time of high flows, would have been well upstream during the summer-fall period when Clark evidently made his observations. Flint and Meyer (1977 unpublished report) stated that the spring run "historically provided a good fishery in Butte Creek"; they also mentioned the presence of a late-fall run which "migrates up Butte Creek in January and February and spawns immediately after arriving at the spawning beds."

Clark (1929) reported the presence of two duck club weirs and three irrigation dams on the creek, but all were low enough to be surmounted by salmon if there was enough water. Clark specifically mentioned a drainage canal ("833") which carried "considerable water" and in which adult salmon became stranded, to "die in the mud." There were a few spawning beds in the lower creek, but he noted that the few fish that entered the creek spawned in the upper reaches, if they were able to surmount the irrigation dams and ditches. As late as 1958-1960, adult spring-run salmon in Butte Creek were being lost to unscreened irrigation diversions (DFG 1960). In recent years there have been as many as ten diversion dams on Butte Creek above Butte Slough that divert water for various uses (for example, power generation, irrigation, domestic supply) and all impair salmon migration, in some cases by

dewatering sections of the stream (Reynolds and others 1993). However, several dams have been dismantled or are scheduled for removal from Butte Creek to aid in wildlife and fisheries restoration (Sacramento Bee, 5 November 1997). These barriers have affected the upstream migration of the different salmon runs to different degrees because of seasonal variation in streamflows; for example, fall-run fish are most affected, having to migrate when flows are inadequate to allow passage over the barriers.

Hanson and others (1940, p 78) stated that Butte Creek was "a very fine salmon stream in the past" but was no longer suitable for salmon due to extensive mining and hydroelectric development that had occurred in the watershed. Yet, Hallock and Van Woert (1959, p 260) reported the presence of "an early spring run," a fall run, and the "remnants of a late fall run" in Butte Creek during the mid-1950s. In reference to the fall run, they noted that "occasionally considerable numbers of fish" surmounted the numerous diversions on the lower creek to reach the spawning beds (Hallock and Van Woert 1959, p 260). Fry (1961) shortly thereafter noted that Butte Creek had a spring run but "almost no fall run," thus setting it apart from most small streams in the northern Sacramento Valley which had mainly, or only, a fall run. The many removable dams on the creek blocked or reduced flows late into the fall, and the fall run could not surmount them. Fry (1961) reported that the spring run ranged from <500 to 3,000 fish during 1953–1959. During the 1960s, the spring run at times numbered >4,000 fish in Butte Creek (DFG 1998), with smaller numbers of fall-run and late-fall-run fish (Reynolds and others 1993). More recently, estimated spring-run numbers were 100 to 700 fish during the 1990s and rose to 7,500 fish in 1995 and 20,000 fish in 1998 (DFG 1998 unpublished data). The source of the surprisingly numerous spring-run spawners that entered Butte Creek in 1998 is not known, but they presumably were largely due to the strong escapement in 1995. The Butte Creek fall run remains small, numbering "a few fish to as many as 1,000" (Reynolds and others 1993, p VII-42), because of the very low late-summer and fall flows (F.W. Fisher, personal observation). There are also late-fall-run salmon in Butte Creek, but their numbers are unknown (Reynolds and others 1993).

The fall-run salmon generally spawn below the Parrott-Phelan Dam (J. Nelson, personal communication, see "Notes"). The spring-run fish in Butte Creek, unlike spring runs in other streams, presently spawn in the lower part of the creek at relatively low elevation (about 1,000 ft), where they are blocked by the Centerville Head Dam. However, the water there is unusually cold, comparable in temperature to that typically found at about 2,000-foot elevation (F. W. Fisher unpublished data). Although spring-run adults in Butte Creek migrate and spawn at the same times as spring-run fish in other streams, it appears to be a somewhat different "breed" in that the fry emerge in December; some of these fry migrate out immediately while others migrate out in the spring (Reynolds and others 1993), and the remaining fraction

remains in the stream until the following fall (one year after they had been spawned) (F.W. Fisher, personal observation). This is in contrast to the pattern seen in streams where spring-run fish spawn in the colder, high-elevation reaches (Mill and Deer creeks). There the fry do not emerge from the gravel until March, and they remain in the streams over the summer to migrate out in September and October (F. W. Fisher unpublished data). Spring-run adults are present in Butte Creek in early February, March, and April, in contrast to Feather River "spring-run" fish (that is, spring-fall hybrids), which do not enter that river until May or June.

Big Chico Creek (Butte County). Big Chico Creek contains marginally suitable habitat for salmon and probably was opportunistically used in the past. Spring, fall and late-fall runs have occurred in this creek (Reynolds and others 1993). In apparent reference to the fall run, Mrs. Annie Bidwell, wife of the pioneer John Bidwell, noted: "In the fall of the year the first run (being the fish in the streams after the first rains) of salmon were considered the best, as later in the season they had more or less germs in them and were consequently not so good to eat" (Bidwell 1980, p 56).

Fry (1961) gave estimates of 50 fall-run (including late-fall-run) fish in 1957, 1,000 spring-run fish in 1958, and 200 spring-run in 1959. Fry (1961) also reported that a barrier had been removed from the creek in summer 1958, thus providing an additional nine miles of habitat for salmon up to Higgins Hole (a deep pool), above which is another natural barrier (Outdoor California 1958; Travanti 1990). The lower barrier—a 14-foot falls in the Iron Canyon area created by rock-slide debris around the time of the 1906 San Francisco earthquake—blocked upstream access for what had previously been a "sizable" salmon run (Outdoor California 1958). The present distribution of salmon in Big Chico Creek thus is probably not much different from what it had been originally. The spring run has been able to ascend farther upstream during spring flows than is reached by the fall run, and thus is both spatially and temporally isolated from the fall run, as is true in some other streams. The current upper limit of the spring run and steelhead is essentially Higgins Hole, about one-half to one mile above the crossing of Ponderosa Way, although with high enough streamflows the fish can ascend a half mile farther upstream (J. Nelson, personal communication, see "Notes"). The fall run typically spawns below the Iron Canyon Fish Ladder in Bidwell Park, in the lower one-third or one-fourth of the creek (J. Nelson, personal communication, see "Notes").

The average annual run size of the spring-run is believed to have been <500 fish during the 1950s to 1960s and more recently has been considered to be only a remnant (Reynolds and others 1993). Big Chico Creek has been heavily planted with Feather River "spring-run" fish, which evidently had been genetically mixed with fall-run fish. In the last decade or so, very few, if any,

of these hybrid spring-run spawners have returned to the creek (F. W. Fisher unpublished data). During the 1990s, estimated spring-run escapements have ranged from zero to 200 fish, averaging 35 fish (DFG 1998). The Iron Canyon fish ladder was damaged by high flows during the winter of 1994–1995, thereby blocking the spring salmon run in 1995. In that year, about 100 salmon were captured below the obstruction and transported farther upstream and another 100 salmon were observed in the stream (J. Nelson, personal communication, see “Notes”; DFG 1998). A relatively large spring-run escapement (about 400 fish) was observed in 1998 (DFG unpublished data), but the source of these fish is unknown. The fall and late-fall runs in recent times have been highly variable, and the fall run occurs in very low numbers due to lack of water in late summer and fall (Reynolds and others 1993). Intensive pumping of water from lower Big Chico Creek for irrigation takes a heavy toll of young salmon migrating downstream and juveniles that enter the stream for rearing, except during very high streamflow conditions (Reynolds and others 1993; USFWS 1995).

Deer Creek (Tehama County). Both spring- and fall-run salmon occurred in Deer Creek, which is a cold, spring-fed stream. The Yahi branch of the Yana people occupied both the Deer and Mill creek drainages, and for whom salmon and other fishes were an important secondary food source (Johnson 1978). The celebrated Ishi, last of the Yahi, demonstrated to anthropologists the Yahi methods of procuring fish, and he was said to have “used a salmon spear most expertly” (Pope 1918, p 199).

Before the 1940s, the spring-run salmon ascended Deer Creek for about 40 miles from its mouth up to 16-foot-high Lower Deer Creek Falls (Hanson and others 1940), located about one mile below the mouth of Panther Creek. According to Hanson and others (1940), salmon were never known to have passed Lower Deer Creek Falls. Clark (1929, p 39) stated that spawning beds extended from the creek mouth (near the town of Vina) to about ten miles into the foothills, which he described as “a good spawning ground when there is water.” Clark, however, was evidently referring only to the fall run.

Clark (1929) reported the presence of two irrigation diversion dams on the creek: Stanford Vina Dam, about three miles east of Vina, five feet high but with a fish ladder and screens installed on the irrigation ditches, and Deer Creek Irrigation District Dam, eight miles east of Vina. The latter dam had no fish ladder, because it was not considered to be an obstruction to salmon, but it also lacked fish screens at that time (Clark 1929). According to Clark (1929, p 39), there was “a small spring run and quite a large fall run” and salmon previously had been “very numerous in Deer Creek until dams were built which took most of the water from the creek.” Clark furthermore stated that “the spring run has never been successful as the fish come up in the spring and summer and lay in the holes until fall before spawning,” and “The water

becomes too warm for them and they die before they can spawn." Clark may have made this latter statement based on limited observations on fish relatively low in the drainage or during years of low streamflows; spring-run fish are presently known to be capable of over-summering in the pools in Deer Creek (for example, Needham and others 1943; F.W. Fisher, personal observation). Clark stated that the fall run was more successful, when there was "sometimes enough water in late fall," but even the fall run was "very small" at that time (1928) due to irrigation diversions from the creek. Decreased streamflows and consequently high water temperatures in the early summer caused mortalities of up to several hundred late-migrating adult salmon in the years 1945–1947 (Moffett 1949).

As part of the Shasta Fish Salvage Plan (to mitigate for construction of Shasta Dam), a fish ladder was constructed around Lower Deer Creek Falls in 1942–1943 (Needham and others 1943; Moffett 1949). By the end of 1943, salmon were able to ascend about five miles farther upstream to Upper Deer Creek Falls, a "sheer drop" of about 20 feet (Hanson and others 1940), which is the present major upstream barrier. There is, however, a fish ladder at the Upper Falls that is occasionally used by a few salmon (P.B. Moyle, personal observation). Hence, the amount of stream available for over-summer holding and for spawning (particularly for the spring run) has been increased. To compensate for the loss of spawning habitat in the upper Sacramento drainage caused by construction of Shasta and Keswick dams, Sacramento River spring-run salmon were caught at Keswick and transported to Deer Creek during the 1940s to mid-1950s (Needham and others 1943; Moffett 1949; Fry 1961), but those transfers had no noticeable effect on the spring run in Deer Creek (Fry 1961). Deer Creek is currently believed to have sufficient habitat to support "sustainable populations" of 4,000 spring-run and 6,500 fall-run salmon (Reynolds and others 1993). In recent years, most of the flow in the lower ten miles of the creek on the valley floor has been diverted, and in "many years" all of the natural flow from mid-spring to fall is depleted by the three diversion dams and four diversion ditches (Reynolds and others 1993). Although all of the diversion structures have fish screens and fish ladders, inadequate flows sometimes impede or prevent the upstream passage of salmon (Reynolds and others 1993).

The fall run presently still exists, spawning at lower elevations than the spring run and later in the fall, after ambient temperatures have become cooler. The two runs thus are both spatially and temporally isolated for spawning. The center of the present summer-holding and spawning areas for the spring run is the A-line Bridge (at about 2,900 ft elev.), which lies between Lower Deer Creek Falls and the US Forest Service (Potato Patch) Campground farther upstream. The spring run spawns from late August to early October (having held over the summer in the upstream reaches), while the fall run cannot enter

the lower creek to spawn until stream flows increase in late October (F.W. Fisher, personal observation).

Fry (1961) reported spring-run population estimates of <500 to 4,000 fish for 1940–1956 and fall-run estimates of <500 to 12,000 fish for 1947–1959. From the 1960s through 1980s, the number of fall-run spawners in Deer Creek ranged from 60 to 2,000 fish (average: 500), and in the present decade (1990–1997) the run has numbered 70 to 1,200 fish (average: 400 from DFG unpublished data). Estimates for the spring run were 400 to 3,500 fish (average: 2,200) annually during 1950–1979 and 80 to 2,000 fish (average: 660) during 1980–1998 (DFG unpublished data). Although spring-run estimates for most years during the 1990s have been in the low- to mid-hundreds, estimated escapements reached 1,300 in 1995 and 2,000 fish in 1998 (DFG 1998 unpublished data). The spring-run population in Deer Creek is one of only three or four remaining naturally spawning spring-run chinook populations in California that can be considered genetically intact and demographically viable (DFG 1990)—two other such populations within the Central Valley drainage being in nearby Mill and Butte creeks.

Mill Creek (Tehama County). Both spring and fall salmon runs are present in Mill Creek, and occasionally late-fall run fish also occur (Reynolds and others 1993). Stone (1874, p 208) mentioned “Mill-brook, near Tehama, ...a small stream, where the salmon rush up to spawn in great numbers, in October and November. They also come up this brook in April, May, and June.” The presence of a large “summer” (that is, spring) run in 1901 was reported by the US Fish Commission (USFC 1904). The “summer” run in 1902 was blocked by newly constructed racks and the fish all died due to excessively high temperature, while the fall run of that year was small due to low streamflows (USFC 1904). Clark (1929, p 39) later described Mill Creek as “a celebrated salmon stream” that had “some very large runs” and he stated that the spawning beds extended from the US Bureau of Fisheries egg station and hatchery (located about one mile above the creek mouth) for a distance of two miles to Clough Dam. Most habitat for salmon, either for holding or spawning, is currently viewed as extending from the mouth of Little Mill Creek (about 1,500 ft elev.) up to the area around Morgan Hot Spring (about 5,000 ft) (F.W. Fisher, personal observation). Some spring-run salmon in Mill Creek reportedly spawn in stream reaches well in excess of 5,000 ft elevation (Reynolds and others 1993) near the boundary of Lassen National Park—among the highest altitudes known for salmon spawning in North America. All the original upstream habitat suitable for spring-run salmon is still intact, and no major changes have been made on this stream (F.W. Fisher, personal observation).

Mill Creek is spring-fed and generally cold enough to sustain a spring run. However, it is unusual in that there is an elevational temperature inversion. The upper creek is fed by water from Lassen National Park, where there are

many hot springs, but farther downstream the lateral influx from coldwater springs results in cooler temperatures (F.W. Fisher, personal observation). Mill Creek also differs from other streams of the eastside Central Valley drainage in having high silt load and turbidity during the spring snow-melt, the silt originating naturally from volcanic and glacial materials in Lassen Volcanic National Park (Reynolds and others 1993).

Clark (1929) reported three dams on Mill Creek: the Molinas Water Company dam with fish screens on its diversion ditches and "not considered an obstruction"; 16-foot Clough Dam, an irrigation diversion project equipped with fish screens but with a poor fishway, which was seldom passable due to low water; and a third, unnamed seven-foot dam farther upstream with screened diversion ditches. However, these dams were in the lower reaches of the creek, essentially on the valley floor, and they probably posed no real obstruction to spring-run fish during the spring flows. In the early 1990s, there were three dams in the lower eight miles of the creek which diverted most of the natural flow (Reynolds and others 1993). All three dams were equipped with fish screens and the lowermost and uppermost dams had operative fish ladders (Reynolds and others 1993). However, the fish ladder on Clough Dam (the middle, tallest dam) functioned poorly during certain flow conditions (Reynolds and others 1993) and therefore may have impeded upstream migration. Clough Dam was breached by flood flows in January 1997 and since then has not obstructed salmon migration (C. Harvey-Arrison, personal communication, see "Notes").

Clark (1929) noted that salmon abundance in this creek was reflected by the egg takes at the US Bureau of Fisheries egg station, which collected eggs from fall-run fish but not from the spring run. The station operated during 1902-1945, closing down after completion in 1945 of the Coleman National Fish Hatchery on Battle Creek (Reynolds and others 1993). The egg takes peaked during 1904-1906 but were generally high from 1903 to 1918, dropping substantially during the later years 1919-1924. Clark stated that female salmon in this system produced about 5,000 eggs each, thus allowing estimates to be made of female spawner abundance from the total egg takes by the station; he also stated that there were "at least half again the number of males" (in other words, males were 50% or more as abundant as females). Thus, at the peak productivity in 1905 (30 million eggs taken), there were an estimated 9,000 spawners present (including 6,000 females). In 1924, one of the years of lowest egg production, 2.3 million eggs were taken, which translated to 450 female and 675 total spawners in the creek.

Clark (1929, p 41) mentioned the presence of both fall and spring runs, but he described the spring run as "very small and decreasing each year." It is possible, however, that Clark did not realize that spring run fish ascended far upstream and held there over the summer, and he therefore may have under-

estimated their presence. Fry (1961) reported spring-run numbers of <500 to about 3,000 fish during 1947–1959, while the fall run ranged between 1,000 to 16,000 spawners. Fry (1961, p 61) stated that most of the fall run spawned below Clough Dam, while “for all practical purposes the entire spring run goes upstream past the dam.”

In recent decades, the spring-run spawning escapement varied from zero fish, during the severe drought in 1977, to 3,500 fish in 1975 (Reynolds and others 1993; DFG unpublished data), but the trend has been downward from an annual average of 2,000 fish in the 1940s to about 300 in the 1980s (DFG 1990). During 1980–1998, the spring run ranged from about 60 to 840 spawners annually (average: 380) (DFG 1998 unpublished data). Fall-run escapements have been zero to 16,000 spawners since 1952, generally hovering near 1,500 fish (DFG unpublished data). The DFG (1993) reported an average annual fall-run escapement of 2,200 fish for the 38 years of record up to that time. In the present decade (1990s), the fall run has numbered about 600 to 2,100 fish but was absent in some years due to low seasonal streamflows. As in Deer Creek, the spring and fall runs in Mill Creek are separated temporally, the fall run ascending the creek during fall flows after the spring-run fish have finished spawning (F.W. Fisher, personal observation). There is also spatial separation of the spring and fall runs in both Mill and Deer creeks, with spring-run fish spawning well upstream from the fall-run fish and thus further minimizing the possibility of hybridization (DFG 1990). Late-fall run salmon have been occasionally observed spawning in the lower reaches of the creek (Reynolds and others 1993).

Antelope Creek (Tehama County). Both spring and fall runs, and probably a late-fall run, originally occurred in Antelope Creek. Spring-run salmon ascended the creek at least to where the North and South forks join (where several salmon were observed a few years ago by Lassen National Forest biologists), and they probably held there over the summer. The few spring-run fish that now enter the creek ascend the North and South forks about five to six miles to the vicinity of the Ponderosa Way crossings, their probable historical upper limit, beyond which there is little suitable habitat (F.W. Fisher, personal observation).

As in Mill and Deer creeks, the low, late summer and fall streamflows limit the accessibility of the creek to fall-run fish. Until at least 1993 there were two water diversions on Antelope Creek, operated by the Edwards Ranch (50 cfs) and by the Los Molinos Mutual Water Company (70 cfs) (Reynolds and others 1993). During the typical flow-diversion season (1 April to 31 October), operation of both diversions usually dried out the lower reach of the stream (Reynolds and others 1993), thus impeding or preventing the upstream migration of both spring and fall runs.

The spring run formerly numbered 200 to 300 fish annually, with lows down to 50 fish (DFG unpublished data). Reynolds and others (1993) gave an estimated historical spring-run size of 500 fish. No regular escapement estimates have been made recently, but occasional checks indicate that Antelope Creek currently has no more than a remnant spring run which probably is not self-sustaining; for example, two to three individuals at most have been seen through much of the 1990s. However, in 1998 about 150 spring-run fish were observed in Antelope Creek (DFG 1998). The fall run in Antelope Creek generally has been small. During 1953–1984, the fall run numbered 50 to 4,000 fish annually (average: about 470 fish) (Reynolds and others 1993; DFG unpublished data.). Population estimates have not been made in more recent years due to the scarcity of the salmon, and the fall run may be extirpated (Reynolds and others 1993).

Battle Creek (Tehama County). Both spring and fall runs of salmon originally occurred in Battle Creek, and there is evidence that a winter-run was also present. The California Fish Commission noted that, “Salmon enter this stream in large numbers during the months of October and November” (CFC 1896, p 23) and averred, “...there being almost no limit to the number of eggs which can be secured there with proper apparatus” (CFC 1896, p 24). Curiously, Stone (1897, p 218) stated:

This Battle Creek is the most extraordinary and prolific place for collecting salmon eggs yet known, though the eggs are limited to the fall run of salmon, as none worth mentioning of the summer run [the current spring run] of fish ascend Battle Creek. The first salmon make their appearance early in the fall, and before November and during that month they are found in almost incredible numbers in the wide lagoon extending about 2 1/2 miles up the creek from its mouth.

It appears that even at that time fishery biologists had not yet fully explored the upper reaches of the stream where the spring-run salmon over-summered. In April 1902, the US Fish Commission emplaced racks in Battle Creek and observed large numbers of salmon during “late spring and early summer,” thus proving the existence of “a large summer run of fish in the creek” (USFC 1904, p 73). A US Fish Commission Report also noted a “site suitable for a branch hatchery for the summer run of salmon ...on Battle Creek, opposite the mouth of Baldwin Creek” (Smith 1905, p 81) Rutter (1904) then reported capturing in Battle Creek (during October 1898 and early October 1900) recently emerged fry (1.5 inches long) that could only have been of the winter run. In 1939, salmon were observed spawning in Battle Creek during May and June (Needham and others 1941), the typical winter-run spawning time (Slater 1963; Fisher 1994). The North Fork of Battle Creek contains a series of springs near the town of Manton which would have provided coldwater flows required for the summertime spawning and rearing of the winter run, despite

Slater's (1963, p 4) assertion that the winter run would not normally spawn successfully in Battle Creek or in Deer and Mill creeks because of high (>70 °F) summer water temperatures. However, the winter run was largely eliminated after hydroelectric development of the creek in 1910-1911, which cut off the spawning habitat. The formerly large spring run also was significantly reduced by the loss of habitat at that time and it may have been completely eliminated for a period thereafter, as indicated in DFG (1990).

Surveys conducted before the construction of Shasta Dam indicated that the reaches above Coleman National Fish Hatchery could support >1,800 spawning pairs of salmon (Reynolds and others 1993). The North Fork of Battle Creek, especially Eagle Canyon, contains deep, cold pools—ideal summer holding habitat for spring-run salmon (Reynolds and others 1993), and significant areas of spawning gravel have been determined to exist from Coleman Powerhouse on the mainstem up to above the Volta Powerhouse (extending to Macumber Dam) on the North Fork and on the South Fork between South Powerhouse and South Diversion Dam (Reynolds and others 1993). It is likely that much of those areas had been previously used by salmon before blockage of migration and the alteration of the streamflow regime. In the North Fork, salmon have been observed as far as Volta Powerhouse above Manton (T. Healey, personal communication, see "Notes"), but the upper distributional limit would have been a waterfall three miles farther upstream (H. Rectenwald, personal communication, see "Notes"). Hanson and others (1940) reported the presence of a waterfall on the South Fork near the Highway 36 crossing, which evidently was a natural barrier to salmon.

Clark (1929) noted that Battle Creek had a fall run and a "small" spring run. As of 1928, there was a US Bureau of Fisheries egg-collecting station and hatchery (Battle Creek Hatchery) located about 1.5 mi above the creek mouth. The station, first established in September 1895 (CFC 1896), collected eggs from the fall run but allowed the spring run to pass upstream (Hanson and others 1940). Spawning by spring-run fish occurred in the five-mile stretch between the egg station and the upstream dams (Clark 1929). Clark (1929) reported the presence of three power dams and plants: the Coleman plant six miles above the mouth, with an operative fish ladder and screens on the diversion canals; a second dam, 30 ft high and equipped with "a good fish ladder and ditch screens," on the South Fork about 20 mi above the Coleman plant; and the Volta plant on the North Fork. Clark stated that despite the presence of fish ladders, the water was often so low that the dams were impassable to fish.

Presently, natural spawning of salmon in Battle Creek is by far heavily concentrated in the stretch between the creek mouth and the Coleman National Fish Hatchery weir six miles upstream, and instream spawning has been said to be "still significant" (Reynolds and others 1993). The predominant fall-run

salmon are blocked at the hatchery weir, and whatever natural spawning that formerly occurred upstream has been largely eliminated by that blockage and low flows due to hydropower operations of Pacific Gas and Electric Company (PG&E) (Reynolds and others 1993). It is not known how much farther fall-run salmon ascended Battle Creek, and we conservatively assume that they were constrained to the vicinity of the hatchery weir. During recent years when streamflows were adequate, small numbers of spring-run and winter-run salmon have been able to ascend past the weir and spawn in upstream reaches (T. Healey, personal communication, see "Notes"). Spring-run and a few winter-run salmon were observed in the Eagle Canyon area of the North Fork Battle Creek during summer 1995 (T. Healey, personal communication, see "Notes"). As of 1993, there were four unscreened hydropower diversions on the North Fork, three unscreened hydropower diversions on the South Fork, two storage reservoirs and a system of canals and forebays in the drainage, as well as two "significant" agricultural diversions (one unscreened) on the main stem (Reynolds and others 1993). Current negotiations to reconfigure the PG&E hydropower system on Battle Creek, including dismantling several dams, will considerably improve access for salmon to the upper reaches (Sacramento Bee, 4 May 1999).

The records for egg takes (for the fall run) at the US Bureau of Fisheries egg-collecting station indicated peak spawner abundances generally occurring in the period 1896–1907, and the egg takes remained fairly high until 1916, after which there seemed to be an overall decline until 1924 (Clark 1929). Translating the egg takes to numbers of females (assuming 5,000 eggs per female, after Clark [1929]) gives a peak of 10,000 females for 1904 and a low of 200 females for 1924. According to Clark (1929, p 41), the spring run, which was allowed to spawn naturally in the creek, amounted to "almost nothing," and only six or seven spring-run salmon were seen in 1928. The old Battle Creek Hatchery, which took fall-run spawners from the creek, continued to operate through 1945 (Fry 1961). The larger Coleman National Fish Hatchery began operations in 1943 and took small numbers (<1,200) of spring-run fish from Battle Creek in 1943–1946, but during that period Coleman National Fish Hatchery received most of its fish (both spring-run and fall-run) from fish salvage efforts at Keswick Dam and from the Balls Ferry Racks on the mainstem Sacramento River (Moffett 1949, Fry 1961). In 1946, Coleman National Fish Hatchery started taking fall-run fish locally from Battle Creek (Moffett 1949; Fry 1961). (See also Black, this volume, for a thorough review of the history of Battle Creek hatchery operations.)

During the period 1946–1956, the spring run numbered about 2,000 fish in most years (Fry 1961; Campbell and Moyle 1990). By the late 1980s, the spring run in Battle Creek was either extirpated or close to it (Campbell and Moyle 1990). Small numbers of spring-run fish have returned in recent years, ranging from 40 to 100 fish (average: 70) in 1995–1997 (DFG 1998). The escapement for

1998 was about 50 to 100 fish (USFWS 1998 unpublished report). Historical abundance data for the winter run in Battle Creek are almost nonexistent, although Slater (1963) reported that on 22 May 1962, 457 winter-run fish were counted and a population size of 2,687 fish was estimated for the two-mile stretch below Coleman National Fish Hatchery. Small numbers of winter-run fish have been observed in recent years, with about 100 spawners estimated for 1998 (USFWS 1998 unpublished report). Numbers of fall-run spawners in Battle Creek were about 3,000 to 30,000 (average: 15,000) during 1946–1959 (Fry 1961). Annual fall-run escapements during the 1980s and 1990s have ranged between 12,700 and 83,900 fish, with averages of 29,600 (in the 1980s) and 46,400 fish (1990–1997) (DFG unpublished data). Hatchery spawners composed 20% to 73% (average: 51%) of the annual runs during 1980–1997 (DFG unpublished data).

The Coleman National Fish Hatchery also has maintained a late-fall run, but returns of adults have not been consistently strong enough to sustain the run and the hatchery has relied on obtaining late-fall-run spawners from the Keswick fish trap below Keswick Dam on the Sacramento River. During 1995–1997, however, numbers of the late-fall run returning to Coleman National Fish Hatchery were 1,300 to 4,600 fish (average: 3,000) (USFWS 1998 unpublished report).

Mainstem Sacramento River and Upper (Little) Sacramento River (Solano, Yolo, Sacramento, Sutter, Colusa, Glenn, Butte, Tehama, and Shasta counties). The Sacramento River, regarded by Clark (1929, p 34) as “the most important salmon stream in the state” and by Fry (1961, p 59) as “the largest and best salmon stream of the Central Valley,” has the sole distinction among the salmon-producing rivers of western North America of supporting four runs of chinook salmon – spring, fall, late-fall and winter runs.

One of the earliest references to salmon of the Sacramento River was by the fur trapper Colonel J. J. Warner who traveled the Central Valley in 1832: “The banks of the Sacramento river, in its whole course through its valley, were studded with Indian villages, the houses of which, in the spring, during the daytime, were red with the salmon the aborigines were curing” (Chamberlain and Wells 1879, p 12; Gilbert 1879, p 12; Elliott 1882, p 161). John Work, of the Hudson’s Bay Company, reported that his party of fur trappers, while moving down the Sacramento Valley (near Putah Creek) on 16 March 1833, obtained “some fine[?] Salmon” (spring-run, or perhaps winter-run) from the native people (Maloney 1943, p 339). Lieutenant Charles Wilkes, reporting on the United States Exploring Expedition of 1838–1842, later described “a substantially-built fish-weir” – undoubtedly for catching salmon (see Curtis 1924b) – which was observed on 31 August 1841 near the present town of Colusa on the lower mainstem Sacramento River (Wilkes 1845, p 187). Another party of the US Exploring Expedition encountered Native American people (probably

Wintu) farther north in the Sacramento Valley and traded with them for salmon—caught by the natives by means of weirs and long, forked fish spears (Dillon 1975). Perhaps the last published record of the intact native fishery on the Sacramento Valley floor was that of a forty-niner who observed in 1849, near “a very large settlement of Indians” on the lower Sacramento River, “a scrap of beach, on which a vast number of miserable spent salmon of enormous size, split, were hung along on poles to dry in the sun” (Kelly 1950, p 73). Unpublished notes by the pioneer H.C. Bailey also alluded to “Sacramento Valley Indians” taking salmon in the springtime before 1853: “During the salmon run (March and April) they caught them in abundance and some times sturgeon. We could buy a 25 pound salmon for a quart of flour. They were the finest fish I ever tasted.” (Latta 1930–1931).

Salmon fishing as a commercial enterprise on the Sacramento River had been initiated by John A. Sutter near his New Helvetia settlement (present-day Sacramento) by about 1842–1843, if not earlier (Wright 1880; Van Sicklen 1945; Bennyhoff 1977). Another fishing entrepreneur was a Mr. Schwartz, whose fishing operation was located six miles downstream of New Helvetia. Concerning Schwartz’s fishery, the pioneer Edwin Bryant noted in his journal for 26 October 1846:

Mr. Schwartz provided us with a breakfast of fried salmon and some fresh milk.... Near the house was a shed containing some forty or fifty barrels of pickled salmon... The salmon are taken with seines dragged across the channel of the river by Indians in canoes. On the bank of the river the Indians were eating their breakfast, which consisted of a large fresh salmon, roasted in the ashes or embers, and a kettle of atôle, made of acorn-meal. The salmon was four or five feet in length, and when taken out of the fire and cut open, presented a most tempting appearance (Bryant 1849, p 345).

The date of the narrative indicates that the salmon were of the fall run. The lower mainstem Sacramento River later became the center of the bustling commercial salmon fishery carried out by immigrant European and Euro-American fishers drawn to California during the Gold Rush and following period (Clark 1929; Skinner 1962). As noted by a gold-miner, “In 1851...the Sacramento river was full of splendid salmon, equal in flavour to those of the Scottish rivers, though in appearance not quite such a highly finished fish, being rather clumsy about the tail” (Borthwick 1857, p 48).

Unquestionably the spring chinook salmon run, and probably lesser numbers of the winter run, occurred in the Upper (Little) Sacramento River (also called the Destruction River in early accounts). In 1841, a detachment of the US Exploring Expedition reconnoitered the Siskiyou Trail from Oregon to the Sacramento Valley. Traveling southward along the Upper Sacramento River, the party passed downstream of “Soda Springs” and Castle Crags and

observed evidence of the spring run during the latter part of the spawning period (early October) (Poesch 1961; Dillon 1975). Titian Ramsey Peale, a member of that party, recorded in his journal for 6 October 1841:

Passed several old Indian camps, at one there were several new graves, over which were bundles of provisions and near by on a stump a bundle of Salmon... One of our hunters saw several more ["Indians"] on the river below our camp fishing for Salmon, which must have been numerous earlier in the season, as quantities of dead ones now lay along the rocky Shores. We saw the remains of fences and weirs for catching them (Poesch 1961, p 194).

A later historical account of Shasta County noted that the sudden influx of gold miners into the Upper Sacramento River valley in the spring of 1855 drove the native people from their usual haunts (near Castle Crags) and prevented them from obtaining "the salmon they were wont to spear," thus precipitating hostilities (Southern 1942, p 66). Salmon normally present at that time of year would have been either the winter or spring runs (or both). Curtis (1924b, p 87) stated that the Wintu people on the Upper Sacramento River caught (spring-run) salmon in midsummer, "with spears fifteen to twenty feet long, in deep quiet pools"; "In the autumn salmon were speared while spawning in the riffles, and in spring spearing was carried on at night by torchlight..." Furthermore, the winter salmon run was said to have spawned in the headwaters near Mt. Shasta (Stone 1874). Stone (1879, p 234) noted that "in July the summer run [currently termed winter run] are spawning at the headwaters of the McCloud and Little Sacramento; in August and September [the spring run spawn] farther down these rivers..." Scofield (1900, p 68) also reported: "In Hazel Creek, a tributary of the Sacramento near Sims, I found, on November 6, 1897, two sizes of young salmon.... Of the smaller size [average length 2.87 inches] only four were taken....they must have hatched from the egg early in August, and allowing three months for hatching, they were spawned early in May." The timing of those smaller fish is indicative of the winter run. The late-fall run, with its requirement of cool summer flows for fry and juvenile rearing, also possibly entered at least the lower reaches of the Upper Sacramento where such flows existed.

Salmon at one time ascended the Upper Sacramento River in large numbers at least to the falls near the town of Sims, about 31 mi upstream of the site of Shasta Dam. Large numbers of juvenile salmon were observed in the vicinity of Sims during the summer of 1898 by Rutter (1904, p 105), who estimated a probable density of "as many as 10,000 young salmon to the mile in the Upper Sacramento...or between a half and three quarters of a million in all the headwaters of that stream" (see also Rutter 1902). Juveniles were also captured in Hazel Creek, "a favorite spawning stream both for salmon and trout," which joins the Sacramento River near Sims (Rutter 1904). Clark (1929) stated that the falls at Sims stopped most of the salmon, although "a few fish" were able

to surmount them. However, Stone (1874, p 180) reported: "Last July [1871] hundreds of salmon, averaging 15 pounds apiece, were caught in the Little Sacramento with a hook and line, near Frye's Hotel, at Upper Soda Springs," upriver of Sims and just below the town of Dunsmuir. Furthermore, the native Wintu people were said to have fished for salmon (during July) above Sims in the reach from Castle Crag depot (five miles below Dunsmuir) to Shasta Retreat (about one mile above Dunsmuir) (Voegelin 1942). According to one Wintu informant, the salmon fishing activities involved "200 to 300 people" and lasted two to three weeks (Voegelin 1942), indicating that substantial numbers of salmon were able to ascend the falls past Sims. Once over the falls, salmon would have had clear access up to the present site of Mt. Shasta City, and it appears that they were able to ascend almost the entire length of the river to the site of present-day Box Canyon Dam and Lake Siskiyou (also called Box Canyon Reservoir), where several spring-fed streams enter the Upper Sacramento River from the east (Mt. Shasta).

Rutter (1904, p 96) reported netting "nearly 500" juvenile salmon in a single seine haul from a pool at the head of Box Canyon, near Sisson in August 1897, and he stated that it was not uncommon "to catch over a hundred at a time in many of the pools of the headwaters." It is possible that the large numbers of young salmon observed by Rutter were to some extent due to large-scale plantings of salmon fry into the Upper Sacramento from Sisson (Mt. Shasta) Hatchery, a practice started in 1888 when that hatchery was built (CFC 1890; USFC 1892; Shebley 1922), and some numbers of juvenile salmon from Baird egg-collecting station on the McCloud River were transferred to the Upper Sacramento River as early as 1880 and 1881 (Stone 1883b; Green 1887). However, salmon evidently were abundant enough in the remote reaches of the Upper Sacramento River before any hatchery plantings to gain notice in the first report of the California Fish Commission (CFC 1871, p 44): "Salmon are caught by the Indians in the small streams that empty into the Sacramento from the sides of Mount Shasta, at an elevation of more than four thousand feet above the level of the sea; to reach which they must have passed through at least fifty miles of almost continuous rapids." The US Fish Commission (USFC 1876a, p xxviii) likewise stated that the salmon "traverse the Sacramento Valley to the headwaters of the Little Sacramento and the McCloud Rivers, about four hundred miles..." A similar quote was attributed to Dr. David Starr Jordan: "They are known to ascend the Sacramento as far as the base of Mount Shasta, or to its extreme headwaters—about four hundred miles" (CFC 1890, p 59). Jordan's statement (probably made before 1890) antedates any possible results (specifically, returning adults) from regular plantings of young salmon into the Upper Sacramento River from Sisson Hatchery in 1888 and later—given the minimum generation time of three years for chinook salmon.

Stone (1874, p 176) stated that salmon ascended the Upper Sacramento River "in great numbers, and make the clear waters of this stream the principal spawning-ground of the salmon of the Great Sacramento River, with one exception" – the McCloud River. Clark (1929) described the Upper Sacramento River as an "ideal spawning stream" with "wonderful spawning beds" along its entire length; "the salmon were extremely abundant" before construction of the Southern Pacific Railroad through the Sacramento Canyon, but "the run was almost destroyed" by construction work in 1883–1884. Erosion of rocks and sediments into the river blocked and muddied the water, and the railroad workers reportedly blasted areas holding the salmon to catch the fish (Clark 1929). As noted by Shebley (1922, p 64), many fish were used to feed the 9,000 laborers camped along the Sacramento River, but "there was wanton destruction in the way they were killed." Again in 1886, blasting for the railroad along the Upper Sacramento River prevented the salmon from entering that stream very far; "quite a number" attempted the ascent but turned back after a few days and entered the McCloud River instead (Green 1887). Furthermore, a mining tunnel, located just above the confluence with the Pit River, essentially prevented the migration of the fall run when flows were low in August and September during the 1880s. The tunnel's diversion of water from a short stretch of the Upper Sacramento River evidently accounted for the greatly depressed fall run "for a long while past," until the tunnel was closed in 1890 (CFC 1890). In the only quantitative assessment of salmon abundance for this stream, Hanson and others (1940) estimated that the Upper Sacramento River in 1938 had a "potential spawning capacity" of 14,303 redds. This should be viewed as a minimal estimate because the spawning capacity estimates given by Hanson and others (1940) for other streams generally are lower than the run sizes that subsequently have been observed for those streams (F. W. Fisher unpublished data).

On the mainstem Sacramento River on the valley floor, the Anderson-Cottonwood Irrigation District (ACID) diversion dam at Redding was an almost complete barrier to salmon during the irrigation season (April through October) for about ten years (1917–1927) (CFGF 1927; Hanson and others 1940). This blockage occurred despite an initial "understanding" during the construction of the dam in 1916–1917 between the California Fish and Game Commission and the Irrigation District's chief engineer "that the dam was not to be raised above a certain level" and "would allow all the salmon to pass the dam and proceed on their way up the McCloud and Pit rivers" (CFGF 1921a, p 20). The ACID authorities contended that an open section of the dam was adequate to allow the passage of salmon (CFGF 1921c), although McGregor (1922, p 149) noted that "With no little humor, they speak of it as a fishway." It was subsequently determined that salmon did not use that spillway and that very few fish surmounted the dam at any point along it (McGregor 1922). Further testimony regarding the ineffectiveness of the original "fishway" was given by upstream residents who reported that salmon had become

“extremely scarce since the erection of the dam”; as one pioneer fisherman of the area noted, “Why would we journey miles down the river from our homes to fish at the dam if we could get fish up where we belong?” (McGregor 1922, p 153). Clark (1929, p 35) stated that the dam “nearly exterminated the salmon run at that point of the river.” Clark presumably was referring to the winter and spring runs because the dam routinely was dismantled during October; the fall run for the most part had clear access up the river and, therefore, was not significantly affected. After installation of a new fish ladder on the dam, it was reported that “quite a number of salmon” passed over, “but nothing to compare with conditions before the dam was constructed” (Clark 1929, p 35). The ACID dam has continued to pose fish passage problems (Reynolds and others 1993).

The Glenn-Colusa Irrigation District (GCID) diversion facility has been another significant obstacle to salmon, but mainly for downstream-migrating juveniles which are destroyed in large numbers by the pumping operations (Phillips 1931; Reynolds and others 1993). However, by far the greatest factor to affect the salmon runs of the Sacramento River in recent times has been Shasta Dam (completed in 1943). With its closure in November 1942, Shasta Dam barred the salmon entirely from their former spawning grounds in the Upper Sacramento, McCloud and Pit River drainages (DFG 1944), thus removing those areas from salmon production. In addition, about 13 mi of salmon habitat in the mainstem Sacramento River above Shasta and Keswick dams up to the confluence of the Upper Sacramento and Pit rivers were no longer accessible. Operation of the Coleman National Fish Hatchery in Battle Creek was intended to compensate for the habitat loss. Presently, the upstream distribution of salmon in the Sacramento River is delimited by Keswick Dam, a flow-regulating dam nine miles below Shasta Dam. Fall-run salmon spawn in the mainstem Sacramento River where spawning gravels occur from Keswick Dam downstream to below the town of Tehama (Clark 1929; E. R. Gerstung, personal observation) – a distance of about 67 miles. Fall-run spawning escapements in the mainstem Sacramento River averaged 217,100 fish annually during 1952–1959; 136,600 fish in the 1960s; 77,300 in the 1970s; 72,200 in the 1980s; and 48,000 fish from 1990 to 1997 (DFG unpublished data).

McCloud River (Shasta County). The McCloud River, once denoted by the California Fish Commission as “the best salmon-breeding river in the world” (CFC 1890, p 33), originally supported both spring and fall runs of salmon, as well as the winter run (Stone 1874; USFC 1900; Hanson and others 1940; Needham and others 1941). According to native Wintu informants, the spring run was “heavier” than the fall run in both the McCloud and Sacramento rivers, and the average size was “approximately twenty pounds,” with occasional fish weighing as much as 65 and 70 pounds (Du Bois 1935, p 15). The winter run appears to have been the least abundant of the three runs, with small numbers

of spawners reported by various workers (Stone 1874; Scofield 1900; USFC 1900, 1904; Rutter 1904, 1907; Hanson and others 1940). Yet, Stone (1876, p 446) reported that during the egg-collecting season (August and September for the spring run) in 1874 “Young salmon a few inches long were very plentiful” – those evidently being winter-run juveniles. Scofield (1900, p 69) noted that salmon had been observed “spawning in considerable numbers in the [McCloud] river above Baird early in May,” again corresponding to the winter run. The observation of one or two salmon spawning in the McCloud River near the hatchery around 20–24 April 1902 (USFC 1904; Rutter 1907) is indicative of early-spawning winter-run fish or perhaps late spawners of the late-fall run (based on life stage timing given in Vogel and Marine 1991; USFWS 1995). In June 1898, two size groups of young salmon were observed in the McCloud River “in large numbers” (USFC 1899)—one group corresponding in size (three to four inches) to fall-run juveniles and a second group of smaller fish (1.5 inches long) of a size indicative of newly emerged late-fall-run progeny.

Salmon ascended the McCloud River up to the impassable Lower Falls (20 ft high), about six miles above present Lake McCloud (Rutter 1904; Wales 1939; Hanson and others 1940). Hanson and others (1940) reported observations of salmon (evidently winter-run) spawning during May and June, 1939, in the McCloud River between Big Springs and Lower Falls (about 1.5 miles). However, the reach from Big Springs up to Lower Falls was ecologically less suitable than areas downstream for salmon because of relatively low streamflows. Big Springs (rm 49) is the location of two large springs which in the past contributed well over half the minimum streamflow of the McCloud River, and Big Springs thus was somewhat of an “ecological barrier” to salmon (Wales 1939). Ethnographic information similarly indicates that salmon did not ascend in significant numbers past a bend in the river at rm 41, one mile below Lake McCloud; according to a Native American informant, the “salmon got no further, just got there” (Guilford-Kardell and Dotta 1980, p 76). That point was the location of a Wintu village named *Nurumwitipom* (“salmon come back”) or *Nurunwititeke* (“falls back where the salmon turn back”) (Guilford-Kardell and Dotta 1980). The native people, primarily interested in harvesting the salmon in quantity, evidently paid little heed to the presumably small numbers of salmon that ascended past the main fishing sites into the less suitable upper reaches. A few salmon reportedly were observed in Squaw Valley Creek, the largest tributary to the McCloud, in September 1938, and they probably also entered the lower reaches of several other tributary streams (for example, Star City, Claiborne, and Caluchi creeks) (Wales 1939).

Clark (1929, p 43) described the McCloud as “a good spawning stream” from its mouth to the falls near its source. As of 1928 there were no dams or other artificial obstructions on the river except for the racks of the US Fish Commission egg station (Clark 1929). Hanson and others (1940, p 47) estimated that the McCloud River potentially could support 25,097 redds, and they reported

salmon spawning in 1939 near the mouth, at Big Springs, and at “several other places below the Lower Falls.” They also estimated that the lower five miles of Squaw Valley Creek, a tributary entering the McCloud River about 29 mi upstream of the mouth, could support approximately 830 redds (Hanson and others 1940).

After its establishment on the McCloud River in 1872 by the noted fish culturist Livingston Stone, the US Fish Commission egg-collecting station (Baird Station) soon was taking the spawn from almost all of the returning spring-run salmon (Clark 1929). During the early years of its operation (1872–1883), most of the eggs collected were shipped out of California for the main purpose of establishing runs in East Coast rivers, which in almost all attempts were failures (USFC 1892; Clark 1929; Towle 1987). However, production of salmon in the McCloud itself could not be sustained and in 1884 the scarcity of salmon led to the temporary closure of the egg station (Stone 1885a, 1897; Clark 1929).

Clark (1929) presented a tabulation of egg takes by the Baird Station in the years 1872–1924, which illustrated the decline in salmon abundance during the later years compared with earlier years. Aside from the first year operation (1872) in which 50,000 eggs were collected, the egg takes ranged from about 1 million to over 12 million eggs during the period 1873–1883, the first phase of operation before its temporary closure (Clark 1929). Eggs were taken from spring-run fish in that early period, but railroad construction along the Sacramento River during 1883 and 1884 blocked the salmon runs (Stone 1885b), and the paucity of the spring run forced the cessation of egg-collecting operations during 1884–1887 (Stone 1885a). In response to the depleted state of the Sacramento River salmon stocks, Baird Station was reactivated in 1888 for the expressed purpose of “aiding in the maintenance of the salmon fisheries of the Sacramento River” (USFC 1892, p 35). The egg station continued activities until 1935 (Hedgpeth 1941), but taking eggs during some years from the fall run to supplement the temporarily depleted spring run (see CFC 1890, 1907). During that later period of productive operation (mainly 1888–1924), between 1 million and 29.9 million eggs were taken annually, and the peak production (in 1903) was from about 5,600 females (Clark 1929). After 1907, the egg takes showed a fairly steady decline down to about 1 million to 1.5 million eggs per year (Clark 1929). By 1924 there were “only about 260 fish at the racks” which produced 1.2 million eggs (Clark 1929, p 43), and in 1935 only 5,200 eggs were collected, “probably from a single female” (Hedgpeth 1941, p 145).

Stone (1876, p 446) had estimated that in 1874, the first year in which a weir was set across the McCloud River for capturing the salmon, “Tens of thousands, not to say hundreds of thousands, which would perhaps be nearer the truth” passed upstream before the weir was finished, and “thousands more”

were blocked after its completion. Stone (1897, p 213) noted that in 1878, there was “an immense gathering of salmon in the McCloud.” He averred:

I have never seen anything like it anywhere, not even on the tributaries of the Columbia. On the afternoon of the 15th of August there was a space in the river below the rack about 50 feet wide and 80 feet long, where, if a person could have balanced himself, he could actually have walked anywhere on the backs of the salmon, they were so thick” (Stone 1880, p 749).

Stone (1880, p 763) also stated that during the 40 days before 5 October 1878, the egg-collecting crew “caught and examined, one by one, nearly 200,000 salmon” – all of which were of the spring run, as eggs were taken from only that run (in other words, “the first or August run”) at Baird Station during the period before 1888 (CFC 1890, p 17; USFC 1892, p xxxv). After the hiatus in the mid-1880s, the salmon (both spring and fall runs) returned in large numbers to the McCloud River in the 1890s and early 1900s – according to elder Wintu informants, “So thick on the McCloud it looked like you could walk across them” (Guilford-Kardell and Dotta 1980, p 82). The runs again declined, and in 1922 there was “no run of salmon whatever in the McCloud River,” due at least partly to abnormally low stream flows (Leach 1923). Clark (1929, p 43) reported spring and fall salmon runs still present in the McCloud River as of 1928, with the fall run “not as heavy as the spring,” but by that time both runs were greatly depleted.

Excessive fishing pressure by commercial gillnetters in the Sacramento River undoubtedly depressed the spawning runs into the McCloud River; for example, illegal fishing in the 1877 season reduced the “unusually large number” of salmon running in the Sacramento River so completely that only “extremely small numbers” reached the McCloud River (Stone 1879, p 799). In the early 1880s, the fishermen reportedly had the Sacramento River completely blocked with their gill nets (CFC 1884; McEvoy 1986). The McCloud River runs were also significantly affected by downstream obstructions in the Sacramento River – first by the Anderson-Cottonwood Dam in the period 1917–1927 (Leach 1922; CFGC 1923, 1927; Clark 1929) and ultimately by Shasta Dam, starting in 1942–1943 (Slater 1963; Reynolds and others 1993). Shasta Dam, about 560 ft high and then the second largest dam in the world, completely blocked access upriver and thereby extirpated all runs of salmon and other anadromous fishes into the McCloud River and other upper Sacramento tributaries (Needham and others 1941).

Pit River (Shasta County). The Pit River formerly was recognized as “a noted salmon stream” (CFC 1886). The Pit River system covers an extensive area, according to Clark (1929) comprising “at least half of the main Sacramento River.” The Achumawi people, historically referred to as “Pit River Indians,” are reported to have controlled about 50 mi of salmon streams in their territory (Olmsted

and Stewart 1978), primarily the mainstem Pit River. They harvested "vast quantities of suckers" by diverting streams as well as salmon "which were taken in great numbers by net and spear" and dried for winter consumption (Curtis 1924a, p 141). The Achumawi fished for a variety of other fishes, including steelhead: "The weir known as *tatsítschi* was set in the main stream for catching *allís* (steelhead trout) on their return to the sea in the autumn" (Curtis 1924a, p 137). The salmon ascended in large numbers at least to Pit River Falls (rm 75), but the falls evidently were not a complete barrier. Voegelín's (1942, p 175) ethnographic account states that "Salmon ascend Pit River as far as falls at site of Pit 1 power house, in Achomawi area." The Pit 1 power house was located at the mouth of Fall River (Clark 1929), a major tributary of the Pit River about four miles above Pit River Falls.

The presence of spring-run salmon in Hat Creek, a tributary of the Pit River below Pit River Falls, was noted by Rutter (1902, 1904), and they were also reported to have ascended the Pit River in the spring of 1926 (DFG 1929). The occurrence of a winter run in the Pit River drainage, spawning in "the headwaters," was indicated by Stone (1874). One ethnographic account stated that among the Atsugewi people ("Hat Creek Indians"), who controlled most of the Hat Creek drainage, "salmon were obtained only by invitation of the western Achumawi on Pit River" (Garth 1978, p 242) to where the Atsugewi made salmon-fishing expeditions in the fall, giving the Achumawi part of the catch as payment to trespass (Garth 1953). Garth's (1953, p 136) survey of Atsugewi informants indicated that salmon were "rarely seen in Hat Creek," and Voegelín (1942, p 175), drawing from an interview in 1936 with a 79-year-old Atsugewi informant, recorded: "Not many salmon in Hat Creek; occasionally a good run." However, Kniffen's (1928, p 315) earlier ethnographic summary, in describing the Hat Creek Valley, stated that "Formerly the streams contained an abundance of salmon, pike, trout, and suckers." Garth (1953, p 136) reported that a waterfall located "about a mile below Caasel [Cassel] on Rising River," was a favorite fishing place of the Atsugewi people, who called it "*ani*" [salmon] "*wecéici*" [jump up]. This reference is evidently to a stretch of Hat Creek which contains cascades and was sometimes called "Rising River"; that stretch is located just downstream of the mouth of the true Rising River. The latter is a wide, slow-flowing tributary to Hat Creek which lacks salmon habitat (E. R. Gerstung, personal observation). Hat Creek was said to have been "where salmon formerly abounded by the thousands during the spawning season," and the California Fish Commission established a salmon hatchery there in 1885 (CFGC 1914, p 63). However, so few salmon ascended to that point in 1886 and 1887 that the hatchery was abandoned in 1888 (CFC 1888; CFGC 1914; Shebley 1922). Rutter (1908, p 110) described Hat Creek as "a salmon stream of some importance, but it has a number of rapids that make its ascent difficult." Available spawning habitat and suitable conditions also occur in Kosk and Burney creeks, two other Pit River tributaries where it is likely that winter-run salmon spawned. The Achumawi people owned fish

weirs situated at Burney Falls, where they evidently caught salmon (Garth 1953). Burney Falls, a 129-foot double waterfall located about one mile above the mouth of Burney Creek, was an obvious historical barrier to salmon.

Rutter (1904), in reference to the spring run, stated that “some of the earlier ones even pass Pit River Falls and ascend Fall River to its source.” Those “earlier ones” he referred to probably comprised some number of winter-run fish. Rutter also stated that “they are not found in Pit River above the mouth of Fall River,” indicating that the salmon runs entered the cool and partially spring-fed Fall River for spawning — “mainly in August” — rather than continuing up the relatively warm Pit River. Garth’s (1953) ethnographic account similarly reported that salmon seldom ascended the Pit River above Fall River Mills, located at the mouth of Fall River, and Kroeber (1925, p 309) also noted, “Salmon hardly ascended beyond Fall River...”

Before Rutter’s (1904) report, the California Fish Commission (1880, p 13) wrote of Pit River Falls, located below the Fall River confluence: “The salmon in vast numbers reach the foot of this fall, and are now unable to pass.” The Commission arranged to have a fishway excavated out of the rock formation on the south side of Pit River Falls, in 1881, to enable the salmon to reach suitable spawning gravels above the falls (Throckmorton 1882). A new fishway was later constructed in 1902 (CFC 1904). Pit River Falls (65 ft high, according to Rutter) was “thought by many to rival in beauty any to be seen in the Yosemite Valley” (Rutter 1908, p 110), and which Rutter, in his 1904 paper, also stated had been impassable for salmon before the modification. Yet Rutter (1908, p 110) later noted that “each side is broken by ledges, so that it is possible in high water for fish to pass” — perhaps suggesting that salmon also could have surmounted the falls on the side opposite where the fishway was constructed. In fact, Powers (1874, p 413 and 1877, p 269), in discussing the first salmon ritual (probably for the spring run) of the Achumawi people on the Pit River, wrote: “After the vast crystal volume of Fall River enters and overcomes the swampiness of the snaky Pit, then salmon are caught, the Indians say, though the whites assert that they do not ascend above a certain tremendous cataract which is said to exist on the lower river.” That “tremendous cataract” undoubtedly was Pit River Falls and which may not have posed a complete barrier to the salmon, if the above statement is taken literally. Powers had made his observations on the Achumawi and other native groups during the early 1870s (primarily in the summers of 1870 and 1871; Heizer 1976), well before any attempt to modify Pit River Falls. However, Powers (1874, p 413) also stated in regard to salmon that, “they do not ascend the Pit to the mouth of Fall River,” and it is puzzling why salmon reputedly would not have ascended farther upstream to the Fall River once they had passed Pit River Falls. Overall, it seems likely that spring-run and perhaps winter-run salmon, if only in limited numbers, originally surmounted Pit River Falls and entered the Fall River some distance up its length — probably nine miles up to

the source springs near Dana. Kniffen (1928, p 312) correspondingly noted that the Fall River delimited the easternmost area where salmon were an important component of the native people's food economy in that region, and "Fall River also marked the upper limit of the salmon run." Likewise, Davis (1974, p 19) stated that the Achomawi and Atsugewi met "annually in the autumn in Fall River Valley when the winter supply of salmon was being laid in."

The historical abundance of salmon in the Fall River cannot be clearly determined. Young salmon were reportedly "common" in the Fall River in August 1898 (Rutter 1902). After construction of the new fishway in 1902, salmon were said to have passed over Pit River Falls "in considerable numbers" (Rutter 1908, p 110). It was reported that within two weeks of the opening of the new fishway (on 1 November 1902), "large numbers of salmon were found in Fall River...which was the first time they were seen in any numbers in those waters" (CFC 1904, p 52). Those fish were clearly fall-run salmon, and their newly observed occurrence in the Fall River indicates that the fall run previously had ascended only as far as Pit River Falls which barred their passage.

Clark (1929) stated that the spawning beds extended from the river mouth (where the river joins the McCloud and Little Sacramento rivers) to the Pit 4 dam, and there were suitable beds also in Squaw Creek and two or three smaller creeks. Access up the river was completely cut off by several power projects dams constructed during 1922-1927. Proceeding from the lowest to highest upriver, they were: Pit 4, seven miles below Burney and Burney Falls, 60 feet high and without fish passage facilities; Pit 3, nine miles above Pit 4, impassable to salmon; and Pit 1, near the town of Fall River Mills on the Fall River and also impassable (Clark 1929).

Stone (1874, p 176) stated that the salmon "come up Pit River in great numbers in the spring," but as the weather became warmer in late June or early July the salmon reportedly all "left Pit River for the colder waters of the McCloud." Stone thought it "probable that they ascend[ed] the upper waters of the Pit River also to a limited extent." Clark (1929) later noted both a spring run and a fall run occurring in the Pit River. Comparing with the earlier years of Stone's time, Clark described the salmon population in the Pit River in 1928 as "very small"; he mentioned statements from long-time residents of the river indicating that the Pit River formerly "was one of the best for salmon" but that the salmon had "decreased considerably" (Clark 1929, p 43). Based on observations made in July 1923, Clark estimated that "at the most" 150 to 200 salmon were stopped at the base of Pit 4 dam, and that they probably comprised the entire spring run (Clark 1929). As with the Little Sacramento and McCloud rivers, construction of Shasta Dam eliminated salmon runs into the Pit River drainage.

Cottonwood Creek (Tehama County). Cottonwood Creek, a tributary on the westside upper Sacramento Valley, historically supported both spring and fall runs and, presumably, also a late-fall run. The spring-run fish formerly migrated to the headwaters of the South and Middle forks of Cottonwood Creek—above Maple Gulch on the South Fork (Reynolds and others 1993) and about eight miles into Beegum Creek on the Middle Fork (DFG unpublished data). According to Hanson and others (1940), the North Fork has a two-part falls (15 ft and 10 ft high) that forms a natural barrier about five miles upstream of Ono; below the falls, the stream has only a limited amount of suitable pools and spawning gravel to support salmon.

The past abundance of salmon in Cottonwood Creek reportedly had been “considerable,” but by 1928 there was only “a very slight fall run” (Clark 1929, p 43). Clark stated that the salmon spawned near the mouth of the creek because low water flows did not allow them to ascend farther upstream. He reported the presence of an irrigation diversion (which lacked a fishway) 25 mi above the mouth on the South Fork, although salmon rarely reached that point, and several other smaller ditches for irrigation diversions. Holmberg (1972) also cited low streamflows as the primary factor limiting the salmon population in Cottonwood Creek, despite the presence of “excellent spawning grounds.”

In recent years before 1993, the fall, late-fall and hybrid fall-spring runs occurred in Cottonwood Creek (Reynolds and others 1993). Annual fall-run escapements ranged between “a few hundred” to >8,000 fish, averaging 1,000 to 1,500 (Reynolds and others 1993), and the latest escapements were about 700 fish in 1991 and 1,600 fish in 1992 (Kano 1998a, 1998b). The late-fall run numbered <500 fish, spawning in the mainstem and the lower reaches of the North, Middle, and South forks (Reynolds and others 1993). The spring run is believed to have averaged about 500 fish historically (Reynolds and others 1993), but there are no recent escapement estimates except for about 480 fish in 1998 (DFG 1998 unpublished data). Eight adult spring-run salmon were observed by DFG personnel during summer 1995 near the North and South forks (T. Healey, personal communication, see “Notes”). Low spring flows and high water temperatures may prevent the upstream migration of the spring run during some years (Reynolds and others 1993). In most recent years there has been only the bare remnants of a salmon run in Cottonwood Creek.

Stony Creek (Tehama County). Stony Creek is a west side tributary in the Sacramento drainage and formerly supported spring run and fall runs (Clark 1929). Stony Creek was said to have been “a very good salmon stream” before the placement of the irrigations dams (Clark 1929, p 45). Kroeber (1932, p 295), drawing from ethnographic data, stated that “Salmon, for instance, ran up Stony creek through Wintun as far as Salt Pomo territory.” The downstream (eastern) bor-

der of the Salt Pomo (Northeastern Pomo) tribe has been placed at the confluence of Stony Creek and Little Stony Creek, about five miles below Stonyford (Kroeber 1925, p 224, McLendon and Oswalt 1978), so that point would have been the minimal upstream range of salmon. By 1928, both spring and fall runs were nonexistent due to irrigation diversions that kept the stream dry except during the rainy season (Clark 1929). At that time, there were two permanent dams on the creek: the Orland Project Dam (20 ft high, built about 1914) four miles west of Stonyford, and a dam on Big Stony Creek (90 ft high, "too high for a fish ladder") (Clark 1929). There was also a dam across Stony Creek where an irrigation canal built by the Glenn Colusa Irrigation District (GCID) crossed the creek about three miles upstream of its mouth. This dam was usually washed out in high water, but most of the time it would have been a barrier to salmon, had there been any water in the creek (Clark 1929). Presently there are three storage reservoirs on the creek (Reynolds and others 1993). There is "excellent" spawning gravel within the about 20 miles of stream between the creek mouth and the lowermost dam, Black Butte Dam, which would be a barrier to salmon (Reynolds and others 1993). However, the GCID canal, which crosses Stony Creek downstream of Black Butte Dam, completely bars salmon migration any farther upstream (Reynolds and others 1993; USFWS 1995). This cross-stream barrier is now seldom washed out except when flood control releases are made from Black Butte Reservoir.

Miscellaneous Small Sacramento Valley Tributaries. In addition to Antelope, Cottonwood, and Stony creeks, more than a dozen other small tributaries in the northern Sacramento Valley occasionally supported fall-run salmon spawning stocks during the period 1940–1959 in years of early and heavy rains, and a few of those streams also had spring runs (Fry 1961). In Clear Creek, spring-run salmon were observed in 1949 and 1956 (Azevedo and Parkhurst 1958 unpublished report); they most likely ascended past the present site of Whiskeytown Reservoir to somewhere above the French Gulch area (about 1,400 ft elev.). Clear Creek in some years still supports a substantial fall run, which was estimated to have numbered up to 10,000 spawners in 1995 (DFG unpublished data). Thomes Creek supported a small spring run. Murphy (1946) observed three adult salmon in early August 1946 in a pool situated within The Gorge area below Lake Hollow, eight miles upstream from the town of Paskenta; however, no salmon were observed in that stream during a later survey in the 1960s (T. Healey, personal communication, see "Notes"). In contrast, spring-run salmon probably did not use the Cow Creek drainage to any significant extent either because there is no suitable over-summering habitat (specifically, deep bedrock pools), particularly lacking in the South Fork, or because natural barriers prevented access to the headwaters, as in the other forks. Fall-run salmon presently occur in the mainstem Cow Creek up to where the South Fork joins, and they ascend the South Fork up to Wagoner Canyon. In the North Fork Cow Creek, fall-run fish are stopped by falls near the Ditty Wells fire station of the California Department of Forestry. Occasionally, late-fall

run salmon also occur in Cow Creek. Fall-run salmon reportedly migrated 20 mi up Stillwater Creek to spawn in 1938, when the fall rains began early (Hanson and others 1940). Cache and Putah creeks, two intermittent streams on the westside lower Sacramento drainage, have supported fall salmon runs only during wet years within historical times (Shapovalov 1947). Decades ago, salmon were observed as far upstream as Capay Dam in Cache Creek (Hanson and others 1940, Shapovalov 1947) and near the town of Monticello in Putah Creek (Shapovalov 1947). Based on archaeological remains from earlier times (about AD 1450–1650), Putah Creek long ago provided salmon to the local Native Americans in at least some minor quantity (Schulz 1994 unpublished manuscript). Fry (1961) reported that the combined fall runs (including late-fall) for the miscellaneous Sacramento tributary streams totaled 1,000 to 13,000 fish annually during 1940–1959. The spring-run totals, available for only three years in that period, were <500 fish in both 1944 and 1945 and 1,000 fish in 1956 (Fry 1961). During 1953–1969, the Cow Creek drainage alone supported a fall run that averaged 2,800 fish (Reynolds and others 1993). In most recent years, the combined fall run in these miscellaneous streams, if existent, has been inconsequential and the spring run essentially has not occurred (Reynolds and others 1993).

Conclusion: Quantitative Assessment of Distributional Changes

It has been estimated that before the placement of man-made obstructions in the streams of the Sacramento and San Joaquin drainages there were “at least 6000 linear miles of streambed suitable and available to spawning salmon” (Clark 1929), although the process by which that figure was determined was not explained. Given the sheer magnitude of that estimate, it is evident that not only spawning habitat but all lengths of stream traversed or occupied by salmon (migration corridors and holding areas) were included. The actual amount of spawning habitat that was originally used by, or available to, Central Valley salmon is not clearly known but as early as 1918 the California Fish and Game Commission (CFG) acknowledged that “Fully 80 per cent of the natural spawning grounds of the Sacramento River basin have been destroyed by the mines, and dams constructed for the purpose of generating electricity, and by the diverting of water for irrigation purposes” (CFG 1921a, p 20). For the period 1924–1926, the CFG reported that “approximately 90 per cent of the spawning areas in these two river systems [Sacramento and San Joaquin rivers] have been cut off from the salmon or destroyed” (CFG 1927, p 35). By 1928, the amount of spawning stream habitat in the entire Central Valley drainage had been reduced to an estimated 510 linear miles with reportedly “At least 80 per cent of the spawning grounds...cut off by obstructions” — which included 11 dams in the San Joaquin system and 35 dams in the Sacramento system that posed partial or complete barriers to salmon (Clark 1929, p 28). Van Cleve (1945) later estimated a somewhat lesser loss of 75% of the orig-

inal spawning habitat due to all causes. In 1993, the total amount of existent spawning habitat for salmon and steelhead in the Central Valley drainage was estimated by the California Department of Fish and Game to be less than 300 miles (Reynolds and others 1993).

We estimated from map distances the stream lengths that have been lost as salmon habitat in each of the major Central Valley watersheds due to installation of barriers or the reduction of streamflows that made passage of salmon impossible under usual conditions (Table 2). We included reaches of streams which salmon are known or can be inferred to have had access to, whether for holding or spawning purposes. These estimated stream lengths are minimal estimates because we have considered only the mainstems and the major forks and tributaries as salmon habitat. Numerous small third- and fourth-order streams very likely were used to some degree by spawning salmon, for which records do not exist, although the numbers of salmon using those smaller streams would have been relatively small. In fact, the full extent of the historical distribution of salmon even in the major stream reaches is not clearly known for some watersheds (for example, Middle Fork American River, mainstem and South Fork Merced River). Furthermore, recent studies have shown that juvenile salmon in large numbers, and some steelhead, enter small temporary streams for rearing (for example, Rock, Mud, Pine, and Toomes creeks in the northern Sacramento Valley) even though spawning by salmon may not necessarily occur in those streams (Maslin and McKinney 1994 unpublished report). Undoubtedly, salmon historically used those and other non-natal "nursery" streams, as probably did steelhead (IEP 1998 unpublished report), but we have no way of accurately assessing the distributional extent of such usage.

Based on the available information, our estimates indicate that the amount of habitat that was lost differs greatly from watershed to watershed. In the Bear River, for example, the length of stream accessible to salmon has changed very little, while in Deer Creek it actually has increased by several miles due to artificially improved fish passage over natural barriers. In lower Battle Creek, the salmon were blocked for many years by the Coleman National Fish Hatchery weir, but in recent years access to upstream reaches has been reopened for the winter- and spring-run fish so that much of the historical range is again available to those runs. However, in most watersheds considerable portions of the former salmon-supporting reaches are no longer accessible to salmon, and some watersheds have been entirely removed from salmon production—namely, McCloud, Pit, Upper (Little) Sacramento, and upper San Joaquin rivers. The general pattern has been the elimination of the higher foothill and mountain reaches in the Sierra Nevada and Cascades from the distributional range of chinook salmon.

Summing the stream-by-stream estimates of accessible salmon habitat (for streams tabulated in Table 2) yields a total of 1,126 mi of main stream lengths presently remaining of the more than 2,183 mi of Central Valley streams that we estimate were originally available to chinook salmon—indicating an overall loss of at least 1,057 mi or 48% of the original total. Our estimate of 1,126 mi is remarkably similar to the figure of 1,075 mi of “chinook habitat” in the Central Valley given by Holmberg (1972) almost three decades ago. Our calculations did not include the Sacramento-San Joaquin Delta, comprising about 700 mi of river channels and sloughs (USFWS 1995), available to various degrees as migration corridors or rearing areas for salmon. In contrast to most previously cited estimates specifying only spawning habitat, our figures include the lengths of stream used by salmon mainly as migration corridors (for example, the lower Sacramento and San Joaquin rivers) in addition to holding and spawning habitat. Our figures include about 200 mi in the lower Sacramento River (below Tehama), about 50 mi in the lower San Joaquin River (below the confluence of the Merced River), and the lower reaches of several tributaries which contain no spawning habitat. It is likely that those lower Sacramento and San Joaquin reaches historically were used as rearing areas (at least during some flow regimes) as the juveniles moved downstream, but in recently they have been less suitable for rearing due to alterations in channel morphology and other degraded environmental conditions. In terms of only spawning and holding habitat, the proportionate loss far exceeds 48% because a relatively large portion of the original spawning habitat was located in upper stream reaches that have been cut off by dams. In contrast, much of the remaining lengths of stream in the lower drainages now traversed by salmon cannot be used for spawning. Of the total length of stream courses presently accessible, less than one-third in the San Joaquin River drainage and probably less than a half in the Sacramento River drainage are suitable as spawning habitat. Excluding the lower stream courses that were used only as adult migration corridors (and only minimally for juvenile rearing)—by our estimate amounting to 709 stream miles—we roughly calculate that at least 72% of the original spawning and holding habitat for salmon in the Central Valley drainage is no longer available. Thus, the DFG’s most recent assessment that about 95% of the original spawning habitat has been lost is perhaps somewhat high but probably roughly accurate (Reynolds and others 1993). However, the earlier estimate by Clark (1929, p 28) that there were “at least 6,000 linear miles of stream bed suitable and available to spawning salmon” probably is overly high by a factor of three.

The amount of habitat loss for steelhead most likely was much higher than that for salmon because steelhead were undoubtedly more extensively distributed. Due to their superior leaping and swimming ability, the timing of their upstream migration which coincided with the winter rainy season, and their less restrictive preferences for spawning gravels, steelhead could have used at least hundreds of miles of smaller tributaries not accessible to even the highest migrating winter-run and spring-run salmon.

Table 2 Estimated changes in lengths of stream available to chinook salmon in the major salmon-supporting watersheds of the California Central Valley ^a

| <i>Watershed</i> | <i>Length (mi) of stream historically available ^b</i> | <i>Length (mi) of stream presently accessible ^c</i> | <i>Length (mi) of stream lost (or gained) ^d</i> | <i>Percent lost (or gained)</i> |
|-------------------------------------|--|--|--|---------------------------------|
| Sacramento River Basin | | | | |
| Mainstem Sacramento R. ^e | 299 | 286 | 13 | 4 |
| Pit River | 99 | 0 | 99 | 100 |
| McCloud River | 50 | 0 | 50 | 100 |
| Upper (Little) Sacramento R. | 52 | 0 | 52 | 100 |
| Eastside Streams | | | | |
| Battle Creek | 43 | 6 [43] ^f | 0 | 0 |
| Antelope Creek | 32 | 32 | 0 | 0 |
| Mill Creek | 44 | 44 | 0 | 0 |
| Deer Creek | 34 | 38 | (4) | (12) |
| Big Chico Creek | 24 | 24 | 0 | 0 |
| Butte Creek | >53 | 53 | >0 | >0 |
| Feather River | 211 | 64 | 147 | 70 |
| Yuba River | 80 | 24 | 56 | 70 |
| Bear River | 16 | 16 | 0 | 0 |
| American River | 161 | 28 | 133 | 83 |

^a The estimates for stream lengths originally available and subsequently lost are in most cases minimal values because the full extent of the former salmon distributions in individual streams is incompletely known. Additional minor streams such as Thomes, Paynes, Cache, and Putah creeks (and perhaps a dozen others in the Sacramento Valley) historically supported salmon (Fry 1961)—probably only the fall run and only during wet years. The historical upstream limits of salmon in those streams is too poorly known to allow inclusion in this table. Current salmon production in those streams is limited because of a number of factors, including low streamflows, habitat degradation and obstruction by irrigation canal crossings (DFG 1993).

^b Lengths of all stream reaches known or presumed to have been traversed or used by salmon in the drainage are included.

^c Length between the mouth of the stream and the current upstream limit.

^d Length of stream gained is given in parentheses; this situation applies only to Deer Creek.

^e From Rio Vista in the north Sacramento-San Joaquin Delta upstream to the confluence of the Upper (Little) Sacramento and Pit rivers.

^f First number pertains to the fall run; second number [in brackets] pertains to the spring and winter runs. The fall run in Battle Creek is stopped by the Coleman National Fish Hatchery weir, six miles above the mouth; the fall run's historical upper limit is not known, but we presume it was not much further upstream of the current limit at the hatchery weir. Spring-run and winter-run salmon currently are allowed to pass upstream and probably ascend to much of the historical range (that is, an additional 37 stream miles above the hatchery weir).

^g From Mossdale in the south Sacramento-San Joaquin Delta upstream to the confluence of the Merced River. This stretch lacks spawning gravels and serves primarily as a migration corridor.

^h Includes the mainstem San Joaquin River above the confluence of the Merced River.

Table 2 Estimated changes in lengths of stream available to chinook salmon in the major salmon-supporting watersheds of the California Central Valley ^a (Continued)

| <i>Watershed</i> | <i>Length (mi) of stream historically available ^b</i> | <i>Length (mi) of stream presently accessible ^c</i> | <i>Length (mi) of stream lost (or gained) ^d</i> | <i>Percent lost (or gained)</i> |
|---|--|--|--|---------------------------------|
| Westside Streams | | | | |
| Clear Creek | 25 | 16 | 9 | 36 |
| Cottonwood Creek | 79 | 79 | 0 | 0 |
| Stony Creek | 54 | 3 | 51 | 94 |
| Cow Creek | 32 | 32 | 0 | 0 |
| San Joaquin River Basin and Sacramento-San Joaquin Delta | | | | |
| Lower San Joaquin R. ^g | 50 | 50 | 0 | 0 |
| Cosumnes River | 31 | 31 | 0 | 0 |
| Mokelumne River | 92 | 64 | 28 | 30 |
| Calaveras River | approx. 38 | 38 | 0? | 0? |
| Stanislaus River | 124 | 58 | 66 | 53 |
| Tuolumne River | 104 | 52 | 52 | 50 |
| Merced River | 107 | 51 | 56 | 52 |
| Upper San Joaquin R. ^h | 173 | 0 | 173 | 100 |
| Kings River | 76 | 0 | 76 | 100 |
| Central Valley Total | 2183 | 1126 | 1057 | 48 |

^a The estimates for stream lengths originally available and subsequently lost are in most cases minimal values because the full extent of the former salmon distributions in individual streams is incompletely known. Additional minor streams such as Thomes, Paynes, Cache, and Putah creeks (and perhaps a dozen others in the Sacramento Valley) historically supported salmon (Fry 1961)—probably only the fall run and only during wet years. The historical upstream limits of salmon in those streams is too poorly known to allow inclusion in this table. Current salmon production in those streams is limited because of a number of factors, including low streamflows, habitat degradation and obstruction by irrigation canal crossings (DFG 1993).

^b Lengths of all stream reaches known or presumed to have been traversed or used by salmon in the drainage are included.

^c Length between the mouth of the stream and the current upstream limit.

^d Length of stream gained is given in parentheses; this situation applies only to Deer Creek.

^e From Rio Vista in the north Sacramento-San Joaquin Delta upstream to the confluence of the Upper (Little) Sacramento and Pit rivers.

^f First number pertains to the fall run; second number [in brackets] pertains to the spring and winter runs. The fall run in Battle Creek is stopped by the Coleman National Fish Hatchery weir, six miles above the mouth; the fall run's historical upper limit is not known, but we presume it was not much further upstream of the current limit at the hatchery weir. Spring-run and winter-run salmon currently are allowed to pass upstream and probably ascend to much of the historical range (that is, an additional 37 stream miles above the hatchery weir).

^g From Mossdale in the south Sacramento-San Joaquin Delta upstream to the confluence of the Merced River. This stretch lacks spawning gravels and serves primarily as a migration corridor.

^h Includes the mainstem San Joaquin River above the confluence of the Merced River.

Acknowledgments

The collective knowledge represented in this report is derived largely from the field experiences of many fishery biologists. We thank our colleagues who contributed their time and information. We are especially indebted to J. B. Snyder, Historian for Yosemite National Park, who provided extensive historical information on salmon in the Merced River, and to J. Nelson (DFG) and T. J. Ford (Turlock and Modesto Irrigation Districts) for data on other streams. We are pleased to acknowledge funding support from the Giles W. and Elise G. Mead Foundation and the Sierra Nevada Ecosystem Project as authorized by Congress (HR 5503) through cost-reimbursement agreement No. PSW-93-001-CRA between the US Forest Service, Pacific Southwest Research Station, and the Regents of the University of California. Additional funding was provided by the Southern California Edison Company and Pacific Gas & Electric Company.

References

- Aginsky BW. 1943. Culture element distributions: XXIV Central Sierra. *Univ Calif Publ Anthropol Rec* 8(4):390-468.
- Angel M. 1882. *History of Placer County, California, with illustrations and biographical sketches of its prominent men and pioneers*. Oakland (CA): Thompson & West. 416 p.
- Audubon JW. 1906. *Audubon's western journal: 1849-1850. Being the MS record of a trip from New York to Texas, and an overland journey through Mexico and Arizona to the gold-fields of California*. Cleveland (OH): Arthur H. Clark. 243 p.
- Barnhart RA. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Southwest). Steelhead. US Fish Wildl Ser Biol Rep 82(11.60), US Army Corps of Engineers, TR EL-82-4. Washington, DC. 21 p.
- Barrett SA, Gifford EW. 1933. Miwok material culture. *Bull Milwaukee Public Mus* 2(4):125-277.
- Bates DB. 1857. *Incidents on land and water, or four years on the Pacific Coast*. Boston (MA): James French. 336 p.
- Beacham TD, Murray CD. 1990. Temperature, egg sizes, and development of embryos and alevins of five species of Pacific salmon: a comparative analysis. *Trans Am Fish Soc* 119(6):927-45.

- Beals RL. 1933. Ethnology of the Nisenan. *Univ Calif Publ Am Archaeol Ethnol* 31:335–410.
- Bennyhoff JA. 1977. Ethnogeography of the Plains Miwok. Center for Archaeological Research at Davis, Publ. nr. 5. Davis (CA): University of California. 181 p.
- Bidwell AEK. 1980. Rancho Chico indians. Hill DJ, editor. Chico (CA): Bidwell Mansion Cooperating Assoc. 72 p.
- Black M. 2001. Shasta salmon salvage efforts: Coleman National Fish Hatchery on Battle Creek, 1895–1992. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1*. Sacramento (CA): California Department of Fish and Game.
- Blake WP. 1857. Geological report nr. 1. Itinerary, or notes and general observations upon the geology of the route. Explorations and surveys for a railroad route from the Mississippi River to the Pacific Ocean. Volume 5, Part II. Washington, DC: War Department.
- Bolton HE. 1930a. Anza's California expeditions. Volume III. The San Francisco Colony. Diaries of Anza, Font, and Eixarch, and narratives by Palóu and Moraga. Berkeley (CA): Univ Calif Pr. 436 p.
- Bolton HE. 1930b. Anza's California expeditions. Vol. IV. Font's complete diary of the second Anza expedition. Berkeley (CA): Univ Calif Pr. 552 p.
- Borthwick JD. 1857. Three years in California. Edinburgh: William Blackwood & Sons. 318 p.
- Bryant E. 1849. What I saw in California: being the journal of a tour, in the years 1846, 1847. New York (NY): D Appleton. 480 p.
- Buffum EG. 1959. Six months in the gold mines: from a journal of three years' residence in upper and lower California 1847–8–9. Caughey JW, editor. Los Angeles (CA): Ward Ritchie Pr. 145 p.
- Bunnell LH. 1990. Discovery of the Yosemite and the Indian War of 1851 which led to that event. Yosemite National Park (CA): Yosemite Assoc. 315 p.
- [DFG] California Department of Fish and Game. 1929. Division of Fish and Game thirtieth biennial report for 1926–1928. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1944. Division of Fish and Game thirty-eighth biennial report for 1942–1944. Sacramento (CA): California Department of Fish and Game.

- [DFG] California Department of Fish and Game. 1946. Division of Fish and Game thirty-ninth biennial report for 1944-1946. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1948. Division of Fish and Game fortieth biennial report for 1946-1948. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1950. Division of Fish and Game forty-first biennial report for 1948-1950. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1953. Division of Fish and Game forty-second biennial report for 1950-1952. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1960. Division of Fish and Game forty-sixth biennial report, July 1, 1958 through June 30, 1960. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1972. Report to the California State Water Resources Control Board on effects of the New Melones Project on fish and wildlife resources of the Stanislaus River and Sacramento-San Joaquin Delta. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1974. Feather River Hatchery administrative report 74-5. Sacramento (CA): California Department of Fish and Game.
- [DFG] California Department of Fish and Game. 1990. Status and management of spring-run chinook salmon. Report by Inland Fisheries Division to California Fish and Game Commission. Sacramento (CA): California Department of Fish and Game. 33 p.
- [DFG] California Department of Fish and Game. 1996. San Joaquin River chinook salmon enhancement. Annual report, fiscal year 1994-1995. Sacramento (CA): California Department of Fish and Game, Region 4. February 1996.
- [DFG] California Department of Fish and Game. 1998. A status review of the spring-run chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River drainage. Report to California Fish and Game Commission. Candidate species status report 98-1. June 1998. Sacramento (CA): California Department of Fish and Game. 378 p.
- Campbell EA, Moyle PB. 1991. Historical and recent population sizes of spring-run chinook salmon in California. In: American Fisheries Society Proceedings, 1990 Northwest Pacific chinook and coho salmon workshop. Arcata (CA): Humboldt State University. p 155-216.

- Carson JH. 1852. Recollections of the California mines. An account of the early discoveries of gold, with anecdotes and sketches of California and miners' life, and a description of the Great Tulare Valley. Reprinted in 1950. Oakland (CA): Bio-books. 113 p.
- Cassidy J, Daley-Hutter M, Nelson C, Shepherd L. 1981. Guide to three rivers. The Stanislaus, Tuolumne and South Fork of the American. San Francisco (CA): Friends of the River Books. 295 p.
- Caton JD. 1869. Trout fishing in the Yosemite Valley. *American Naturalist* 3:519-22.
- [CFGC] California Fish and Game Commission. 1914. Twenty-third Biennial Report for 1912-1914. Sacramento (CA): California Fish and Game Commission.
- [CFGC] California Fish and Game Commission. 1921a. Report of the Department of Fish Culture. Twenty-sixth Biennial Report for 1918-1920. Sacramento (CA): California Fish and Game Commission. p 19-22.
- [CFGC] California Fish and Game Commission. 1921b. San Joaquin River salmon. In: Shebley WH, editor. Hatchery notes. *California Fish and Game* 7(1):51-2.
- [CFGC] California Fish and Game Commission. 1921c. An important decision on the fishway law. *California Fish and Game* 7(3):154-6.
- [CFGC] California Fish and Game Commission. 1923. Twenty-seventh biennial report for 1920-1922. Sacramento, Calif.
- [CFGC] California Fish and Game Commission. 1927. Report of the Department of Fish Culture. Twenty-ninth biennial report for 1924-1926. Sacramento, Calif. p 33-8.
- [CFC] California State Board of Fish Commissioners. 1871. (1st) Rep. Comm. Fish. State of California for 1870 and 1871. Reprinted in January 1933. *California Fish and Game* 19(1):41-56.
- [CFC] California State Board of Fish Commissioners. 1875. (3rd) Rep. Comm. Fish. of the State of California for 1874 and 1875. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1877. (4th) Rep. Comm. Fish. of the State of California for 1876 and 1877. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1880. (6th) Rep. Comm. Fish. of the State of California for 1880. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1884. (8th) Biennial Rep. Comm. Fish. of the State of California for 1883-4. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1886. (9th) Biennial Rep. Comm. Fish. of the State of California for 1885-1886. Sacramento, Calif.

- [CFC] California State Board of Fish Commissioners. 1888. (10th) Biennial Rep. Comm. Fish. of the State of California for 1886–1888. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1890. (11th) Biennial Rep. Comm. Fish. of the State of California for 1888–1890. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1896. Fourteenth Biennial Rep. Comm. Fish. of the State of California for 1895–1896. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1900a. Fifteenth Biennial Rep. Comm. Fish. of the State of California for 1897–1898. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1900b. Sixteenth Biennial Rep. Comm. Fish. of the State of California for 1899–1900. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1904. Eighteenth Biennial Rep. Comm. Fish. of the State of California for 1903–1904. Sacramento, Calif.
- [CFC] California State Board of Fish Commissioners. 1907. Nineteenth Biennial Rep. Comm. Fish. of the State of California for 1905–1906. Sacramento, Calif.
- Chamberlain WH, Wells HL. 1879. History of Sutter County, California. Oakland (CA): Thompson & West. 127 p. Reprinted in 1974. Berkeley (CA): Howell-North.
- Clark GH. 1929. Sacramento-San Joaquin salmon (*Oncorhynchus tshawytscha*) fishery of California Division of Fish and Game. Fish Bulletin 17. p 1–73.
- Clark GH. 1930. Salmon spawning in drainage canals in the San Joaquin Valley. California Fish and Game 16(3):270.
- Clark GH. 1943. Salmon at Friant Dam – 1942. California Fish and Game 29(3):89–91.
- Clark WVT. 1973. The journals of Alfred Doten 1849–1903. Volume 1. Reno (CA): Univ Nevada Pr. 808 p.
- Coleman CM. 1952. PG and E of California. The centennial story of Pacific Gas and Electric Company 1852–1952. New York (NY): McGraw-Hill. 385 p.
- Collins C. 1949. Sam Ward in the gold rush. Stanford (CA): Stanford Univ Pr. 189 p.
- Collins JW. 1892. Report on the fisheries of the Pacific coast of the United States. US Comm. Fish and Fish., Rep. Comm. for 1888. Appendix 1:3–269.
- Cook SF. 1955. The aboriginal population of the San Joaquin Valley, California. Univ Calif Publ Anthropol Rec 16:31–80.
- Cook SF. 1960. Colonial expeditions to the interior of California. Central Valley, 1800–1820. Univ Calif Publ Anthropol Rec 16:239–92.

- [CRA] California Resources Agency. 1972. California protective waterway plan, 1972. Appendix by C. Trost. Sacramento, Calif.
- [CSHA] California State Historical Association. 1929. Millerton, landmark of a vanished frontier. *California History Nugget* 2:114–7.
- Curtis ES. 1924a. *The North American Indian*. Volume 13. Reprinted in 1970. New York (NY): Johnson Reprint. 316 p.
- Curtis ES. 1924b. *The North American Indian*. Volume 14. Reprinted in 1970. New York (NY): Johnson Reprint. 284 p.
- Cutter DC. 1950. Spanish exploration of California's Central Valley [PhD dissertation]. Berkeley (CA): Univ Calif Pr. 275 p.
- Cutter DC. 1957. *Diary of Ensign Gabriel Moraga's expedition of discovery in the Sacramento Valley 1808*. Los Angeles (CA): Glen Dawson Pr. 37 p.
- Davis WN, Jr. 1974. *California Indians 5. Sagebrush corner. The opening of California's northeast*. New York (NY): Garland Publishing. 553 p.
- Dillon R. 1975. *Siskiyou Trail. The Hudson's Bay Company route to California*. New York (NY): McGraw-Hill. 381 p.
- Du Bois C. 1935. Wintu ethnography. *Univ Calif Publ Am Archaeol Ethnol* 36:1–148.
- EA Engineering, Science and Technology. 1990. Report to the Federal Regulatory Commission. Application for license – major unconstructed project. Clavey River Project Nr. 100181. Exhibit E, report 3: fish, wildlife, and botanical resources. Submitted by Tuolumne County and Turlock Irrigation District.
- EA Engineering, Science and Technology. 1992. Lower Tuolumne River spawning gravel availability and superimposition report. EA Engineering Fishery Report, Appendix 6. February 1992.
- Eigenmann CH. 1890. The food fishes of the California fresh waters. (11th) Biennial report of the State Board Fish Comm. of the State of California for 1888–1890. Sacramento, Calif. p 53–65.
- Elliott WW. 1882. *History of Fresno County, California, with illustrations*. San Francisco (CA): W Elliott & Co. 258 p. Reprinted in 1973. Fresno (CA): Valley Publishers.
- Fariss [no initials], Smith CL. 1882. *Fariss and Smith's History of Plumas, Lassen and Sierra counties, California, and biographical sketches of their prominent men and pioneers*. Reprinted in 1971. Berkeley (CA): Howell-North. 507 p.

- [FERC] Federal Energy Regulatory Commission. 1993. Final Environmental Impact Statement. Proposed modifications to the lower Mokelumne River Project, California. FERC project nr. 2916-004. November 1993. 624 p.
- Ferguson AD. 1914. General conditions and some important problems. State of California Fish and Game Comm. In: Twenty-third biennial report for 1912-1914. Sacramento, Calif. p 27-9.
- Fisher FW. 1994. Past and present status of Central Valley chinook salmon. *Conserv Biol* 8(3):870-3.
- Frémont JC. 1848. Geographical memoir upon Upper California, in illustration of his map of Oregon and California. Report to the US Senate, 30th Congress, 1st Session, Misc. nr. 148. Washington, DC. 64 p.
- Fry DH, Jr. 1961. King salmon spawning stocks of the California Central Valley, 1940-1959. *California Fish and Game* 47(1):55-71.
- Garth TR. 1953. Atsugewi ethnography. *Univ Calif Anthropol Rec* 14(2):129-212.
- Garth TR. 1978. Atsugewi. In: Heizer RF, editor. *Handbook of North American Indians*. Volume 8. California. Washington, DC: Smithsonian Inst. p 236-248.
- Gay T. 1967. James W. Marshall. The discoverer of California gold. A biography. Georgetown (CA): Talisman Pr. 558 p.
- Gayton AH. 1936. Estudillo among the Yokuts: 1819. In: *Essays in anthropology present to A.L. Kroeber in celebration of his sixtieth birthday June 11, 1936*. Berkeley (CA): Univ Calif Pr. p 67-85.
- Gayton AH. 1946. Culture-environment integration: external references in Yokuts life. *Southwestern J Anthropol* 2:252-68.
- Gayton AH. 1948a. Yokuts and Western Mono ethnography I: Tulare Lake, Southern Valley, and Central Foothill Yokuts. *Univ Calif Publ Anthropol Rec* 10:1-142.
- Gayton AH. 1948b. Yokuts and Western Mono ethnography II: Northern Foothill Yokuts and Western Mono. *Univ Calif Publ Anthropol Rec* 10:143-302.
- Gerstung ER. 1989. Fishes and fishing in the forks of the American River: then and now. In: *The American River. North, Middle and South forks*. Auburn (CA): Wilderness Conservancy. *Protect American River Canyons*. 320 p.
- Gifford EW. 1932. The Northfork Mono. *Univ Calif Publ Am Archaeol Ethnol* 31:15-65.
- Gilbert FT. 1879. *History of San Joaquin County, California*. Oakland (CA): Thompson & West. Reprinted in 1968. Berkeley (CA): Howell-North. 142 p.

- Gilbert GK. 1917. Hydraulic-mining debris in the Sierra Nevada. US Geological Survey professional paper nr. 105. Washington, DC.
- Green LW. 1887. Salmon in the McCloud River during the season of 1886. Bull US Fish Comm 6(1886):334-6.
- Gudde EG. 1962. Bigler's chronicle of the West. The conquest of California, discovery of gold, and Mormon settlement as reflected in Henry William Bigler's diaries. Berkeley (CA): Univ Calif Pr. 145 p.
- Guilford-Kardell M, Dotta J. 1980. Papers on Wintu ethnography: 239 Wintu villages in Shasta County circa 1850. Occasional papers of the Redding Museum nr. 1. Redding (CA): Redding Mus Art Center. 131 p.
- Hallock RJ, Fry DH Jr., LaFaunce DA. 1957. The use of wire fyke traps to estimate the runs of adult salmon and steelhead in the Sacramento River. California Fish and Game 43(4):271-98.
- Hallock RJ, Van Woert WF. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin Rivers. California Fish and Game 45(4):227-96.
- Hallock RJ, Van Woert WF, Shapovalov L. 1961. An evaluation of stocking hatchery-reared steelhead rainbow trout (*Salmo gairdnerii gairdnerii*) in the Sacramento River system. Fish Bulletin 114. p 1-74.
- Hanson HA, Smith OR, Needham PR. 1940. An investigation of fish-salvage problems in relation to Shasta Dam. US Bur Fish Spec Sci Rep nr. 10. Washington, DC. 202 p.
- Hatton SR. 1940. Progress report on the Central Valley fisheries investigations. California Fish and Game 26(4):334-73.
- Hatton SR, Clark GH. 1942. A second progress report on the Central Valley fisheries investigations. California Fish and Game 28(2):116-23.
- Healey MC. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). In: Groot C, Margolis L, editors. Pacific salmon life histories. Vancouver, BC: Univ British Columbia Pr. p 313-393.
- Hedgpeth JW. 1941. Livingston Stone and fish culture in California. California Fish and Game 27(3):126-48.
- Heizer RF, editor. 1967. Ethnographic notes on California Indian Tribes III. Ethnological notes on central California Indian tribes, by C. Hart Merriam. Reports of the Univ Calif Archaeol Surv nr. 68. Part III. p 257-448.
- Heizer RF, editor. 1976. A collection of ethnographic articles on the California Indians. Ramona (CA): Ballena Pr. 103 p.

- Heizer RF. 1993. The destruction of California Indians. Lincoln (NE): Univ Nebraska Pr. 321 p.
- Holmberg JJ. 1972. Salmon in California. Report for the US Bureau of Reclamation, Division of Planning, March 1972. Sacramento, Calif. 91 p.
- Hubbs CL. 1946. Wandering pink salmon and other salmonid fishes into Southern California. *California Fish and Game* 32(2):81-6.
- Hutchings JM. 1990. Yosemite Valley and the Big Tree Groves. In: Browning P, editor. *The heart of the Sierras*. Lafayette (CA): Great West. 505 p.
- Jacobs D, Chatfield E, Kiley L, Kondolf GM, Loyd L, Smith F, Walker D, Walker K. 1993. *California's rivers. A public trust report*. Sacramento (CA): California State Lands Commission. 334 p.
- Jewell DP. 1987. *Indians of the Feather River. Tales and legends of the Concow Maidu of California*. Menlo Park (CA): Ballena Pr. 184 p.
- Johnson JJ. 1978. The Yana. In: Heizer RF, editor. *Handbook of North American Indians*. Volume 8. California. Washington, DC: Smithsonian Inst. p 361-369.
- Kano RM. 1998a. Annual report. Chinook salmon spawner stocks in California's Central Valley, 1991. *Inland Fisheries administrative report nr. 98-8*. Sacramento (CA): California Department of Fish and Game. 40 p.
- Kano RM. 1998b. Annual report. Chinook salmon spawner stocks in California's Central Valley, 1992. *Inland Fisheries administrative report nr. 98-10*. Sacramento (CA): California Department of Fish and Game. 40 p.
- Kelley R. 1989. *Battling the inland sea. American political culture, public policy, and the Sacramento Valley 1850-1986*. Berkeley (CA): Univ Calif Pr. 395 p.
- Kelly W. 1950. *A stroll through the diggings of California*. Oakland (CA): Biobooks. 206 p.
- Kniffen F. 1928. Achomawi geography. *Univ Calif Publ Am Archaeol Ethnol* 23:297-332.
- Kroeber AL. 1925. *Handbook of the Indians of California*. Bur Am Ethnol Smithsonian Inst Bull 78:1-995. Reprinted in 1976. New York (NY): Dover.
- Kroeber AL. 1932. The Patwin and their neighbors. *Univ Calif Publ Am Archaeol Ethnol* 29:253-423.
- Latta FF. 1929. Uncle Jeff's story. A tale of a San Joaquin Valley pioneer and his life with the Yokuts Indians. *Tulare (CA): Pr Tulare Times*. 88 p.
- Latta FF. 1977. *Handbook of Yokuts Indians*. Santa Cruz (CA): Bear State. 765 p.

- Lawrence JH. 1884. Discovery of the Nevada Fall. October 1884, second series. Overland Monthly 4(22):360-71.
- Leach GC. 1922. Propagation and distribution of food fishes, 1921. Report of the US Commission of Fisheries for 1921. Appendix IX. p 26-7.
- Leach GC. 1923. Propagation and distribution of food fishes, 1922. Report of the US Commission of Fisheries for 1922. Appendix XVII. p 39-40.
- Lee GD. 1998. Walking where we lived. Memoirs of a Mono Indian family. Norman (OK): Univ Oklahoma Pr. 208 p.
- Maloney AB, editor. 1943. Fur brigade to the Bonaventura. John Work's California expedition of 1832-1833 for the Hudson's Bay Company. Calif Hist Soc Quart 22:193-222, 323-48.
- Maniery JG. 1983. A chronicle of Murphys Rancheria (Mol-Pee-So): an historic Central Sierra Miwok village. J Calif Great Basin Anthropol 5(1 and 2):176-98.
- McEvoy AF. 1986. The fisherman's problem. Ecology and law in the California fisheries, 1850-1980. New York (NY): Cambridge Univ Pr. 368 p.
- McEwan D, Jackson TA. 1996. Steelhead restoration and management plan for California. Sacramento (CA): California Department of Fish and Game. 234 p.
- McGregor EA. 1922. Migrating salmon at Redding Dam. Calif Fish and Game 8(3): 141-54.
- McLendon S, Oswalt RL. 1978. Pomo: introduction. In: Heizer RF, editor. Handbook of North American Indians. Volume 8. California. Washington, DC: Smithsonian Inst. p 274-88.
- Moffett JW. 1949. The first four years of king salmon maintenance below Shasta Dam, Sacramento River, California. California Fish and Game 35(2):77-102.
- Morgan DL. 1970. In pursuit of the golden dream. Reminiscences of San Francisco and the northern and southern mines, 1849-1857, by Howard C. Gardiner. Stoughton (MA): Western Hemisphere. 390 p.
- Moyle PB. 1970. Occurrence of king (chinook) salmon in the Kings River, Fresno County. California Fish and Game 56(4):314-5.
- Moyle PB. 1976. Inland fishes of California. Berkeley (CA): Univ Calif Pr. 405 p.
- Muir J. 1902. Our National Parks. Boston (MA): Houghton Mifflin. 370 p.
- Muir J. 1938. John of the Mountains. In: Wolfe LM, editor. The unpublished journals of John Muir. Boston (MA): Houghton Mifflin. 459 p.

- Muir J. 1961. *The mountains of California*. Garden City (NY): Doubleday. 300 p.
- Muir J. 1988. *The Yosemite*. San Francisco (CA): Sierra Club. 215 p.
- Murphy GI. 1946. A survey of Stony Creek, Grindstone Creek and Thomes Creek drainages in Glenn, Colusa and Tehama counties, California. Inland Fisheries Branch administrative report nr. 46-14. Sacramento (CA): California Department of Fish and Game.
- [NCHRSP] Northern California Historical Records Survey Project. 1940. Inventory of the county archives of California. No. 10. Fresno County (Fresno). Division of Professional and Science Projects, Work Projects Administration. July 1940.
- Needham PR, Hanson HA, Parker LP. 1943. Supplementary report on investigations of fish-salvage problems in relation to Shasta Dam. US Fish Wildl Serv Spec Sci Rep 26. 30 June 1943. 52 p.
- Needham PR, Smith OR, Hanson HA. 1941. Salmon salvage problems in relation to Shasta Dam, California, and notes on the biology of Sacramento River salmon. *Trans Am Fish Soc* 70:55-69.
- O'Brien R. 1951. *California called them. A saga of golden days and roaring camps*. New York (NY): McGraw-Hill. 251 p.
- Olmsted DL, Stewart OC. 1978. Achumawi. In: Heizer RF, editor. *Handbook of North American Indians*. Vol. 8. California. Washington, DC: Smithsonian Inst. p 225-35.
- Outdoor California. 1958. Salmon get a freeway up a rugged canyon. August 1958. p 4-5.
- Perlot JN. 1985. *Gold seeker. Adventures of a Belgian argonaut during the Gold Rush years*. Bretnor HH, translator. Lamar HR, editor. New Haven (CT): Yale Univ Pr. 451 p.
- Phillips JB. 1931. Netting operations on an irrigation canal. *California Fish and Game* 17(1):45-52.
- Poesch J. 1961. *Titian Ramsay Peale and his journals of the Wilkes Expedition*. Philadelphia (PA): Am Philos Soc. 206 p.
- Pope ST. 1918. Yahi archery. In: Heizer RF, Kroeber T, editors. *Ishi, the last Yahi. A documentary history*. Berkeley (CA): Univ Calif Pr. p 172-201. Reprinted in 1979.
- Powers S. 1874. *The California Indians*. Nr. XI. — various tribes. *The Overland Monthly* XII:412-24.
- Powers S. 1877. *Tribes of California*. In: Heizer RF, editor. *Contributions to North American Ethnology, Volume III*. Washington, DC: Department of the Interior, US Geographical and Geological Survey of the Rocky Mountain Region. Reprinted in 1976. Berkeley (CA): Univ Calif Pr. 480 p.

- Reynolds FL, Mills TJ, Benthin R, Low A. 1993. Restoring Central Valley streams; a plan for action. Sacramento (CA): California Department of Fish and Game. 129 p.
- Rose G. 1992. San Joaquin. A river betrayed. Fresno (CA): Linrose. 151 p.
- Rutter C. 1902. Studies in the natural history of the Sacramento Salmon. Seventeenth biennial report of the State Board of Fish Commission of the State of California for 1901-1902. p 64-76.
- Rutter C. 1904. Natural history of the quinnat salmon. A report of investigations in the Sacramento River, 1896-1901. Bull US Fish Comm 22(1902):66-141.
- Rutter C. 1907. Do quinnat salmon return to their native streams? Nineteenth biennial report of the State Board of Fish Commission of the State of California for 1905-1906. Appendix. p 93-7.
- Rutter C. 1908. The fishes of the Sacramento-San Joaquin Basin, with a study of their distribution and variation. Bull US Bur Fish 27(1907):103-52.
- San Joaquin Valley Drainage Program. 1990. Fish and wildlife resources and agricultural drainage in the San Joaquin Valley, California. Volume 1. October 1990. Sacramento, Calif. 166 p.
- Sanchez HVG. 1932. California and Californians. Volume I. The Spanish period. San Francisco (CA): Lewis Publishing. 569 p.
- Scofield NB. 1900. Notes on an investigation of the movement and rate of growth of the quinnat salmon fry in the Sacramento River. Fifteenth biennial report of the State Board of Fish Commission of the State of California for 1897-1898. p 66-71.
- Scofield WL. 1954. California fishing ports. California Department of Fish and Game. Fish Bulletin 96. p 1-159.
- Seymour AH. 1956. Effects of temperature upon young chinook salmon [PhD dissertation]. Seattle (WA): Univ Washington.
- Shapovalov L. 1947. Report on fisheries resources in connection with the proposed Yolo-Solano development of the United States Bureau of Reclamation. California Fish and Game 33:61-88.
- Shebley WH. 1922. A history of fish cultural operations in California. California Fish and Game 8(2):62-99.
- Shebley WH. 1927. History of fish planting in California. California Fish and Game 13(3):163-73.
- Skinner JE. 1958. Some observations regarding the king salmon runs of the Central Valley. Water projects miscellaneous report nr. 1. California Department of Fish and Game. 14 October 1958. 14 p.

- Skinner JE. 1962. An historical review of the fish and wildlife resources of the San Francisco Bay area. Water projects branch report nr. 1. California Department of Fish and Game. June 1962. Sacramento, Calif. 225 p.
- Slater DW. 1963. Winter-run chinook salmon in the Sacramento River, California with notes on water temperature requirements at spawning. US Fish Wildl Serv Spec Sci Rep. Fisheries nr. 461. November 1963. 9 p.
- Smith HM. 1905. Report on inquiry respecting food fishes and the fishing grounds. US Commission on Fish and Fisheries report for the year ending June 30, 1903. p 75-100.
- Southern MH. 1942. Our stories landmarks. Shasta County, California. Redding (CA): Shasta Hist Soc. 100 p.
- Stanley C, Holbek L. 1984. A guide to the best whitewater in the state of California. Palo Alto (CA): Friends of the River. 281 p.
- Steele J. 1901. Camp and cabin. Mining life and adventure, in California during 1850 and later. Chicago (IL): RR Donnelley & Sons. 377 p. Reprinted in 1928 by The Lakeside Press.
- Stone L. 1874. Report of operations during 1872 at the United States salmon-hatching establishment on the M'Cloud River and the California Salmonidae generally; with a list of specimens collected. US Commission on Fish and Fisheries report for 1872 and 1873. Appendix B. p 168-215. Washington, DC.
- Stone L. 1876. Report of operations during 1874 at the United States salmon-hatching establishment on the M'Cloud River, California. US Commission on Fish and Fisheries report for 1873-4 and 1874-5. Appendix. p 437-78. Washington, DC.
- Stone L. 1879. Report of operations at the United States salmon-hatching station on the M'Cloud River, California, in 1877. US Commission on Fish and Fisheries report for 1877. Appendix. p 741-70. Washington, DC.
- Stone L. 1880. Report of operations at the United States salmon-hatching station on the M'Cloud River, California, in 1878. US Commission on Fish and Fisheries report for 1878. Appendix. p 741-70. Washington, DC.
- Stone L. 1883a. Account of operations at the McCloud River fish-breeding stations of the United States Fish Commission, from 1872 to 1882 inclusive. Bull US Fish Comm 2(1882):217-236.
- Stone L. 1883b. Report of operations at the United States salmon-hatching station on the M'Cloud River, California, during the season of 1880. US Commission on Fish and Fisheries report for 1880. Appendix, Part XXI p 597-612. Washington, DC.

- Stone L. 1885a. History of operations at the fish hatching stations on the McCloud River, California, from the beginning, August 1872, to October 1884. *Bull US Fish Comm* 5(1885):28-31.
- Stone L. 1885b. Report of operations at the United States salmon-breeding station on the McCloud River, California, during the year 1883. US Commission on Fish and Fisheries report for 1883. Appendix, Part XI. p 989-1000. Washington, DC.
- Stone L. 1897. The artificial propagation of salmon on the Pacific Coast of the United States, with notes on the natural history of the quinnat salmon. *Bull US Fish Comm* 16(1896):203-235.
- Sullivan MS. 1934. The travels of Jedediah Smith. A documentary outline including the journal of the great American pathfinder. Santa Ana (CA): Fine Arts Pr. 195 p.
- Sumner FH, Smith OR. 1940. Hydraulic mining and debris dams in relation to fish life in the American and Yuba rivers of California. *California Fish and Game* 26(1):2-22.
- Swezey SL, Heizer RF. 1977. Ritual management of salmonid fish resources in California. *Calif J Anthropol* 4:6-29.
- Theodoratus DJ, editor. 1976. An ethnographic study of the New Melones Lake Project. New Melones Ethnographic Research Project. Report to the US Army Corps of Engineers, Contract nr. DACW05-76-0033. July 1976. Sacramento, Calif. 529 p.
- Throckmorton SR. 1882. Description of the fish-way in Pitt River, California. *Bull US Fish Comm* 1:202-3.
- Toffoli EV. 1965. Chemical treatment of the Merced River, Mariposa County. California Department of Fish and Game Inland Fisheries Branch administrative report nr. 65-14. Sacramento, Calif. 12 p.
- Towle JC. 1987. The great failure: nineteenth-century dispersals of the Pacific Salmon. *Calif Geograph Soc* 27:75-96.
- Travanti L. 1990. The effects of piscicidal treatment on the fish community of a northern California stream [MS thesis]. California State University, Chico. 67 p.
- Tudor-Goondenough Engineers. 1959. Summary report on the Tri-Dam Project. Stanislaus River, California. January 1959. San Francisco, Calif. 99 p.
- [USFC] US Commission of Fish and Fisheries. 1876a. The propagation of food-fishes in the waters of the United States. US Commission of Fish and Fisheries report for 1873-4 and 1874-5. Washington, DC.

- [USFC] US Commission of Fish and Fisheries. 1876b. Correspondence relating to the San Joaquin River and its fishes. US Commission of Fish and Fisheries report for 1873-4 and 1874-5. Part XXIII. p 479-483. Washington, DC.
- [USFC] US Commission of Fish and Fisheries. 1892. Rep. Comm. for 1888. US Commission of Fish and Fisheries report for July 1, 1888 to June 30, 1889. p xxxv-xxxvi. Washington, DC.
- [USFC] US Commission of Fish and Fisheries. 1899. US Commission of Fish and Fisheries report for the year ending June 30, 1898. p xciii-xcvii. Washington, DC.
- [USFC] US Commission of Fish and Fisheries. 1900. US Commission of Fish and Fisheries report for the year ending June 30, 1899. p xcvi-c. Washington, DC.
- [USFC] US Commission of Fish and Fisheries. 1904. US Commission of Fish and Fisheries report for the year ending June 30, 1902. p 71-74. Washington, DC.
- [USFWS] US Fish and Wildlife Service. 1995. Working Paper on restoration needs: habitat restoration actions to double natural production of anadromous fish in the Central Valley of California. Volumes 1, 2, and 3. 9 May 1995. Prepared for the US Fish and Wildlife Service under the direction of the Anadromous Fish Restoration Program Core Group. Stockton, Calif.
- Van Cleve R. 1945. Program of the Bureau of Marine Fisheries. California Fish and Game 31(3):80-138.
- Vandor PE. 1919. History of Fresno County, California. Volume 1. Los Angeles (CA): Historic Record. 2,603 p.
- Van Sicklen HP. 1945. A sojourn in California by the King's orphan. The travels and sketches of G. M. Waseurtz af Sandels, a Swedish gentleman who visited California in 1842-1843. San Francisco (CA): Book Club Calif. 95 p.
- Voegelin E. 1942. Culture element distributions: XX. Northeast California. Univ Calif Pub Anthropol Rec 7:47-252.
- Vogel DA, Marine KR. 1991. Guide to upper Sacramento chinook salmon life history. Report to US Bureau of Reclamation, Central Valley Project. Redding (CA): CH2M Hill. 55 p.
- Wales JH. 1939. General report of investigations on the McCloud River drainage in 1938. California Fish and Game 25(4):272-309.
- Warner G. 1991. Remember the San Joaquin. In: Lufkin A, editor. California's salmon and steelhead. The struggle to restore an imperiled resource. Berkeley (CA): Univ Calif Pr. p 61-9.
- Wilkes C. 1845. Narrative of the United States Exploring Expedition during the years 1838, 1839, 1840, 1841, 1842. Volume V. Philadelphia (PA): Lea & Blanchard.

- Wilson NL. 1972. Notes on traditional Foothill Nisenan food technology. In: Papers on Nisenan environment and subsistence. Center for Archaeological Research Publication nr 3. Davis (CA): Univ Calif Davis. p 32-8.
- Woodhull C. 1946. A preliminary investigation of the Mokelumne River from Tiger Creek to Pardee Reservoir. California Division of Fish and Game, Bureau of Fish Conservation administrative report nr. 46-16. 28 p.
- Woodhull C, Dill W. 1942. The possibilities of increasing and maintaining a run of salmon (*Oncorhynchus tshawytscha*) in the Kings River, California. California Division of Fish and Game, Bureau of Fish Conservation administrative report nr. 42-26. 32 p. + figures.
- Woods DB. 1851. Sixteen months at the gold diggings. New York (NY): Harper Bros. 199 p.
- Wright GF. 1880. History of Sacramento County, California. Oakland (CA): Thompson & West. Reprinted in 1960 by Howell-North. 294 p.
- Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. *N Am J Fish Manage* 18:487-521.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. Sierra Nevada Ecosystem Project: Final report to US Congress. Volume III, assessments, commissioned reports, and background information. p 309-62.

Unpublished Documents

- Azevedo RL, Parkhurst ZE. 1958. The upper Sacramento River salmon and steelhead maintenance program, 1949-1956. US Fish and Wildlife Service. 96 p.
- [DFG] California Department of Fish and Game. 1955. Fish and game water problems of the Upper San Joaquin River. Potential values and needs. Statement submitted to the Division of Water Resources at hearings on the San Joaquin River water applications. 5 April 1955. Fresno, Calif. 51 p.
- DFG letter no.1. Letter dated 23 April 1941 from H.A. Kloppenburg, US Forest Service District Ranger, to R. Van Cleve, DFG.
- DFG letter no. 2. Letter dated 29 April 1941 from R. Belden to the California Fish and Game Commission.
- DFG unpublished field data and notes. Stream survey data, fish counts at dam fishways, notes and photographs on file at DFG offices, Red Bluff, Sacramento and Rancho Cordova.

- Dill W. Letter dated 24 September 1946 to Donald H. Fry, Jr., California Department of Fish and Game, Fresno.
- Dunham R. 1961. Report on the pollution of the Mokelumne River. California Department of Fish and Game. 27 June 1961. Sacramento, Calif.
- Flint RA, Meyer FA. 1977. The De Sabla-Centerville Project (FERC No. 803) and its impact on fish and wildlife. California Department of Fish and Game report. October 1977. Sacramento, Calif.
- Gerstung ER. 1971. A report to the California State Water Resources Control Board on the fish and wildlife resources of the American River to be affected by the Auburn Dam and Reservoir and the Folsom South Canal and measures proposed to maintain these resources. California Department of Fish and Game. June 1971. Sacramento, Calif.
- Hedgecock D, Banks MA, Rashbrook VK, Dean CA, Blankenship SM. 2001. Applications of population genetics to conservation of chinook salmon diversity in the Central Valley. In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1. Sacramento (CA): California Department of Fish and Game.
- [IEP] Interagency Ecological Program-Steelhead Project Work Team. 1998. Monitoring, assessment, and research on Central Valley steelhead: status of knowledge, review of existing programs, and assessment of needs. Draft report. 2 November 1998. Sacramento, Calif. 37 p.
- Latta R, editor. 1930-1931. Papers, publications: H.C. Bailey, pioneer California sketches. Yosemite Research Library Archives, Yosemite National Park.
- Latta F. Unpublished papers, field notes. Frank Latta interview with Pahmit (William Wilson), 1 July 1933. Yosemite Research Library Archives, Yosemite National Park.
- Maslin PE, McKinney WR. 1994. Tributary rearing by Sacramento River salmon and steelhead. 30 October 1994. Department of Biology, California State University, Chico. 46 p.
- Northern California Power Authority. 1993. Griswold Creek Diversion Project application for license for major unconstructed project. Submitted to US Federal Energy Regulatory Commission. December 1993.
- Schulz PD. 1994. Fish remains from YOL-182: a prehistoric village in the lower Sacramento Valley, October 10, 1994. Brienens, West and Schulz, P.O. Box 184, Davis, CA 95617. 18 p.
- Snyder JB. 1993 Memorandum to Park Superintendent Mike Finley. Did salmon reach Yosemite Valley or Hetch Hetchy? 9 May 1993 manuscript. P.O. Box 577, Yosemite National Park. 8 p.

[USFWS] US Fish and Wildlife Service. 1998 unpublished report. Status of key Fish and Wildlife Service activities in the Battle Creek watershed. July 1998. Redding, Calif. 2 p.

Notes

Phil Bartholomew. DFG, retired. Region 4, Oakhurst, Calif.

Stephen R. Boyd. East Bay Municipal Utility District. Oakland, Calif.

Ralph Cutter. Truckee, Calif.

Leon Davies. Department of Wildlife, Fish and Conservation Biology, University of California, Davis.

William A. Dill. DFG, retired. Region 4, Fresno, Calif.

Richard Flint. DFG, Region 2. Oroville, Calif.

Tim J. Ford. Turlock and Modesto Irrigation Districts, Turlock, Calif.

Colleen Harvey-Arrison. DFG, Region 1. Red Bluff, Calif.

Terry Healey. DFG, Region 1. Redding, Calif.

John Hiskox. DFG, Region 2. Nevada City, Calif.

Randy Kelly, DFG, Region 4. Fresno, Calif.

Pete Lickwar. US Fish and Wildlife Service, Energy and Power Branch. Sacramento, Calif.

William E. Loudermilk. DFG, Region 4. Fresno, Calif.

Fred Meyer. DFG, Region 2. Rancho Cordova, Calif.

Joe Miyamoto. East Bay Municipal Utility District. Oakland, Calif.

John Nelson. DFG, Region 2. Rancho Cordova, Calif.

Robert C. Nuzum. East Bay Municipal Utility District. Oakland, Calif.

Harry Rectenwald. DFG, Region 1. Redding, Calif.

James B. Snyder. Historian, Yosemite National Park, National Park Service.

Eldon Vestal. DFG, retired. Region 4, Fresno, Calif.

Shasta Salmon Salvage Efforts: Coleman National Fish Hatchery on Battle Creek, 1895–1992

Michael Black

Dedication

This paper is dedicated to the memory of wily fisherman and indefatigable salmon champion Nat Bingham. Named for a New London, Connecticut, whaling ship's captain, Nathaniel Shaw Bingham knew the best way to chart salmon futures was by peering unflinchingly into their and our own respective pasts.

I. The Early Years on Battle Creek

For well over a century, Californians have sought to compensate for depleted salmon runs in the upper Sacramento River Basin by creating fish hatcheries. Beginning in 1872, fish culturalist Livingstone Stone located the West's first fish hatchery on the lower McCloud River. Between 1870 and 1960, 169 significant public and private fish hatcheries and egg collecting stations were operated throughout the state (Leitritz 1970, p 11). The fifth hatchery to be owned and managed by the US Commission of Fish and Fisheries (later renamed the US Fish Commission), was the Battle Creek Station located near Anderson.

Originating on the western slopes of Mt. Lassen, Battle Creek flows some forty-two miles before emptying into the Sacramento River. Due largely to melting snow, Battle Creek enjoys a cold, year-round supply of filtered water. Porous volcanic rock acts as a sponge to absorb and gradually release stored underground waters. This Cascade stream also enjoys a reasonably steep gradient, falling some 5,000 feet, which made it a prime candidate for early hydroelectric development (Reynolds 1980, p 23). In 1901, five years after fish culturalists began harvesting Battle Creek's thriving populations of fall-, winter-, and spring-run chinook salmon, developers sought to cash in on its hydroelectric potential. The Volta plant would generate peak load power for a proposed copper smelter at Keswick, near Mountain Copper's Iron Mountain mine (Reynolds 1980, p 29).

Before this hydroelectric system went into effect, fish culturalists enjoyed an optimum five-year window for harvesting returning stocks of Battle Creek salmon. In 1893, J.P. Babcock (later named the station's Chief Deputy and director) recommended to California's Fish Commissioners that a new Sacramento River spawning station be established (Leitritz 1970, p 24). In September 1895, a hatchery was erected near the mouth of Battle Creek, in Tehama County (SBFC 1896, p 23). Investigators reported large numbers of salmon entering this stream during the months of October and November. Between October 21, and November 12, 1895, the hatchery's full capacity of 10 million eggs was easily reached (SBFC 1896, p 24). Hatchery personnel noted "...there [was] almost no limit to the numbers of eggs which can be secured there with proper apparatus" (SBFC 1896, p 24). John J. Brice, then US Commissioner of Fisheries, was approached about supplying that "proper apparatus" by erecting a much larger facility on Battle Creek.

In August, 1896, the US Fish Commission erected temporary structures at the Battle Creek site to handle any surplus spawn. During 1896 and 1897, the Battle Creek Station, as it was called, was jointly operated by the State of California and the US Fish Commission (SBFC 1898, p 35). In the 1896 season, the facility gathered twenty-six million eggs and in the following year, forty-eight million eggs (SBFC 1898, p 35). California's Fish Commissioners reported:

The location and operation of the Battle Creek station has been the most successful propagation work ever undertaken on this coast, and in its magnitude and importance equals any work of its kind in the world (SBFC 1898, p 35).

During winter 1897, Congress set aside funding to purchase the State's interest in the Battle Creek facility, and it soon became the fifth federal breederly in the State (Biennial Report 1897-1898, p 35). Upon receipt of payment, California's Fish Commissioners shifted their investment to Mount Shasta City's Sisson hatchery.

In its early years, the Battle Creek facility was capable of producing as many as 60 million fertilized eggs (Leitritz 1970, p 24). In a letter dated December 5, 1904, G. H. Lambson, Superintendent of the US Bureau of Fisheries stations in California, remarks:

There is a large run of fish in both Battle and Mill creeks and there is hardly any limit to be placed on the number of eggs we could take if we had the room. We could have taken fully eighty to one hundred million at Battle Creek and about sixty million at Mill Creek if we could have fished daily (SBFC 1904, p 107).

Recognizing the need to overcome "...the double odds of natural and human enemies," biologist Cloudsley Rutter pointed toward artificial propagation as

the sole hope for the Sacramento River salmon (SBFC 1904, p 106). Believing that “the relative efficiency of natural versus artificial propagation is about one percent and eighty-five percent, respectively,” (SBFC 1904, p 105) Rutter wrote:

Artificial propagation is keeping up the supply of salmon in the Sacramento River. With one exception, there are now no natural spawning beds in the Sacramento basin that amount to anything. All of the Feather, Upper Sacramento, and Pit rivers, with their tributaries have been practically abandoned, with the exception of the streams where the hatcheries are located. The only natural spawning beds still occupied are in the main river, between Redding and Tehama, which are yet visited by a considerable number of salmon (SBFC 1904, p 106).

When Rutter assisted at the Battle Creek Station in August, 1897, he and his colleagues helped catch a record number of fall-run Sacramento salmon ascending Battle Creek (8,784 fish were spawned yielding 48,527,000 eggs). Between their weirs and nets, Schofield reports they “took almost every fish in the river,” making artificial propagation the sole tool of choice for saving the Sacramento’s beleaguered salmon (Jennings 1996, p 16; Schofield, as cited in SBFC 1898, 1900, p 69). Writing four years later, a confident Rutter concluded: “Artificial propagation of salmon has not yet reached such proportions as to entirely supplant natural propagation, with the exception of the work on the Sacramento River” (Rutter, as cited in SBFC 1904, p 105).

The Battle Creek Station remained in operation through 1945 when a new set of threats to fish and fisheries was felt throughout Western watersheds. From the Pacific Northwest’s Columbia River to California’s Sacramento River, federal agencies like the US Bureau of Reclamation (the Bureau) built pharaonic dams like Grand Coulee and Shasta. Attempts at reconciling anadromous fish losses with massive water development stemmed from the Grand Coulee Dam’s construction. In rapid succession, experimental “fish salvage” efforts occurring on the Columbia River were attempted in the Sacramento River basin where the Coleman National Fish Station was erected¹.

1. As former DFG biologist Richard Hallock points out, the original Battle Creek Station site was essentially abandoned.

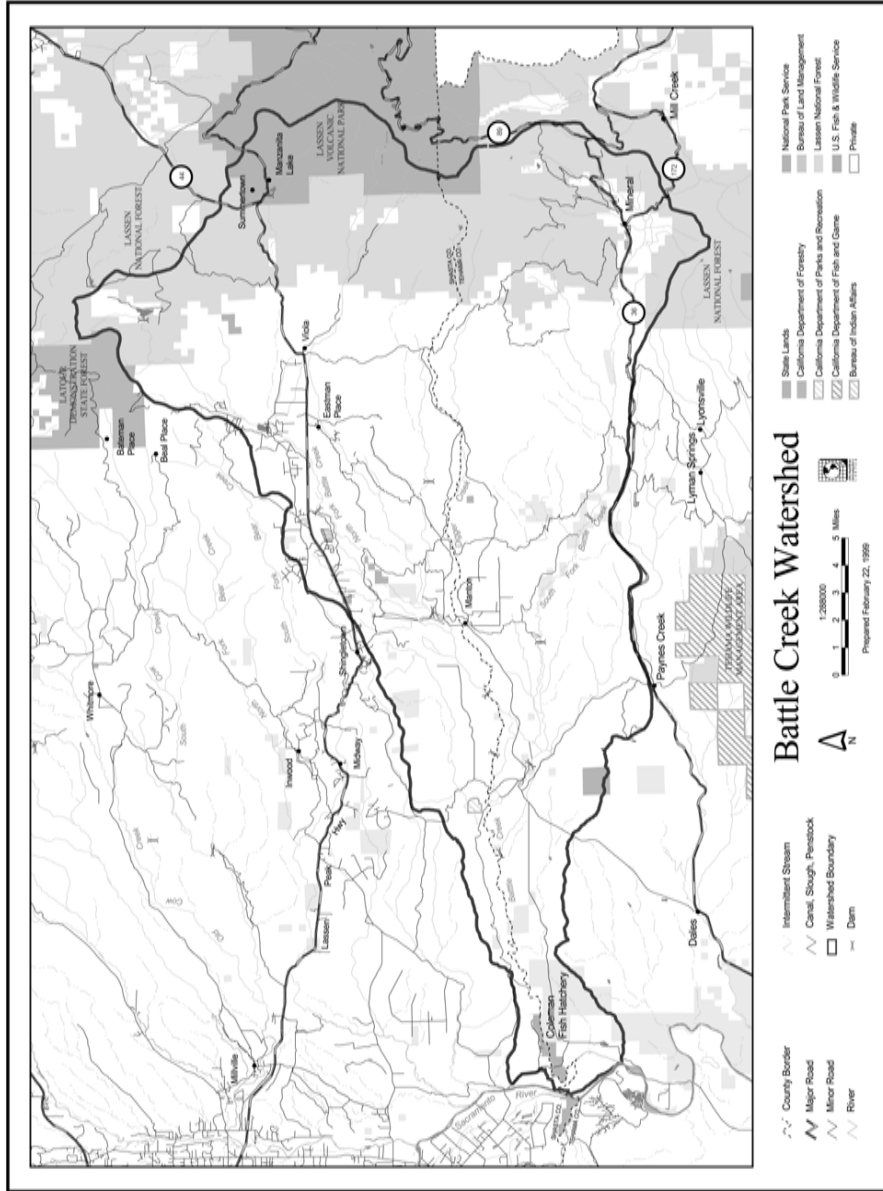


Figure 1 Battle Creek Watershed

II. Columbia River Antecedents

Upon its completion in 1941, the Columbia River's Grand Coulee Dam prevented roughly 100,000 chinook, sockeye, and steelhead from ascending 1040 miles of prime upstream habitat. Originally slated by the US Army Corps of Engineers to have been a "low dam" like Bonneville, the project had, by 1935, metamorphosed under Franklin D. Roosevelt's Public Works Administration and the Bureau, into the largest dam ever erected in North America (Reisner 1986, p 162-163). Impassable to migratory fish, it also became the proving grounds for subsequent, large-scale "fish salvage" efforts throughout the arid West. When it came to federal and State-level institutions, personnel, scientific, and technological precedents, fish rescue strategies at Grand Coulee foreshadowed what was later attempted on California's Sacramento River.

Willis H. Rich greeted the big dam era with trepidation (Rich 1939). The Stanford University professor (a classically educated biologist) was retained in 1938 by the Oregon Fish Commission to direct their new Research Division (Taylor 1996, p 355)². Rich was dubious about excessive reliance on hatcheries as a means of mitigating fishery losses (Lichatowitch, personal communication, see "Notes"). In 1939, speaking before assembled ichthyologists at Stanford University, Rich concluded:

Biologists in general are skeptical of the claims made for artificial propagation...because these claims have often been extravagant and the proof is entirely inadequate. Indeed, many conservationists feel that the complacent confidence felt by fishermen, laymen, and administrators in the ability of artificial propagation to counterbalance any inroads that man may make...is a serious stumbling block in the way of the development of proper conservation programs (Rich as cited in Taylor 1996, p 354).

Rich was more circumspect in his criticism of hatcheries. He recognized that enormous dams transformed hatcheries into self-fulfilling prophecies: dramatically shrinking natural habitats meant escalating hatchery programs (Taylor 1996, p 352). During the 1920s and 1930s, Alaska and British Columbia provided rare instances where hatchery-driven salmon production was deliberately scaled back due to excessive costs. Within these unique cases, however, artificial propagation could only be traded for intact spawning grounds (Taylor 1996, p 348; Calkins and others 1939b, p 6). Rich had no alternative but to accommodate himself to the big dam era, hoping that some day "general principles" might be discovered which reconciled massive water develop-

2. This account greatly benefits from Joseph E. Taylor's thoughtful synopsis of fish salvage efforts surrounding Grand Coulee Dam (Taylor 1996, p 350-360). The narrative that follows refers to the various roles Willis H. Rich played in his advisory capacity.

ment with the biological requirements of anadromous fish (Taylor 1996, p 355).

There was also the added matter of federal institutional precedents which had, for seventy years, informally mitigated for habitat losses by means of technological remedies like hatcheries (Black 1995). National fish mitigation policies accompanying dam construction finally became formalized under the Federal Power Act of 1920, spelling out compensatory obligations accompanying water projects. States, too, exhibited a strong predilection toward relying on hatcheries to rescue fisheries blocked by dams. Beginning roughly in 1906, Washington State shifted toward a policy of hatcheries "in lieu" of dams. Oregon began embracing the practice in 1909 (Taylor 1996, p 351).

The Mitchell Act³ was passed by Congress in 1938 directing the Bureau and the Army Corps of Engineers to assist the US Bureau of Fisheries in saving salmon (Taylor 1996, p 357). The traditional mix of technological mitigations was amended by the desire to relocate, to downstream tributaries if possible, fish stocks displaced by massive dams. For example, the Grand Coulee Fish Maintenance Project (GCFMP) was designed to sustain the production of mid-Columbia River salmon and steelhead populations at levels comparable to those before dam construction. By restoring natural propagation within the downstream Wenatchee, Entiat, Methow, and Okanogan tributaries, biologists hoped to expand suitable substitute habitats for displaced wild fish (Mullan 1992, p iii; Hobart, personal communication, see "Notes"). Returning migratory species were trapped at downstream Rock Island Dam before being hauled and released upstream of temporary weirs, or transferred to the Leavenworth, Entiat, and Winthrop national fish hatcheries for artificial propagation (Mullan 1987, p iii).

As environmental historian Joseph Taylor observes, the Grand Coulee Fish Maintenance Project required that a century's accumulated managerial and technological precedents be systematically recombined and directed at relocating and producing fish on an undreamed of scale. Successful fish salvage efforts hinged upon: (1) identification and restoration of downstream tributaries suitable for fish transplantation and reproduction; (2) construction of a greatly expanded hatchery system; and (3) invention of a new means of moving fish around (Taylor 1996, p 358).

Several stages were required to achieve the objectives of the Grand Coulee Fish Maintenance Project. The initial task necessitated gathering a comprehensive inventory of downstream watersheds and their inhabitants. This included devising a means of measuring existing fish populations, evaluating their ecological suitability for fish habitats, and identifying adverse conditions

3. See Statute 345, 75th Congress, 3rd Session, May 11, 1938.

capable of undermining fish survival (like unscreened irrigation diversions and pollution). Works Projects Administrations' laborers cleared streams of obstacles like beaver dams, constructed fishways around instream blockages, and screened irrigation diversions.

Next came a program for significantly increasing hatchery production. Initially, Bureau policymakers presciently suggested setting aside "...some streams as fish refuges on which no conflicting water development would be made" (Bureau memorandum, as cited in Taylor 1996, p 358-359; ff. 76). However, Bureau leaders lacked sufficient power and political gumption to risk angering competing developmental interests, many of whom were agency supporters (Taylor 1996, p 358). Instead, they resorted to fine tuning and expanding existing hatcheries and constructing new facilities such as the Leavenworth plant on Icicle Creek.

As a tributary of the Wenatchee River, Icicle Creek proved to be a curious hatchery site. This facility, which anticipated handling 76.5 million eggs annually, sought to reproduce an annual run equivalent to 36,500 fish (Calkins and others 1939b, p 4)⁴. However, the creek's waters completely dried up during late summer months. Bureau engineers nonetheless guaranteed Leavenworth a year-round supply of water by boring a two-thousand-five-hundred foot tunnel from nearby Upper Snow Lake. With sufficient engineering talent and money, even significant mitigation obstacles like these were retired with dispatch.

The project's final task lay with moving salmon around. By May, 1939, federal and State workers began trapping incoming salmon at Puget Sound Power and Light's Rock Island Dam. During the first year alone, eight Bureau-supplied tank trucks relocated 36,000 salmon to the Wenatchee, Methow, Okanogan, and Entiat rivers (Taylor 1996, p 359). In 1940, once holding ponds at the new Leavenworth hatchery had been completed, US Fish and Wildlife Service personnel began hauling fish to be ripened for artificial propagation. Finally there was the matter of sockeye (or "blueback") salmon, which had once migrated to reproduce in upper Columbia River nursery lakes. Most sockeyes were transported for rearing in Wenatchee and Osoyoos lakes, located on Wenatchee and Okanogan rivers (Mullan 1987, p 31).

Board of Consultants Recommendations: Round One

In 1938, Secretary of the Interior Harold L. Ickes appointed a "Board of Consultants" (Board) to review fish salvage proposals on the Columbia (and later the Sacramento) River. Consisting of two Stanford University professors and a

4. Consisting of 41 million chinook, 21.5 million sockeye, and 14 million steelhead eggs (Calkins and others 1939, p 4).

third faculty member from the University of California. (Stanford contributed W. F. Durand, Professor Emeritus of Mechanical Engineering and Willis H. Rich, Professor of Biology. Berkeley supplied R. D. Calkins, Professor of Economics). Their selection reflected the Department of the Interior's and the Bureau's predisposition toward finding cost-effective engineering solutions in significantly altered western watersheds. Doubtless these individuals were chosen for their particular areas of expertise, for their perceived autonomy as faculty members at prestigious universities, and for subtly distancing the sponsoring agency from any political repercussions arising from the Board's judgment.

Within their October 3, 1938 letter of appointment, Secretary of the Interior Ickes instructed Professors Calkins, Durand, and Rich that:

Your report should review all phases of the situation and the proposed plans of the state with a view to determining their feasibility from physical and biological standpoints, and whether the program as a whole, and the various features thereof, are economically justifiable...Your recommendation is also desired as to what proportion of the cost of such works...should be charged against the funds provided by the federal government for the construction of Grand Coulee Dam and what proportion should equitably be borne by other agencies such as the State of Washington and the US Bureau of Fisheries (Calkins and others 1939b, p i).

Their Columbia River document was subdivided into two sections; the first of which addressed temporary means for salvaging some portion of the threatened 1939 and 1940 salmon runs. Washington State Department of Fisheries biologists counted a total of 28,000 chinook and sockeye salmon and steelhead passing upstream from Rock Island Dam. Of this total, biologists estimated that 10 percent entered the Wenatchee, Methow, Okanogan, and Entiat rivers, while 90 percent proceeded upstream from the Grand Coulee site into the upper Columbia River Basin (Calkins and others 1939, p 4). The Board of Consultants report recommended: (1) peak run fish trapped at Rock Island Dam be temporarily transported upstream of Grand Coulee Dam; (2) eight 1,000-gallon tank trucks be secured to experimentally transport anadromous fish; (3) during 1940 and 1941 Grand Coulee reservoir levels be maintained at an optimum level to facilitate downstream fish passage; and (4) a source of "eyed eggs" be secured for placement within the four tributaries between Grand Coulee and Rock Island dams (Calkins and others 1939a, p 14-15).

The blue ribbon panel instructed the Bureau to construct a hatchery for, among other species, steelhead trout, which they called "...one of the principal sport fish of the area" (Calkins and others 1939a, p 15). In 1937, Washington State authorities issued a total of 199,000 state and county hunting licenses. Hunters and sportfishers expended some four million dollars a year on addi-

tional recreational goods and services, leading panelists to conclude: "...that a serious importance [be] attached to this form of recreation and to the game fish in the Upper Columbia River..."(Calkins and others 1939a, p 17). While a hatchery capable of propagating steelhead, chinook and sockeye was to be built at federal expense, its subsequent administration, operation and maintenance would fall to the State and remain entirely a State enterprise (Calkins and others 1939a, p 18)⁵.

Part Two of "Fish Problems of the Upper Columbia River" responded to a detailed fish salvage plan submitted by the Washington State Department of Fisheries. The scheme sought to transfer fish once spawning above Grand Coulee Dam to the four tributaries immediately below (Calkins and others 1939b, p 65). Biologists proposed expanding the carrying capacity of the Wenatchee, Methow, Okanogan, and Entiat rivers to raise their fish populations to historic levels. Two hundred seventy-five thousand dollars in State monies were allotted to accomplish "stream rehabilitation." In addition, Board members ratified State recommendations calling for a combination of "...artificial spawning, hatching, feeding, rearing, and planting..." sufficient to compensate for 1,100 miles of blocked, upper river habitats. Up to one million chinook salmon fingerlings were also to be raised and released just before their seaward migration. (Calkins and others 1939b, p 1-2, 10, 77).

Under the guidance of Service biologists like Fred J. Foster, Regional Director of Seattle's Division of Fish Culture, artificial propagation figured prominently in the overall fish salvage effort⁶. Washington State's plan called for an initial expenditure of \$2,760,000 at an annual operating cost of \$184,000 (Calkins and others 1939b, p 65)⁷. In addition to the prominent Leavenworth facility, other "auxiliary hatcheries" capable of handling "eyed eggs" were called for on the Entiat, Methow, and Okanogan rivers (Calkins and others 1939b, p 3). Citing a "factor of safety" provided by hatcheries, Board members characterized the overall effort "...as an experiment in fish culture on a large scale..." (Calkins and others 1939b, p vi).

-
5. The Board of Consultants recommended that the whole project be administered by "...the Federal Bureau of Fisheries, with the organization of a joint Advisory Board representing the states of Washington and Oregon and the US Bureau of Reclamation" (Calkins and others 1939b, p 8). State of Oregon resistance to federal interference in its fisheries are well documented by Taylor (1996).
 6. See Fred J. Foster, "Outline of Artificial Propagation of Fish on the Lower Columbia River" (c. July 1937), box 611, fldr. 826.53, Entry 269; cited in Taylor 1996, p 357.
 7. The document notes parenthetically that the Washington State Report of 1938 was "...later modified by some reduction in the size of proposed hatchery plants" (Calkins and others 1939b, p v).

Board members were candid in acknowledging the unpredictable nature of their proposed undertaking:

...[W]e recognize fully the experimental nature of the attempt to replace natural propagation above Grand Coulee by artificial propagation of the same fish populations at hatcheries located below the dam. We believe that no one can be assured of the success of such a venture but, on the other hand, this plan appears, in the present instance, to be the only feasible means to the desired end (Calkins and others 1939b, p 7).

The hoped for gamble was twofold: artificial propagation could eventually be replaced by natural propagation within restored lower river tributaries, and, among intensely exploited fisheries, hatcheries could support much higher levels of fish productivity (Calkins and others 1939b, p 6-7).

By 1943, dam boosters (including the Bureau), touted the success of the Grand Coulee Fish Maintenance Project. Queried by a Reader's Digest editor, one representative of the US Fish and Wildlife Service (the Service) characterized the entire program as "highly satisfactory" (Taylor 1996, p 360). Assuaging a skittish public of their legitimate concerns about threatened sportfish may have invited an optimistic rush to judgment. Not all participants were as sanguine, however. Willis H. Rich wrote of artificial propagation:

...[that] actual accomplishment has seldom shown a sufficiently clear improvement over natural propagation to warrant the expenditure except in the case of a few small isolated runs (Rich, as cited in Calkins and others 1939b, p 6).

Rich knew that this was no small project. Biologists like Rich, however, lacked the luxury of contemplation, as large dams continued being erected throughout the arid West. One such was at Kennett, on California's Sacramento River, where prior institutional precedents, personnel, techniques and rationale were recast in a renewed effort at salvaging salmon.

III. The Central Valley Project Era

When Shasta Dam construction began interfering with salmon passage on November 8, 1942, the Central Valley Project's centerpiece drastically affected an array of migratory salmon stocks. Sacramento River runs were once distinguishable by their many attributes including run-timing, size, and varying spawning habitats. Winter-run stocks once relied upon spring-fed headwaters like those provided by the Little Sacramento, the Pit, the McCloud, and Fall rivers, and in nearby Battle Creek (Yoshiyama and others 1998, p 490-491; Ward and Kier 1998, p 10-11; USFWS and Richardson 1987c; USFWS 1998)⁸. Spring-run stocks arrived in "pre-reproductive and peak physical condition" and frequented extreme elevations within mountainous streams fed by snow-melt. Late fall-run stocks spawned within the upper Sacramento's mainstem and those tributary reaches blocked by the Shasta-Keswick complex (and perhaps in upper tributaries like the American River). Fall-run stocks arrived about ready to spawn but the fish were often in a somewhat compromised physical state. They predominated within the lower river and its foothill reaches at elevations of 500 feet or less (Yoshiyama and others 1996, p 312-313; Rutter 1904; Fisher 1994)

Once erected, the Shasta-Keswick complex excluded now-endangered winter-run salmon from all of their historic spawning grounds (save for Battle Creek) (Hedgpeth 1941; Slater 1963). Spring-run salmon also lost access to their extreme headwater habitats. The late fall-run was cut off from most of its historic spawning beds. Least adversely affected were fall-run fish, whose lower river spawning gravels remained relatively intact. By one estimate, fall-run chinook salmon lost an estimated 15 percent of its upper river habitat due to the erection of Shasta-Keswick dams⁹.

US Bureau of Fisheries biologists Harry A. Hanson, Osgood R. Smith, and Paul R. Needham, among others, were given barely three years to complete their Bureau sponsored investigation into the dam's full effects. Working at a breakneck pace, the investigating team made a number of recommendations

8. At the turn of the century, biologist Cloudsley Rutter captured newly emerged winter-run salmon fry in September and early October within Battle Creek's waters (Rutter 1902, 1903). As fisheries scientists Michael Ward and William Kier observe, the fish could not have originated within the downstream Sacramento River's mainstem due to lethal water temperatures (Kier and Ward 1998, p 10). Recently compiled Fish and Wildlife Service evidence documents existing Coleman hatchery-origin winter-run stocks in addition to "...a remnant population of wild winter-run [fish]" (USFWS 1998, as cited in Kier and Ward 1998, p 10).

9. See the accompanying historic run estimates provided by the California Department of Fish and Game within this document's appendix.

for “salvaging” some portion of the estimated 27,000 chinook salmon which passed the damsite in 1939¹⁰. Within their 1940 report, *An Investigation of Fish-Salvage Problems in Relation to Shasta Dam* (also called “Special Scientific Report Number 10”), Hanson, Smith and Needham proposed four competing mitigation plans for consideration by members of an advisory panel appointed by the Department of the Interior.

During winter 1940, discussions ensued between members of the Board of Consultants and the federal and State fisheries biologists charged with proposing possible salvage plans. As had occurred on the mid-Columbia River, the blue ribbon panel was again called upon to evaluate cost-effective salmon salvaging efforts on the soon-to-be-dammed Sacramento River. Professors Calkins, Durand and Rich reviewed reports submitted by the US Bureau of Fisheries and the California Department of Fish and Game (DFG).

In March 1940, additional meetings occurred at Stanford University with a broader representation of Bureau of Fisheries personnel. In attendance were Fred J. Foster, Regional Director of Seattle’s Division of Fish Culture (within the Bureau of Fisheries), together with Seattle-based Harland B. Holmes, Director of the North Pacific Fishery Investigation. Foster provided specific knowledge about the potential role of artificial propagation in the project while Holmes advised Board members on the proper design of fish ladders, traps, and other fish engineering problems. At this session, informal draft copies of “Special Scientific Report Number 10” were circulated and “...discussions resulted in some suggestions for [its] modification” (Calkins and others 1940a, p 1).

In early April, 1940, the final version of Hanson, Needham and Smith’s document was made available to all parties. It included three detailed plans for rescuing upper Sacramento River salmon and a fourth whimsical proposal for hauling displaced fish to the Trinity River. The detailed schemes included “The Stillwater Plan,” “The Battle Creek Plan,” and “The Sacramento River Natural Spawning Plan” (Hanson and others 1940, p 95)¹¹. Before revealing

10. Within a 1943 “Supplementary Report on Investigations of Fish-Salvage Problems in Relation to Shasta Dam,” Paul Needham, Harry Hanson, and Lewis Parker concluded that 1940 and 1941 salmon populations “...could not have been less than 50,000...and were probably much greater than 60,000.” They wrote that “...the salvage plan must be adjusted to great fluctuations in numbers of salmon and that no count to date has established the maximum numbers of salmon that may have to be handled” (Needham and others 1943, p 14).

11. The Trinity River strategy proposed relocating displaced Sacramento River fisheries into the Klamath Basin. That plan was soon dropped, however, due to costs, to probable competition with existing, indigenous Trinity River salmon stocks, and to pending dam construction on the lower Trinity.

particular aspects of each proposal, however, the document's general recommendations deserve some scrutiny.

Within their report, Hanson, Needham and Smith noted a number of critical problems dogging any kind of fish salvage effort. First and foremost was the issue of run-timing, for, as Shasta Dam neared completion, 1941's returning fish would already find themselves excluded from their ancestral spawning grounds. Second, in addition to fall- and spring-run fish, the report cited the "possible existence" of a separate "winter-" or "black" run of salmon on the McCloud River, which may be dispersed throughout the entire upper river basin (Hanson and others 1940, p 42-43)¹². Third, and importantly, they warned of the dangers of releasing excessively warm Shasta reservoir waters to downstream salmonids. This was particularly threatening to spring-run fish which arrive "green" from the ocean and hold for long periods before spawning. Advising biologists urged the Bureau to significantly lower the dam's penstocks below the reservoir's warm water thermocline. Finally, there were the issues of dangerous levels of mining leachate in and around Shasta Reservoir, maintaining minimum instream flow requirements, and unscreened agricultural diversions. Aspects of their document remain prescient to this day.

Hanson, Needham, and Smith's fish salvage recommendations fell into three broad categories and reflected what had been attempted on the mid-Columbia River. These recommendations included (1) sustaining the runs by means of artificial propagation; (2) capturing and transferring the fish to suitable downstream tributaries for re-establishment in a new stream; and (3) some combination of artificial and natural propagation (Hanson and others 1940, p 14)¹³. After weighing these various options, the biologists dismissed reliance solely on artificial propagation as being too costly, too risky, and too fraught with unknowns. On the other hand, a paucity of year-round tributaries within the lower-middle Sacramento Basin (from the mouth of the Feather River to the proposed Keswick Dam site) ruled out exclusive confidence in natural habitat replacement for upper river fish¹⁴. Hanson and his colleagues settled on a combined natural and artificial strategy. They came to believe that a balanced combination of each would prove most biologically tenable and cost effective

12. The winter-run had been identified as early as 1882 by Livingston Stone in his reports on the McCloud River salmon. See Slater (1963) and Fisher (1994).

13. The Trinity River proposal was to be completely reliant on natural reproduction.

14. As will become clear, many promising downstream tributaries like Battle Creek were fraught with a multitude of competing water development interests. Members of the Bureau and the Service were loath to challenge those individuals and interests who long since held riparian or appropriative rights to California's precious water.

because each separate propagation path could serve as a “buffer” or a “safety factor” on the other (Hanson and others 1940, p 17).

Attending biologists reasoned that a hatchery-dominant path would require handling roughly 100 million eggs annually, and, in addition, there was the vexing problem of the spring-run salmon. This stream-type stock must be held in their natal streams for months before spawning. “Where would that be accomplished?” they asked. Hatchery sites required cold, pristine spring water, or so they believed. One location mentioned was Darrah Springs on upper Battle Creek, but its 35 cubic feet per second was no match for this scale of operation (Hanson and others 1940, p 14). In conclusion, they wrote:

The risk as well as the high initial and permanent costs of handling the entire run artificially at either Big Springs [on the upper McCloud] or Fall River Mills have made it necessary to omit these possibilities from further consideration. (Hanson and others 1940, p 15)

Attending biologists were openly skeptical about using hatcheries to sustain incoming year-classes of spring-run fish.

As had been done on the Columbia River, an exhaustive stream survey to identify candidate streams for “naturally” transferring the upper Sacramento River salmon was conducted. Between the Shasta dam site and the Feather River, twelve tributaries entering the Sacramento from the east were counted. Of the twelve, eight showed no promise for housing displaced runs of fish. Only Churn Creek, Battle Creek, Deer Creek and Stillwater Creek exhibited attributes conducive to a potential salmon restoration effort¹⁵. Of the five streams emptying into the mainstem from the west, most were dry an appreciable part of the year. Larger tributaries like the American and the Yuba rivers were also evaluated but each was eliminated due to the century-old accumulation of mining debris. Finally, and perhaps in desperation, investigating biologists turned to the Klamath Basin’s Trinity River as a potential transplant site. But it, too, was ruled out due to its excessive distance, to existing indigenous runs of fish, and to pending proposals for dams along its lower reaches.

Hanson, Needham and Smith developed alternative plans, a summary of which follows, along with discussion of the principal advantages and disadvantages of each.

15. To date, I have discovered no mention by the Bureau of setting aside certain downstream tributaries as “refugia” for returning migratory fish. Apparently that idea was stillborn on the Columbia River in 1938.

“The Stillwater Creek Plan”

The aptly named Stillwater Creek is dry during the summer and early fall months before it enters the Sacramento River near Redding. It had several advantages over other candidate tributaries including prime potential salmon habitat, downstream proximity to proposed salmon trapping facilities at Keswick Reservoir, and excellent prospects for being “rewatered.” Most significantly, due to its intermittent flow, Stillwater Creek was unencumbered when it came to competing water rights. Hanson, Needham and Smith recommended diverting and importing 150 cubic feet per second from the upper McCloud River (alternative sources included either the Pit River or the still less desirable water from Shasta Reservoir) via some combination of gravity-flow supply ditch (40 miles long) or tunnel (14 miles long) and a suspension bridge over the Pit River¹⁶.

The Stillwater Plan called for constructing a separate “standby reservoir” at its highest point together with a hatchery and holding ponds suitable for rearing 50 million eggs. In the event a breakage interrupted their water source, biologists proposed a closed-loop watering and cooling system for all hatchery operations. The biologists calculated that a rewatered 24-mile-long stream had sufficient room for 5,000 redds. They set their total combined artificial and natural production objectives at 30,000 salmon.

Several of Stillwater’s advantages stemmed from an assurance of the best upriver water available—fabled McCloud River water¹⁷. Secondly, and importantly, there were no conflicting interests with other water users. In addition, hauling distances from fish trapping sites at Keswick Dam to release points were the shortest of any proposed plan. Finally, since Stillwater Creek lay downstream from the proposed Keswick trapping operations, it was hoped that future returning migrants could reenter the creek on their own.

16. No doubt biologists also had winter-run chinook on their minds as they sought to import McCloud River water into the lower middle Sacramento River Basin.

17. Livingston Stone referred to the McCloud River “as the last best hope for the Sacramento River salmon,” a sentiment subsequently echoed by biologist Joel Hedgpeth. See Hedgpeth (1941).

Stillwater's liabilities stemmed from its excessive construction and maintenance costs. Construction alone was appraised at \$4.3 million dollars (Hanson and others 1940, p 102). Somewhat paradoxically, these same scientists faulted Stillwater Creek's limited areas for natural spawning and they cited downstream erection of the proposed Iron Canyon Dam (above Red Bluff) as deeply troubling¹⁸. Since the whole operation was contingent on a dependable upriver water supply, a break in the system remained an ever-present danger. Finally, diverted McCloud River water at Shasta Dam's turbines were calculated by Bureau engineers at an annual firm power loss of \$62,500 (Hanson and others 1940, p 101).

"The [Combined] Battle Creek / Deer Creek Salvage Plan"

Due to its year-round flow and its existing US Bureau of Fisheries Hatchery, Battle Creek held promise in any fish recovery effort (Hanson and others 1940, p 102). This salvage plan revolved around establishing a large hatchery facility (or two hatcheries working cooperatively), while using lower Battle Creek for natural spawning. The trick would be to avoid jeopardizing Battle Creek's native fall and spring runs. In addition, a variation on the proposal called for transferring as many spring-run salmon into Deer Creek as possible.

This design required a permanent hatchery "salvage" program for a total of 16,000 fall-run and 6,000 spring-run fish. Biologists believed that fall-run migrants passing Shasta Dam would produce 50 million eggs annually, well beyond the modest capability of the long existing Battle Creek Hatchery (at 12 million eggs)¹⁹. Hanson, Needham, and Smith recommended building a sizable hatchery capable of handling 75 million eggs, inclusive of those already handled by the historic Battle Creek facility.

The report specifies Battle Creek's native runs as occupying a restricted space between the river's mouth and Pacific Gas and Electric's Coleman Power-

18. Citations about the proposed Iron Mountain and Table Mountain dams were scattered throughout the report. Should a lower river dam be built, biologists warned, all efforts to mitigate for the Shasta-Keswick complex would be "nullified." In 1944, federal and State biologists minced no words when they declared that "adequate protection should be provided [salmon] during [dam] construction periods: to [among many grounds,] prevent any man-made catastrophe which might eliminate for all time a portion of, or a whole, annual cycle of salmon." They urged a reexamination of the entire Table Mountain Dam project, for, "...as presently proposed, the dam will probably spell the doom of salmon and steelhead runs into the upper Sacramento River" (Rich and others 1944, p 7, 11).

19. In one year, peak production at the turn-of-the-century Battle Creek Hatchery produced 60 million eggs. However, substantial water development, aggressive broodstock harvesting, and intense fishing pressures reduced that number to a modest 12 million-egg capacity. (Leitritz 1970, p 25; USFWS and Richardson 1987a, p 4).

house. A stream survey cites room for 720 redds within a three mile reach between the upper racks and Coleman's tailrace (Hanson and others 1940, p 103). The two racks were installed to trap and hold fall-run chinook salmon. Additional spawning grounds above Coleman Powerhouse are dismissed as too limited "...to warrant the expense and difficulty of purchasing the power development on Battle Creek (Hanson and others 1940, p 103)." Biologists tailored their strategies so as not to disturb PG&E's existing operations and water rights²⁰.

Spring-run fish, the biologists specify throughout, require ripening and holding under tightly bounded conditions. Hanson, Needham and Smith believed Battle Creek to be excessively warm during the summer months (at one point a lower stretch reached 73 degrees Fahrenheit). Darrah Springs was suggested as one local source for cold, pure, spring water, where holding ponds might prove satisfactory. However, its modest 35 cubic feet per second (cfs) flow would be suitable for only a limited number of salmon. There was also the matter of a lengthy 32 mile commute from the trapping site near Redding. In addition, PG&E's consent would also be required before the facility could become fully functional to raise water some thirty feet to exit the hatchery (Hanson and others 1940, p 105).

Deer Creek is mentioned as the only other suitable lower Sacramento River tributary where spring-run salmon might also be transferred. In a Combination Battle Creek/Deer Creek Plan, Hanson and his colleagues record that the latter has sufficient spawning area for about 3,700 salmon between its mouth and the falls above Polk Springs (Hanson and others 1940, p 107). During summer months, however, irrigators pumped enough water out of Deer Creek to dry up its lower reaches. "Rewatering" Deer Creek required moving water around. Scientists urged that mainstem Sacramento River water be pumped to irrigators to compensate for Deer Creek's proposed restoration. This proposition was dismissed by members of the Board and others as being too costly.

20. For instance, they recommended supplying the proposed hatchery with water derived from Coleman Powerhouse's tailrace rather than from the creek itself. Service biologist Scott Hamelberg points out that "[e]ven though placing the [water] intake in Coleman Powerhouse's tailrace may have been "non-disruptive" to PG&E operations, we still recognize today there are major advantages to having the intake located at this site" (USFWS and Hamelberg 1999, p 1).

The formal Battle Creek proposal called for a 75 million-egg hatchery to be located below the Coleman Powerhouse for fall-run salmon. The Darrah Springs facility was to house at least 30 million spring-run eggs, or a second facility was to be located on or near Deer Creek²¹. Weirs, collecting systems, traps, and the like, would capture incoming fish. A fleet of 18 tanker trucks could haul fish the 60 miles required to their destinations. Interestingly, Hanson, Needham and Smith prepared no accompanying cost estimates for this plan. While they were operating under tight time constraints, evidence suggests they favored the much more costly Stillwater Plan.

The Combined Battle Creek/Deer Creek plan's advantages are "...its lower initial costs and the fact that it would not entail a power loss at Shasta Power Plant" (Hanson and others 1940, p 109). Biologists also believed they would find an "ample supply of cold water in Deer Creek" suitable for spring-run salmon to become reestablished. Liabilities included complete "[d]ependence upon artificial propagation as the sole salvage measure" (for the fall-run at least), total reliance upon Coleman Powerhouse's tailrace for incoming hatchery water, and excessive competition possibly culminating in overcrowding hatchery and native runs in both Battle and Deer creeks. They also lamented long hauling distances to Deer Creek, and, last but not least, the "necessity of replacing irrigation water with a permanent pumping plant if Deer Creek is to be used" (Hanson and others 1940, p 109).

"The Sacramento River Natural Spawning Plan"

Under the Sacramento River Natural Spawning Plan, most of the fall-run would be held within the river's mainstem where they could naturally reproduce. Two or more racks would be installed to disperse incoming fish to achieve their maximum sustained reproductive yields. Whatever remainder occurred, including all of the spring-run fish, were to be trapped and hauled to a Battle Creek hatchery situated at either Coleman or Darrah springs. Deer Creek was also specified as a possible holding area for naturally spawning spring-run fish.

The plan specified the building out of a hatchery facility capable of rearing 47 million eggs. Such a plant would supplant the existing Battle Creek operation as well as handle incoming fish from the Sacramento River. The plan called for building three removable racks in the mainstem Sacramento River, together with trapping and hauling facilities. The endeavor would cost an estimated \$1.6 million with annual operating expenses of \$40,000 (Hanson and others 1940, p 112).

21. A spring-run hatchery on or near Deer Creek was called for in the event that the combined Battle Creek/Deer Creek Plan was embraced.

Advantages of a Sacramento mainstem holding plan included low initial capital costs, more natural spawning areas than were presented in other plans, and suitably cool water temperatures for 75 percent of the fall run. Disadvantages stemmed from uncertainty. How would fish behave behind in-river weirs? Would they tend to fall back, bunch up and overcrowd one another, or disperse downstream as hoped for? Biologists just didn't know. There was also the controversial matter of copper contamination from Iron Mountain and other upriver sites. Excessive water temperatures posed yet another hazard to incubating eggs and young salmon. Biologists were especially concerned with the mainstem Sacramento (below Redding) because stream temperatures reached well beyond 60 degrees Fahrenheit from May through October (Hanson and others 1940, p 113). Such elevated temperatures could be raised ever higher by drought conditions, potentially culminating in the loss of entire year-classes of fish. Finally, and perhaps most ominously, proposals loomed to construct either Table Mountain or Iron Canyon dams which would inundate mile upon mile of remaining prime spawning areas²². In closing their document, Hanson, Needham and Smith refer to fish salvage programs at both Grand Coulee and Shasta dams as little more than "large-scale experiments" (Hanson and others 1940, p 115).

Board of Consultant's Recommendations: Round Two

The Board of Consultants entrusted with selecting among the range of fish mitigation strategies presented by biologists Hanson, Needham and Smith eventually embraced a hybridized plan. Details of the "Sacramento River, Battle Creek, and Deer Creek Plan" (also called "The Foster Plan") were spelled out in a supplemental report prepared by Fred J. Foster. The report had several essential elements:

- Trapping and hauling an estimated 1,500 spring-run fish (about one quarter out of a total of 6,000 spring-run fish) to Deer Creek for natural spawning (Calkins and others 1940a, p 9-10).
- Trapping and hauling an additional quarter spring-run to a natural-type holding pool in Deer Creek.

22. In a 1947 California Department of Fish and Game report, biologists stated that "Iron Canyon [D]am will destroy the entire salmon run now spawning between its site and Keswick Dam..." Members of the Statewide Water Committee of the California State Chamber of Commerce took issue with this assertion. Their research department argued that ample spawning gravel existed downstream from the proposed dam sites, that recent biological conclusions about the ill effects of Shasta-Keswick dams were contradictory, and that spiny rayed fishes had a significant place in the new West. See Blote 1946, p 175.

- Trapping and hauling the remaining spring-run to a holding pond at Darrah Springs on upper Battle Creek.
- Trapping and hauling about 4,000 early fall-run fish to planned holding ponds at Battle Creek's Coleman Hatchery site (to avoid potentially lethal Sacramento mainstem temperatures).
- Holding the remaining fall-run between racks within the mainstem Sacramento where they would spawn naturally.
- Construction of a hatchery at the Coleman site on Battle Creek suitable for 42 million eggs and/or advanced fry and 21 million fingerlings.
- Abandonment of the Bureau's historic Battle Creek Station but with retention of holding ponds for use by Battle Creek's fall-run salmon.

Low capital costs, extensive use of natural spawning areas, and suitably low mainstem water temperatures for perhaps three quarters of the fall-run were this plan's advantages. Its drawbacks included uncertainty of fish behavior when fish are caught behind racks, copper pollution from upriver mining leachate, high instream temperatures during summer and early fall months, and pending construction of Table Mountain and Iron Mountain dams (Calkins and others 1940a, p 10).

The Board of Consultants embraced Foster's Sacramento, Battle Creek, and Deer Creek Plan, but with a twist. They recommended deferring the Deer Creek portion until a better understanding of summer water temperatures was obtained. Once conditions looked sufficiently promising, they advised installing a Deer Creek natural-type pond which, they believed, should prove adequate for ripening and holding spring-run fish. Board members rejected outright a Sacramento River pumping station and means of conveyance to compensate irrigators for rewatering lower Deer Creek (Calkins and others 1940a, p 26).

The Board of Consultants endorsed installing three racks in the Sacramento mainstem, the lowermost falling just upriver from Battle Creek's mouth (Calkins and others 1940a, p 28). They suggested locating a fish counting device on the lowest rack and keeping precise fish passage records. The Board advocated combining a trapping device with one of the instream weirs. Calkins, Durand, and Rich sanctioned a fleet of four trucks to ferry captured salmon to the proposed Coleman hatchery and to other holding ponds at Darrah Springs and within Battle Creek. Capital costs were placed at \$1,064,500 (not including Deer Creek) with an annual operating expense of \$35,000. Their justification for these expenditures invites a look at their calculations.

Board members believed they were compensating for a run of salmon from between 20,000 to 25,000 fish arriving at Redding in two well-marked peaks (Calkins and others 1940a, p 18). The spring run reached Redding between the middle of April and July, and consisted of 5,000 to 6,000 fish. The fall run arrived between mid-September and late-November and consisted of 15,000 to 20,000 fish. Any mention of a possibly existing winter-run went unacknowledged within their report.

Economist R. D. Calkins probably penned the Board's cost-benefit analysis on economic losses attributable to fish blockage at Shasta Dam. Any figures (he noted, and the Board ratified) depended on the "number, weight, and value of the fish taken in the commercial fishery" (Calkins and others 1940a, p 21). They recorded that one million pounds of fish were caught annually by an in-river net fishery while four million pounds of fish derived from ocean trolling. Since "...no more than half of the river catch is derived from above Redding," they reasoned that half of the Sacramento River District's current \$57,000 fishery was in jeopardy. Board members concluded "...that no more than half, or \$28,000, of this [in-river fishery] may be regarded as the value of fish derived from spawning above the Shasta Dam" (Calkins and others 1940a, p 22).

As for the more indeterminate ocean fishery, Board members reasoned that "...probably no more than one third to one half the California ocean catch is derived from the Sacramento [River]" (Calkins and others 1940a, p 23). Since between 1929 and 1938, ocean catches below the Mendocino County line averaged 1,781,000 pounds, their total assessed market value was \$139,000. Assuming further that "...one third of these fish are from the Sacramento-San Joaquin river systems, and that one half of these are from above Redding, we reach a value of \$23,000" (Calkins and others 1940a, p 24). By combining this figure with the in-river figure, the Board placed the gross value of upper Sacramento River salmon to commercial fishermen at \$51,000, or possibly as high as \$87,000 (Calkins and others 1940a, p 24).

The Board dismissed the value of salmon loss to California's sports catch as indeterminate. They stated that sports fishing losses, like steelhead, stemming from Shasta Dam, "...[were] of small or even negligible value" (Calkins and others 1940a, p 32-33). Calkins, Durand, and Rich echoed a sentiment expressed in their mid-Columbia River Report by questioning whether the Bureau had any role whatsoever in compensating for sports fisheries losses. Lester A. McMillan, Executive Officer of the State of California's Division of Fish and Game, took issue with this omission. In a letter to W. F. Durand dated August 12, 1940, McMillan concluded:

An additional economical value of the salmon run was brought to your attention in that a considerable sports catch of salmon occurs in California. Recent figures...[show] that 160,000 salmon were taken by sportsmen in 1939. This

is between 1,600,000 and 2,000,000 pounds of fish. If one quarter of these fish, or 500,000 pounds, would have reached the Redding Dam, and represent a value of \$1.00 per pound, which we have placed upon other sports fishes, the value of the run at Redding increases considerably (McMillan, as cited in Calkins and others 1940b, p 12).

DFG members did a far better job than federal representatives in defending the recreational interests of sportsmen loath to abandon prized sports fish as an inevitable price of progress. It would require another six years before steelhead achieved sufficient status to warrant artificial propagation at Coleman.

On October 5, 1940, the Board of Consultants formally responded to the State of California's concerns within a "Supplemental Report" (Calkins and others 1940b)²³. Board members appeared responsive to a future enlargement of the Battle Creek Hatchery and to possible construction of another hatchery on Deer Creek. They raised from eight to fourteen the number of rearing ponds at the Battle Creek hatchery. Calkins, Durand and Rich concurred in using Battle Creek's natural holding ponds solely for adult fish. They increased the number of fish transport trucks from four to seven. Federal reviewers agreed that Keswick Dam should serve both as a river regulating structure and as a fish trapping site. Finally, on the sticky legal point of formalizing an agreement between the State of California and the Department of the Interior over fish salvage matters, Board members stated that it was not within their power to define the "...jurisdiction and responsibility of each agency" (Calkins and others 1940b; Moffett 1949, p 79)²⁴.

Implementing Fish Salvage Principles

The Board of Consultants 1940 recommendations were implemented with a few "minor revisions" (Needham and others 1943, p 7). By June 1, 1943, the

23. Recall that on the mid-Columbia River, Bureau of Fisheries biologists and members of the Board of Consultants responded to a fish salvage program prepared by the Washington State Department of Fisheries. On the Sacramento River, although one may have existed, I find no evidence of a separately existing, state-commissioned, fish salvage report. From the outset, it appears that state and federal regulators were in broad agreement about what needed to be done to save threatened Sacramento River salmon. Grand Coulee Dam's plan may have provided a compelling model for subsequent state and federal fish rescue efforts.

24. State fisheries regulators also proposed an experimental plan to ferry some salmon fingerlings above Shasta Dam to see what would become of them. Throughout the early 1950s, the US Army Corps of Engineers conducted experimental fish passage studies through Shasta Dam's turbines. Coleman's 1953 Annual Report makes mention of a lone, tagged salmon which managed to migrate from Shasta Reservoir and out to sea before returning to the Keswick trap. Board members dismissed the proposal as unworkable.

Bureau had placed in operation the following features of the “Sacramento River, Battle Creek, and Deer Creek Salvage Plan” (called by the Bureau “The Sacramento River Migratory Fish Control Program,” or more generally known as “The Shasta Salmon Salvage Plan”):

- Fish ladder, traps and lifts in the Keswick Afterbay Dam and the Balls Ferry Rack for capturing and removing salmon under high and low water conditions, respectively (Needham 1943, p 8; Moffett 1949, p 79).
- Seven tank trucks for transferring salmon from the Balls Ferry and Keswick Dam traps to the Coleman National Fish Station on Battle Creek, and to Deer Creek;
- Construction of a Battle Creek hatchery infrastructure capable of handling 58 million eggs and approximately 29 million fingerlings. Twenty-eight outdoor rearing and holding ponds were constructed.
- Five racks in Battle Creek provide four holding and ripening areas for adult spring-run transferred from the Sacramento River (Needham 1943, p 8).
- Three removable Sacramento River racks, the lowermost at Balls Ferry. The Balls Ferry rack serves as a trap, as an aid in upstream spawner distribution, and as a barrier to incoming fish.
- One rack on Deer Creek for holding transferred fish upstream and for counting the native runs of fish.
- A fish ladder around Deer Creek’s lower falls to open up five additional miles of spawning stream.

Within a 1943 supplemental report (“Special Scientific Report Number 26”) issued on The Shasta Salmon Salvage Plan, Paul R. Needham, Harry A. Hanson, and Lewis P. Parker amended and updated efforts already underway to save threatened salmon. In it, scientists estimated at greater than 60,000 the actual number of salmon migrating past Redding, a sizable increase over 1939 and 1940s modest, drought-modulated estimates (numbering some 20,000 to 25,000 fish). The updated report warned that “...the [original] salvage plan must be adjusted to great fluctuations in numbers of salmon and that no count to date has established maximum numbers of salmon that may have to be handled” (Needham and others 1943, p 2). Biologists nevertheless recommended transferring 10,000 spring-run fish to Deer Creek with an additional 2,000 being held within Battle Creek for artificial propagation. Eighteen-thousand “summer” fish²⁵ (as they termed them) or early-fall-run fish would be

25. By “summer” fish, I can only assume that Needham and others meant fall-run fish which, they believed, were particularly vulnerable to high water temperatures during the late summer and early fall period (Needham and others 1943).

transferred to Battle Creek for artificial propagation, while 30,000 fall-run salmon would be distributed between Sacramento River mainstem racks for natural propagation (Needham and others 1943, p 7). The biologists reached the conclusion that only two Sacramento River tributaries, Battle and Deer creeks, held any promise for transplanting displaced upper river salmon.

“Special Scientific Report 26” also documents heavy losses occurring among the 1943 year-class of spring-run fish. Mortalities derived from:

A long delay in the completion of trapping facilities in Keswick Dam [which] resulted in serious losses to the 1943 spring-run. Many salmon confined below the dam during this delay were so badly bruised by jumping against the rocks and base of the dam that they died before the transfers began (Needham and others 1943, p 23).

A 24.4 percent mortality occurred among spring-run salmon before successful spawning within Deer Creek²⁶.

Theories are often humbled by the acid tests of time and reality. Implementation of the aforementioned goals began disintegrating from the outset. Moreover, beginning in 1945, the leading institutional role being played by the Bureau (in tandem with the Central Valley Project beneficiaries), was being reevaluated and substantially rescinded. Piece by institutional piece, the Bureau abandoned to the Service (and indirectly, to the DFG) the responsibility for caring for, paying for, and operating ongoing fish salvage efforts.

Throughout the remainder of the 1940s, multiple components of the Shasta Salmon Salvage Plan broke down or were abandoned as unworkable. These fundamental features included (1) the failure of the Sacramento River’s mainstem fish racks; (2) the Coleman National Fish Station’s retreat from and abandonment of its attempts to ripen, hold, and propagate spring-run chinook salmon; (3) the Fish Transport System having higher than expected mortality rates, and (4) the spring-run transfer to Deer Creek being abandoned as unworkable. Finally, in June of 1950, the on-again, off-again Keswick Fishtrap and Loading Facilities were turned over to the Service by an exiting Bureau.

Sacramento River Fish Racks

Bids for the first of three proposed mainstem racks, at Balls Ferry, were received on August 15, 1941 (Needham and others 1943, p 11). This weir was

26. Mention was made of the winter-run fish which “...were very ripe and on several occasions deposited eggs in the truck while enroute from Keswick Dam” to [Deer Creek] (Needham and others 1943, p 23). Once transferred, winter-run salmon deposited their spawn almost immediately in Deer Creek.

the lowermost downstream and it contained a low-water salmon trapping and removing device. Construction began in September 1941 but was discontinued by December due to high water. Construction resumed the following May with the base of the rack completed by year's end. However, in January 1943, a modest flood (73,000 cfs) "...washed out four bents and damaged several more" (Needham and others 1943, p 12)²⁷. The rack had been repaired and made fully operable by late spring. This on-again, off-again pattern continued until this rack was finally abandoned as unworkable in 1945 (Moffett 1949, p 86).

A middle rack was located about 12 miles upstream from the Balls Ferry structure. Substantially completed by September or October 1942, it could never be made "fish-tight" due to a combination of uneven bedrock and unstable gravels (Needham and others 1943, p 16). On November 14, 1942, a modest rainfall occurred, washing downstream great quantities of debris from construction at Shasta and Keswick dams. On the night of November 17, dam debris put sufficient pressure on the structure to "bend 8 by 8 inch stringers" (Needham and others 1943, p 16). The structure became increasingly unstable as workers were unable to clean out accumulating debris. Within a matter of days it washed out, save for an isolated segment near one bank. Engineers concluded that "...it may not be possible to maintain fish-tight racks without permanent sills on which to set tripods" (Needham and others 1943, p 16).

By early 1943, participants decided to abandon constructing a third rack. None of the weirs was ever made "fish-tight" and the units seldom survived longer than the next freshet. By 1946, any pretense of functioning instream racks was dropped as unworkable. Instead, the Bureau entered negotiations with the Anderson Cottonwood Irrigation District (ACID) to use its seasonal diversion dam at Redding as an upstream fish barrier (Moffett 1949, p 87). On November 6, 1950, the Fish and Wildlife Service suspended this weir practice due to excessive fish mortalities observed. The first element of the salvage plan was branded a failure.

The Keswick Fishtrap

Closely tied to the combination Balls Ferry rack and trap was the upstream Keswick Dam Fishtrap. If the former were operable under low water conditions, the latter remained functional at higher rates of flow²⁸. Consisting of a fish ladder, sweep chamber, brail and trap, loading crane and elevator,

27. "Bents" were posts upon which the removable fish racks were held in place.

28. Controversy later erupted because the Keswick Fishtrap became inoperable at flows in excess of 16,000 cfs. The Service asked the Bureau for a significant redesign and negotiations ensued over making the facility functional during periods of high flow.

Keswick Dam's permanent fishtrap began at a slow pace. A temporary "stop-work order" issued by the War Production Board all but halted its construction. Alarmed Service biologists pointed to accumulating year-classes of salmon below and urged some sort of emergency measure. During spring 1942, Service and Bureau personnel improvised a solution from materials they had on hand. By June 1, 1942, the temporary fishtrap began operation (CAR 1943, p 7).

Construction by the Bureau of a permanent trap began during March 1943. However, once it was erected, improvisation was necessary to make it fully functional. The Keswick Fishtrap began operating on April 22, 1943 and continued through August 31, 1943. In the process, surprised biologists learned that "...although the Balls Ferry rack has been installed and closed for some time, fish continued to enter the trap at Keswick Dam" (CAR 1944, p 8). Passing migrating salmon continued defying the lowermost Balls Ferry rack and the upstream rack until both racks washed out altogether.

Considerable fine-tuning was required of Keswick's Fishtrap over the next two years for it to become dependable. During mid-February 1944, experimental trapping of winter-run fish was conducted at the Keswick Dam site. By the end of May, 145 fish were captured and hauled to Coleman Hatchery for "experimental holding purposes" (CAR 1945, p 4). By late August of that same year, 894 winter- and spring-run salmon were captured and moved to other locations.

Following a fairly routine year of trapping, the 1946 season turned things upside down. Failure and abandonment of both lower Sacramento River spawning racks raised fears about serious upstream overcrowding. The Bureau began negotiating with the ACID to use their dam near Redding as an upstream fish barrier. Consequently, the Keswick Fishtrap was "neither required nor in operation" throughout the entire year (CAR 1947, p 1). This would continue through 1950.

While the Bureau continued operating the Keswick Fishtrap, language shifting responsibility between the Bureau and the Service was contained within a September 21, 1948 Memorandum of Agreement. It read: This agreement "...does not specifically provide for the operation of the Keswick Fishtrap or for the transportation of fish therein to the Coleman Hatchery" (CAR 1949). The trap was used minimally during 1947 and the Bureau continued reimbursing the Service's transport costs.

On November 6, 1950, the ACID irrigation dam ceased operating as a fish barrier and the Keswick Fishtrap was again placed in operation. Fish and Wildlife Service personnel questioned the dam turned fish weir's "...value and the extreme probability that numbers of adult salmon were being injured and

destroyed before they could spawn" (CAR 1950, p 3). The Bureau was amenable a discontinuance of ACID's lease as a fish blocking device. The continuing operation of the Keswick Fishtrap remained a cooperative effort between both agencies.

Fish Transport

During 1941, spring-run salmon were captured in a temporary loading and trapping facility located at the ACID dam near Redding. Fish left that site in a tanker truck loaned by the national hatchery at Leavenworth, Washington (CAR 1942, p 15). Fish were hauled to nearby Battle Creek where, lacking suitable unloading facilities, they were released in a way meant to prevent injury.

The following year, Service personnel learned from the Bureau that it had been unable to obtain seven new truck frames which were to be fitted with tanks. Trucks were critical to the ongoing war effort and fish salvage was deemed "nonessential". The Bureau arranged for and received seven semi-trailers upon which tanks were mounted. Describing the results as "very dissatisfactory," Service personnel launched their own campaign to secure new trucks. They eventually succeeded and took delivery of them in early May 1942 (CAR 1943, p 9).

Major difficulties subsequently encountered hinged upon the significant distances between Sacramento River trapping sites and Deer Creek.

Deer Creek was a distant 92 miles from Shasta Dam, thus creating a taxing ride for the fish. To make matters worse, salmon that were held before being transported began the journey in a weakened state. While there were subsequent improvements, the added stress of transporting fish may have influenced decision makers to abandon Deer Creek altogether.

By late 1950, the Service was poised to assume responsibility for the fish transport operation from the Bureau. Service personnel anticipated transferring fish from the Keswick Fishtrap to the Coleman Hatchery and other sites for years to come. Coleman's Director wrote:

It is contemplated to continue the transfer of the adults for an indefinite number of years in the future, or until the run in the Sacramento River so stabilizes itself as not to require further transfers (CAR 1950, p 3).

The Deer Creek Natural Spawning Option

Stream surveys conducted throughout the 1940s concluded that Deer Creek had sufficient space for 15,000 salmon (Moffett 1949, p 93). Reconciling those high expectations with low native stock counts (ranging from 635 fish in 1941

to a high of 4,257 in 1946) was one of many puzzles facing biologists (Moffett 1949, p 89). Despite its obvious problems, Deer Creek still provided the best hope for transferring displaced spring-run salmon.

Experiments conducted during 1941 demonstrated that it was feasible to haul and establish fish in Deer Creek from upstream Sacramento River sites. However, early on, fish were left in a vulnerable state due to hauling delays before their arduous overland journey. Through the end of June 1943, the entire spring- and "summer" -run was trapped and hauled to Deer Creek. A total of 5,243 fish was transferred to Deer Creek with another 944 interned at Coleman Hatchery holding ponds (CAR 1943, p 8). By July 21, known mortalities reached 1,273 fish, almost a quarter of those transferred (Moffett 1949, p 90).

That following year, the spring-run was largely hauled to Deer Creek with the remainder moved to Battle Creek. Upon completion of the seasonal hauling, with 7,868 fish instream, Deer Creek's temperatures rose to 82 degrees Fahrenheit. Within three days, 1,135 fish perished, raising total observed mortalities to 16 percent (Moffett 1949, p 90). Excessive instream temperatures continued to erode efforts at establishing spring-run fish in Deer Creek.

During 1945, 1,606 spring-run salmon were hauled to Deer Creek while only 167 were transferred the following year (Moffett 1949, p 90). Numbers declined for several reasons. First, biologists theorized that significantly cooler water temperatures within the mainstem Sacramento River caused this race to hold and ripen farther downstream than ever before. Second, Deer Creek's status as a first-rate salmon stream fell prey to high agricultural diversions, unscreened irrigation diversions, and significant instream obstructions (like the Stanford-Vina Dam). A means of substituting Sacramento River water for Deer Creek's diversions was never created, thereby making the latter untenable for supporting large populations of fish. Despite the installation of fish ladders and other fish passage improvements, excessive losses "...cast doubt on the ultimate success of the transfer activities" (Moffett 1949, p 91). Serious spring-run transfers ceased by 1946.

Writing in 1948, Service biologists Cramer and Hammack summarized Deer Creek's potential this way: "The progeny of the transplanted salmon are doomed to a gradual or rapid extinction unless the conditions under which both populations are forced to live are changed enough to accommodate them" (Cramer and Hammack 1948, p 15). Without development of a substitute irrigation supply from the Sacramento River, "judicious channelization" at the creek's mouth, and removal of instream dams and obstructions, Deer Creek transfers would remain pointless.

Coleman National Fish Station

A hatchery on Battle Creek was always viewed as essential for perpetuation of the Sacramento River's spring-run fish and for a small segment of the early fall-run. Especially critical times were 1943 and 1944, "...when both Shasta and Keswick dams blockaded upstream passage but stored insufficient water to adequately lower downstream river temperatures" (Moffett 1949, p 79).

Recall that Professors Calkins, Durand and Rich had instructed that one half of what they believed constituted the spring run (or 3,000 out of 6,000 total spring-run fish) and about 4,000 early fall run (of 16,000 total fall-run fish) be transferred to the Coleman Hatchery site on Battle Creek. Coleman was designed to handle about 58 million eggs or advanced fry with any surplus space going to fingerlings.

Under the Bureau contract, hatchery construction began at Coleman in 1942 with the hatchery building completed in November of that year (Needham and others 1943, p 10). It was not until the early summer 1943, however, that Coleman's rearing ponds were capable of receiving spring-run salmon.

Some "experimental holding" of spring-run salmon on Battle Creek was attempted during the 1942 season (CAR 1942, p 15). In early July, a pond was created at an irrigation intake adjacent to Battle Creek. Forty percent of the fish held there died within 16 days of being transferred from the ACID dam. None of the 126 transplanted salmon were recovered for subsequent spawning at Coleman, signaling possible trouble ahead (CAR 1942, p 15-16). Simultaneously, 40 spring-run salmon were placed between racks within Battle Creek to commingle with its native fish. Transplanted and native fish mortalities were high, with 34 fish dying during July, 34 during August, and 27 during September. Thirty-six thousand five hundred eggs were eventually recovered but there was no way of identifying the parent stock (CAR 1942, p 16).

During 1945, Coleman's Annual Report estimated populations of Sacramento River spring- and fall-run chinook salmon to be in excess of those established during the previous year (while their formal counts were diminishing). Biologists resolved this paradox by arguing that spring-run salmon "...did not ascend the river due to the lower water temperatures" (CAR 1945, p 2). They speculated that prevailing cooler water temperatures "...may have caused these salmon to lay in the river until [becoming] near ripe instead of trying to get to the upper waters in the early summer" (CAR 1945, p 4). Whatever the cause, there would be fewer spring-run fish transferred either to Coleman Station, Battle Creek or to Deer Creek. Which fish stocks would take up the slack? The answer, as depicted in Table 1, was predominately lower river, fall-run fish.

Table 1 Annual egg production at Coleman Hatchery, 1943–1950^a

| <i>Year</i> | <i>Spring chinook salmon</i> | <i>Fall chinook salmon</i> | <i>Steelhead trout</i> |
|-------------|------------------------------|----------------------------|------------------------|
| 1943 | 1,053,665 | 8,320,853 | |
| 1944 | 4,040,650 | 11,298,880 | |
| 1945 | 1,281,272 | 20,759,463 | |
| 1946 | 2,763,000 | 25,178,000 | |
| 1947 | 165,000 | 10,875,000 | 31,250 |
| 1948 | | 3,770,000 | 18,104 |
| 1949 | 206,513 | 13,221,464 | 178,052 |
| 1950 | 870,469 | 10,590,509 | 326,303 |

^a Source: CAR 1950, p 17.

By 1945, Coleman raised 16 times the number of fall-run as spring-run fish, a ratio which generally climbed through 1950 (CAR 1946). In 1947, the hatchery raised roughly 66 times the number of fall-run as spring-run salmon. That following year, spring-run production plummeted to zero. The widening gap between spring- and fall-run production may have presented Coleman's Superintendent John Pelnar with an opportunity: he could substitute new species of sportfish – specifically steelhead – for diminishing spring-run fish and maximize production at his large hatchery facility.

In 1946, spring-run transfers to Deer Creek were rejected as unattainable. Beginning in 1947, hatchery production struck out in new directions with an experimental program involving steelhead. By 1950, Coleman accepted all of Keswick Fishtrap's spring-run transfers despite the hatchery's difficulty at holding and propagating these stream-type fish. In retrospect, we now know that it takes heroic measures and 1990s technologies to propagate winter-run salmon. It is no wonder Coleman failed fifty years earlier at replicating similar conditions to save diminishing spring-run fish. In late 1951, Service personnel concluded that perpetuation of the spring-run fish was best served by leaving them undisturbed within the mainstem Sacramento River (CAR 1952).

Early Steelhead Production at Coleman

It is ironic that steelhead were included among sportfish rescued under The Grand Coulee Fish Maintenance Program while they were dropped, initially at least, from consideration under The Shasta Salmon Salvage Plan. How can we account for this historic omission? There are biological, cultural, economic,

institutional, and political factors that underscored an exclusive focus on Sacramento River salmon mitigation.

Recall that members of the Washington State Department of Fisheries wrote the initial draft of the Grand Coulee Fish Maintenance Program. From the outset, that state agency placed a significantly higher economic and political value on the role played by tens of thousands of sportfishers than did their federal counterparts.²⁹ In addition, they argued that the economic “multiplier effects” arising from a vigorous recreational industry made steelhead integral to the region’s economy. Lose steelhead production, so the argument went, and whole communities dependent upon outdoor recreational sports would miss out on a substantial part of their yearly incomes.³⁰

Within their March, 1939 report, members of the Board of Consultants portrayed steelhead in a much less flattering light. They dismissed steelhead production in the mid-Columbia Basin as “not of great commercial importance.” Even worse, however, the Board cautioned that “steelhead are predatory on the salmon.” Hence, to boost the value of commercial fisheries, Rich and his colleagues urged,

...it would seem far better to center attention upon the production of Chinook salmon in the streams of this region and to eliminate rather than attempt to increase the steelhead (Calkins and others 1939b, p 10).

Leavenworth Hatchery’s eventual annual production of 14 million steelhead eggs is more a compromise between the states of Oregon and Washington and federal authorities than a reflection of the Board’s actual preference of exclusively focusing on salmon restoration.

In their 1940 Bureau of Fisheries report, federal biologists Hanson, Needham, and Smith placed steelhead in their “coarse” fish category, together with various species of native eels, Sacramento pike minnow, and the like. Members of the Board of Consultants reiterated that, in addition to being salmon predators, steelhead had little to no commercial value. The Board of Consultants also dismissed the numbers of steelhead passing the Shasta Dam site as “negligible” (Calkins and others 1940a). Steelhead advocacy eventually fell to Service personnel like Coleman Superintendent John Pelnar, members of the DFG, and inland recreational fisheries advocates like Henry Clineschmidt.

29. The same can be said for the California Department of Fish and Game. See Executive Director Lester A. McMillan’s letter to W. F. Durand, dated August 12, 1940 (Calkins and others 1940b, p 11–13).

30. Additional pressure may have been exerted by sportsmen organized to protect their threatened major resources. For a general treatment of sportsmen and the conservation movement, see Reiger (1986).

Clineschmidt was a close friend of John Pelnar and a “very active” Commissioner with the DFG (Hallock, personal communication, see “Notes”). The fact that “Steelhead Unlimited” and “Kamloops, Incorporated” were the same organization went a long way toward explaining the more or less simultaneous introduction of kokanee, Kamloops, and steelhead production at Coleman National Fish Station.³¹ Beginning in 1947, the hatchery experimentally undertook steelhead propagation, a program which continues to this day.³²

The Myth of a Successful CVP Mitigation

Throughout the 1940s, Coleman National Fish Station gradually abandoned its first objective of producing sufficient spring-run fish to perpetuate one-half of the upriver race. The Coleman facility did succeed at the propagation of lower-river, fall-run fish, thereby meeting its 1940 goal of reproducing one-quarter of the fall run among early migrants.³³ Beginning mid-February 1944, the facility experimentally held and attempted rearing winter-run salmon. No evidence pointed to any degree of success. Three years later, Coleman undertook producing steelhead for the first time. Immediately following the decade’s close, Coleman’s hatchery production objectives were broadened as hatchery personnel began stocking Shasta and later Whiskeytown reservoirs with “put-and-take” Kamloops trout and kokanee salmon from British Columbia. Coleman hatchery production objectives diversified from exclusive focus on salmon production to a broader range of recreational fisheries.

31. Under Clineschmidt’s leadership, “Steelhead Unlimited” would later channel money to Coleman via The California Department of Fish and Game and “California Kamloops.” California Kamloops issued the checks for steelhead propagation on behalf of Steelhead Unlimited (USFWS 1956).

32. A recent U. S. Fish and Wildlife Service Draft Report argues that “[construction of Shasta and Keswick dams] potentially denied [steelhead] access to large areas of natural spawning and rearing habitat” (USFWS 1997; USFWS and Hamelberg 1997, p 4).

33. It would take over two decades to recognize that late fall-run chinook salmon constituted a genetically unique stock. During the early years, mixing sometimes occurred at Coleman Hatchery of fall- and late fall-run stocks (Hallock, personal communication, see “Notes”).

This significant transition began during July 1944, in a series of yearly Memoranda of Understanding (MOUs). Bureau administrators began making clear that they wanted to remove themselves from the fish salvage business. It is important to remember that the Bureau consisted of dam builders who moved rivers around as opposed to fish tenders. Fish maintenance, they insisted, was the business of the Service.³⁴ Why not let the Service tend to fishery affairs while the Bureau stuck to what it did best? There was also the contentious issue of signing over to the Service, mitigation budgets over which the Bureau had little or no control. Ron Brockman, Fisheries Program Manager with the Bureau's Sacramento office, believes the Service, via Coleman, sought an autonomous foothold in their California salmon restoration efforts (Brockman, personal communication, see "Notes"). Brockman observes a kind of historic tug-of-war occurring between the Bureau and the Service over who did what, when, (and for how much) at the hatchery facility. From Brockman's point of view, there was always reluctance to have the Bureau involved in shaping operations at Coleman Station.

If precedents on the Columbia River were any guide, Bureau administrators also sought—as soon as practicable—to declare victory and get out of the fish mitigation business (Taylor 1996, p 360). Nor was it the Bureau's intent to remain saddled with costly, long-term mitigation expenditures (Calkins and others 1939b, 1940a). On both the Columbia and Sacramento rivers, or so the theory held, hatcheries constituted capital-intensive means for artificially augmenting fish production within downstream tributaries until natural propagation might take hold. Bureau-supported hatchery mitigations were never intended to be an open-ended proposition with no end in sight (Calkins and others 1939b).

Such views were reflected within successive MOUs as each generation contained more and more equivocal language about the Bureau's responsibilities and obligations to the Service under the original "Sacramento River Migratory Fish Control Program." By mid-year 1948, an institutional mitosis ensued whereby both agencies inventoried, then cleaved, their separate properties and holdings. Initially at least, the Service enjoyed a cost-free, lease-back arrangement. However, that external support did not last for long.

Negotiations discussing Coleman's fate continued to intensify. In June 1947, Coleman Station's Superintendent John Pelnar reported that the station was

34. Roy Wingate, archivist at the Bureau of Reclamation's Denver Regional headquarters, advised me that comprehensive Bureau records ceased being assembled in 1945. That means that events like these occurring subsequent to that year would be difficult to track and were perhaps better retrievable at the regional office level. My trip to the Service's Portland Regional Office was due, in part, to his advice (Wingate, personal communication, see "Notes").

being "...contemplated for abandonment and closure" (CAR 1947, p 50). One month later, the MOU dated July 5 specified the withholding of Bureau funds for fish culture. In addition, the 1948 MOU did "...not specifically provide for the operation of the Keswick fishtrap or for the transportation therein to the Coleman Hatchery" (CAR 1948).

Within the September 21, 1948 Memorandum of Agreement (MOA), the Bureau of Reclamation formally launched the process of a hatchery transfer to the Fish and Wildlife Service. In retrospect, there appears to have been a simultaneous "push" and "pull" to this transaction. Significant numbers of returning mainstem spawners (above and below Red Bluff, and within Battle Creek) left many to argue that the Bureau-funded salvage program had indeed succeeded. For example, biologist James Moffett cites rough estimates of fish spawning above Red Bluff (144,000 in 1944, 106,000 in 1945, and 96,900 in 1946) and concludes that "Natural spawning in the Sacramento River was remarkably successful as is indicated by examinations of dead salmon and the hourly rate of catch in fyke nets of young salmon" (Moffett 1949, p 101). Indeed, a clause within the 1948 MOA stated:

WHEREAS, the Bureau and the Service are agreed that as a result of the salmon maintenance program and the operation of Shasta Dam with a regard for the welfare of the fishery, the salmon runs above Shasta Dam appear to have become established below the dam in numbers equal to the numbers existing before the dam was built...(Engle 1957, Part II, p 421).

Negotiations transferring Coleman from the Bureau to the Service did, however, require the resolution of one final stumbling block. A September 8, 1948 memorandum stated the Service sought to compel the Bureau to underwrite "...the excessive cost of replacing the present Balls Ferry Fish Rack with a good fish-tight structure" (USFWS 1948b). The memorandum concluded that responsibility for the fish rack was "...the only matter upon which there had been a difference in interpretation of the terms of the proposed agreement..." (USFWS 1948b). Acting Service Director Johnson clearly wanted to take possession of a functional Balls Ferry Fish Rack. In a memorandum dated August 11, 1948, he complained the rack "...has not resulted in a fish-tight barrier and because of this, has never been a satisfactory facility for use in connection with operation at the Coleman Fish Hatchery (USFWS 1948a).

Bureau Commissioner Michael B. Straus countered that replacing the structure “would run into seven figures” and, instead, proposed to maintain the temporary structure “...as long as it [stood]” (USFWS and USBR 1948). The Coleman facility enjoyed Bureau funding during the first half of 1949 after which the Service assumed full funding responsibility (CAR 1949, p 1). In addition, the July 1, 1949 MOA declared Coleman Station to be separate from the Bureau’s Central Valley Project obligations.³⁵

The US Fish and Wildlife Service was eager to assume control of the Coleman facility. As former Coleman Superintendent Jerry Grover explained, by seeking a direct appropriation from Congress, the Service could run the facility and pocket a ten percent administrative overhead charge (which once reverted to the Bureau). Absorption of the Coleman facility also “built up” the national hatchery budget by approximately four percent, while the Service picked up added national and regional stature (Grover, personal communication, see “Notes”). A Service-run Coleman was also freed up to operate in a fundamentally new way. In something resembling a paradigm shift, Superintendent Pelnar could diversify Coleman’s production objectives in accordance with a broader, nonreimbursable set of “recreational” criteria, and forego haggling with the Bureau over funding. Since the upstream reservoirs were created by a federal project, federal obligations existed to “...provide and maintain a sports fishery...” (USFWS 1963, p 33; USFWS and Richardson 1985). No longer exclusively tied to CVP mitigation objectives, the Service saw new opportunities in stocking Shasta (and later Whiskeytown) reservoirs with exotic game fish like Kamloops trout and kokanee salmon, in folding in steelhead production, and in achieving additional recreational objectives.³⁶ A heightened federal interest in sports fisheries surely drew applause from California’s senators and congressmen, as well as from California’s Department of Fish and Game.

In the end, elevated egg takes and salmon populations persuaded many State and federal biologists that the Shasta Salmon Salvage Plan had succeeded. Citing State Bureau of Marine Fisheries reports, Martin Blote of the California Chamber of Commerce recounts that catch records were broken in 1945 when salmon landings in California totaled 13,367,523 pounds. This commercial peak was exceeded in 1946 with a total catch of 13,649,673 pounds of fish

35. The Bureau and the Service’s 1948 MOA did contain one fragmentary reminder about CVP fishery responsibility. “WHEREAS, the continued maintenance of the Sacramento River salmon runs is recognized as one of the purposes of the Central Valley Project in operating Shasta Dam,...” This clause reappeared 35 years later as a reminder that the Bureau was responsible for Coleman’s attempts at mitigating for disappearing salmon (and steelhead). See Forbes (1983, p 4).

36. Concomitant to the Service’s takeover at Coleman, Kamloops trout eggs were introduced into California from British Columbia in June of 1948 (CAR 1949, p 43).

(Blote 1948, p 7). Salmon landings in the upper San Francisco Bay, the Sacramento-San Joaquin Delta, and the Sacramento and San Joaquin rivers, totaled 5,467,960 pounds in 1945 and 6,642,050 pounds in 1946 (Blote 1948, p 7). Egg takes at Coleman were also invoked as grounds for optimism. Counts from 1945 (22,040,735 eggs) were surpassed by Coleman's 28,297,100 eggs captured in 1946 (Blote 1948, p 32). In 1947, Superintendent John Pelnar summarized Coleman's artificial propagation and fingerling rearing activities:

...the station, being one of the most efficient and producing units in the world, planned to attain a record undreamed of by fisheries workers. We successfully held and reared 25,794,652 chinook salmon fingerling, all of which had been fed for considerable time before being released....[T]he weight of the fish reared at Coleman during 1947, totaled 109,799 pounds, which is a record for other fisheries workers to look at with wonder and admiration (CAR 1947, p 1).

The temperature regime within the lower river had been so improved by the Shasta-Keswick complex, or so argued Blote, that spring-run salmon "spawned themselves" within the lower mainstem Sacramento River (Blote 1948, p 32). Blote also pondered how continuing reservations about the success or failure of the Shasta Salmon Salvage Plan could be reconciled with record numbers of returning fish (Blote 1948). Although clearly impressed by these and subsequent high abundance figures, biologist James Moffett withheld final judgment, cautioning, in a paper's closing remarks, that "Experience has been insufficient to establish definitely the success or failure of the [Sacramento River] salmon maintenance work..." (Moffett 1949, p 102). What was held as true among many, however, was the belief that a sizable salmon fishery had become reestablished on yet another dramatically altered western river.

A Failed Mitigation Program Confronts Historic Salmon Populations

In retrospect, we can forgive those caught up in events for having made the best judgments possible at a given historic moment. History is sometimes less forgiving, however, as cumulative choices and events often give rise to a cascading series of institutional, economic, and ecological backlashes. Unanswered is how does Coleman's primary failure to mitigate for upstream losses (like spring-run fish) affect the achievement of other key 1940s Bureau of Reclamation "Sacramento River Migratory Fish Control Program" objectives? A reflection on what occurred among other key features of the Shasta mitigation program may answer the query. To reiterate:

- The Sacramento River fish racks essentially failed before being used.
- The Keswick Fish Trap operated on an on-again/off-again basis, and it became inoperative at moderate flows exceeding 16,000 cfs.

- The Fish Transport service often delivered weakened fish to inferior waters.
- Coleman National Fish Station was never able to propagate one half of the threatened spring run.
- The Deer Creek fish transfer was completely abandoned as unworkable by 1946.

In the end, what is concluded is that the mitigation failed.

The two surviving pieces of the original Shasta Salmon Salvage Plan were the Coleman Station itself and the Bureau-run Keswick Fishtrap. From the Service's point of view, Coleman Station did succeed at producing significant numbers of fall-run chinook salmon.

Although perhaps not in direct alignment with the [originally] proposed mitigation responsibility, the contribution of Coleman NFH in maintaining the ocean and sport fishery and upper river escapement of fall chinook salmon, while the quality of the Central Valley watershed was continually degraded, (Yoshiyama and others, this volume; USFWS and Hamelberg 1997, p 7).³⁷

Within ensuing years, the Bureau's Keswick Fishtrap also continued being called upon to capture incoming cohorts of salmon. Most of the time the fishtrap functioned satisfactorily. However, even under moderate flow conditions of 16,000 cfs or greater, the fish trapping apparatus became inoperative (Hallock 1987, p 32).

What was lost with the building of the Central Valley Project's keystone Shasta-Keswick complex? Based upon initial 1940 run-estimates, the answer is roughly:

- 15% of the fall-run's upriver habitat.³⁸

37. An earlier version of this document was reviewed by unnamed Service biologist(s) stationed at Red Bluff's Northern Central Valley Fish and Wildlife Office. Subsequent correspondence attributed those comments to biologist Scott Hamelberg. This final version is clearly stronger for Hamelberg's efforts (USFWS and Hamelberg 1997, 1999).

38. Late fall-run fish would require years before being identified as a separate phenotype. Their upriver spawning habitats were more adversely affected than those of the fall-run salmon. DFG biologist Richard Hallock observes that late fall salmon eggs taken at Keswick Trap (between January and March) sometimes made up one-half to one-third of the total Coleman egg take. He adds that Coleman stopped taking late fall eggs when too many "green" salmon (winter-run) were being hauled back to Coleman hatchery (Hallock, personal communication, see "Notes").

- Save for upper Battle Creek, 100% of the winter-run's historic habitat.
- 100% of the spring-run's habitat in the watershed above Keswick.
- 90% of the steelhead's habitat.³⁹

However, this was not all. Within their supplemental report to the original 1940 Shasta salmon salvage estimates, biologists Needham, Hanson, and Parker concluded that 1940 and 1941s runs were "...near 60,000 salmon by early December" (Needham and others 1943, p 14). Admitting that total runs "...might actually have been far greater than 60,000..." these scientists concluded that 1940 and 1941s combined runs

...could not have been less than 50,000 in either season " ...and that the salvage plan must be adjusted to great fluctuations in numbers of salmon and that no account to date has established the maximum numbers of salmon that may have to be handled (Needham and others 1943, p 14).

The salmon abundance estimates of 1943 roughly doubled previous drought-moderated figures under the Shasta Salmon Salvage Plan. Their new benchmarks included:

- 12,000 spring-run salmon (captured between January 1 and June 30).
- 18,000 summer and early-fall salmon (captured between June 16 and October 10 for artificial propagation).
- 30,000 fall-run (captured between October 1 and December 31 for natural propagation within the mainstem Sacramento River) (Needham and others 1943, p 7).

39. Recall from earlier discussions that steelhead propagation was folded into Coleman's operations in 1947. We have scant evidence of historic steelhead populations. I assume that historically, steelhead may have used spawning beds as far as 10 miles below Keswick Dam, hence the approximation of a 90 percent loss. If one assumes steelhead never spawned within the Sacramento River's mainstem, then estimates for what is missing climb upwards toward 100 percent.

More sobering still are recently prepared DFG spawning habitat estimates of historic salmon and steelhead populations above Keswick and Shasta dams (see Appendix A)⁴⁰. Using recent and early spawning gravel surveys⁴¹, biologists computed the number of nesting sites lost above Keswick and Shasta dams as a percentage of the entire Sacramento River run. These calculations assumed that each redd was 40 square feet above Shasta Dam (Hanson and others 1940) and 50 square feet downriver (Rieser and Bjorn 1979). In 1939, roughly 15 percent of the total fall run's estimated spawning areas occurred above Keswick Dam. Computations were based on 24,847 salmon spawning sites upriver from Shasta Dam and 5,945 salmon spawning sites occupying the stretch between Shasta and Keswick dams. The recommended space for spawning pairs during the mating process is 145 square feet for spring run and 215 square feet for fall-run salmon (Rieser and Bjorn 1979).

The most critical feature of the lost spawning grounds above Shasta and Keswick dams was not the absolute number of fish excluded but rather the quality of that drought-proof habitat. The McCloud River, the Little Sacramento River, and the Pit River were resistant to drought and the mortality caused by elevated water temperatures. These upper watersheds produced high quality habitats because of their higher elevations and their volcanic geomorphology. These rivers absorbed much of the wet seasonal runoff, then gradually released it in abundant cold spring flows throughout the dry season. The respectable counts of salmon and steelhead returning to the areas above Shasta Dam at the close of 1939's drought cycle attested to the drought-resistant character of these stream reaches. The habitat above Shasta Dam also provided for the natural spatial separation of the different races of salmon; especially spring-run and winter-run chinook.

Estimates of usable spawning habitat available in the first 130 river miles below Keswick Dam varied greatly among the four available studies. The pre-Shasta Dam estimates of 1939 occurred immediately following one of the worst droughts in recent history. That makes redd counts extremely low compared to the post-Shasta Dam era where estimates climbed due to higher and cooler river flows. The 1939 estimate for the 60-mile reach between Keswick and Red Bluff was placed at 18,413 spawning sites, while figures for this same

40. Within an unpublished paper, H. D. Radtke and S. W. Davis use Northwest Power Planning Council methodologies to estimate historic Central Valley salmon abundance. They reconstruct populations at between 2 million to 4 million fish (as cited in Gresh and others 1998, p 7). Using commercial catch figures, DFG biologist Frank Fisher estimated historic Central Valley salmon populations to have been 2 million fish (Fisher 1994). By drawing on USFWS derived run-size estimates, Thomas Richardson estimates pre-1915 peak Sacramento River salmon runs to have been between 800,000 to one million fish, with a yearly average of 600,000 (Richardson 1987, p 6; USFWS 1984).

41. Historic survey data derive from Hanson and others (1940, p 25, 31, 48).

reach after Shasta Dam averaged 120,588 sites. There was no comparable 1939 estimate for the 70-mile reach below Red Bluff Diversion Dam because it appeared to observers to be of excessively poor quality. However, if it is assumed that in 1939 there were the same numbers of sites above as below Red Bluff (18,413), this was significantly lower than the estimate of 70,908 sites determined in a 1976 mapping.

The spawning habitats below Shasta Dam were apparently increased during periods when there were cold high volume water releases from Shasta Dam. There is a danger, however, in counting on these conditions if they were transitory (as described in Moffett 1944). Even if there were assurances of making the lower elevation habitats below reservoirs reliable, they certainly did not possess quality conditions comparable to those found above Shasta Dam. The below-dam habitats remained drought-prone and they did not provide spatial isolation between overlapping stocks of spring- and fall-run salmon. Currently, below Shasta Dam, the winter-run salmon have 40 miles of river with suitable spawning habitat available during 90 percent of the water years with no available habitat under the worst drought conditions (USBR 1991; DFG 1992; NMFS 1992). To make matters worse, DFG biologist Richard Hallock demonstrated that over a 17-year period, Red Bluff Diversion Dam greatly undermined downstream reproductive conditions where lower river water temperatures were suitable for winter-run spawning and incubation 22 percent of the time (Hallock 1987, p 55).

Above-Shasta populations of winter-run salmon once had an estimated 34,634 spawning sites available in the Little Sacramento, the McCloud, and the Pit river systems. Save for Battle Creek, 100 percent of the winter-run race spawned upriver from the Shasta-Keswick complex (Hallock and Rectenwald 1989).

Pre-Shasta populations of spring-run salmon once had at least 51,377 spawning sites dispersed throughout the Little Sacramento, the McCloud, and Pit rivers. In the 1920s, Pacific Gas and Electric's Pit River dams cut off an additional 7,444 upriver spawning sites without benefit of mitigation.⁴²

Despite substantial evidence of widespread failure, the Bureau, the Service, the DFG, and many interested observers, convinced themselves that the "Sacramento River Migratory Fish Control Program" had succeeded. In the end,

42. This figure is based upon DFG computations. For insights into the proposed damming of the lower Pit River, see Hopson and Means (1915). G. H. Clark observes that Pit Dam No. 4, PG&E's lowermost dam on the Pit River, blocked upstream passage of salmon. The structure was completed in May 1927, and, as biologist Clark observes, "...is impassable with no provisions to take care of the fish." Pit No. 3 is located nine miles upriver. Also impassable, it was completed in 1925 (Clark 1929, p 42-43).

the spectacle of considerable fish in the Sacramento River provided the screen to hide the salvage program's cumulative failures. A myth had been created and it would require considerable time before the Shasta Dam's full effects came into plain view.

IV. Coleman Hatchery Production: The 1950s

Throughout the 1950s, a Service-directed Coleman Station produced a wider assortment of fish species reared for a greater number of northern California destinations and clients. In addition to fall-, winter- and spring-run chinook salmon, Coleman produced or handled coho salmon, steelhead, rainbow trout (mostly provided by the State of California), Kamloops trout, kokanee salmon, and even a few warm water fishes. Specific clients came to include "Kamloops, Incorporated" and "Steelhead Unlimited" of Redding, Beale Air Force Base (near Marysville), and Stead Air Force Base.

Between 1949 and June, 1957, the Bureau of Reclamation sponsored cooperative state and federal research consisting of life cycle assessments and data accumulation on the continuing fish maintenance program. Writing within their summary report, Service biologists Robert L. Azevedo and Zell E. Parkhurst observed that:

...during the 1943–1949 period [the upper Sacramento River changed]...from primarily [being] a salmon salvage program to a program of maintenance and evaluation. The Bureau of Reclamation continued to finance the fishery program beyond the salmon salvage stage because evaluation studies, as well as hatchery operations, were considered an integral and necessary part of the conservation of natural resources associated with the Central Valley Project (Azevedo and Parkhurst 1957, p 3–4).

The ensuing eight-year program principally consisted of:

- Spring-run chinook salmon being left to spawn naturally within the Sacramento mainstem and other accessible tributaries.
- Fall- and some winter-run chinook salmon being taken at Keswick Fishtrap and hauled to Coleman Hatchery for artificial propagation.
- Fall-run chinook spawners being diverted from Battle Creek into the Coleman facility.
- Data gathering to determine annual fluctuations in populations, fishing pressures, adverse effects of mining leachate, and so forth (Azevedo and Parkhurst 1957, p 4–5).

Within what Kai Lee has subsequently called an “industrialized ecosystem,” riverine studies such as these were useful in determining how best to coordinate Coleman’s migratory releases coincident with natural fish migrations and other identifiable windows of opportunity (Lee 1993; Azevedo and Parkhurst 1957, p 6). For instance, water temperature records aided in determining optimal periods for releasing salmon fingerlings. In addition, by carefully tracking upriver pollution deriving from sites like Iron Mountain mine, Coleman Hatchery’s personnel even sought to avoid excessive fishkills.

These and other similar data provided Coleman Superintendent John Pelnar with means of maximizing fish escapement. Within a dramatically altered ecosystem, Coleman-reared fish arguably possessed certain advantages never enjoyed by their wild counterparts. For instance, Superintendent Pelnar knew the best times of the year to avoid hatchery releases due to excessive downstream irrigation (Hallock, personal communication, see “Notes”). It was certainly helpful knowing about mainstem Sacramento River water exports considering the “...335 separate diversions, utilizing a total of 448 pumps, along the Sacramento River between Redding and Sacramento” (Hallock and Van Woert 1959, p 263). Coleman also provided State and federal biologists with increasingly sophisticated means of marking outgoing and incoming cohorts of anadromous fish (Cope and Slater 1957). DFG biologists, in particular, conducted elaborate marking experiments for tracking the whereabouts, perils, and life cycle patterns exhibited by anadromous fish.

Fall-run chinook salmon and steelhead production predominated at Coleman with a small but steady supply of imported Kamloops trout and kokanee salmon for Shasta Reservoir. The hatchery’s last major attempt at spring-run production occurred in 1951 (after which it was begrudgingly abandoned).⁴³ In 1955, an experimental trapping of winter-run salmon occurred in which only two females out of 184 total fish spawned (CAR 1955, p 20). Experimentation with winter-run stocks reoccurred during 1958 when they stripped eggs and milt from a total of 191 fish (CAR 1958, p 20). Attempted propagation of winter-run fish ceased during the following year, only to occur again in 1962.

In 1952, British Columbia- and Montana-derived Kamloops trout and kokanee salmon were obtained by Coleman Hatchery for a recreational fishery in Shasta Reservoir.⁴⁴ Henry Clineschmidt’s Redding-based group(s), “Kam-

43. Well, almost. During 1954 they propagated a total of four spring-run chinook (CAR 1955).

44. Richard Hallock observes that during the 1950s, marked yearling Kamloops trout were also released in the Sacramento River to produce a resident trout fishery near Redding. The fish, however, took an unexpected turn and headed out to sea, only to return with incoming steelhead. Hallock also points to evidence of hybridization between Kamloops and steelhead (Hallock, personal communication, see “Notes”).

loops, Incorporated," (and "Steelhead Unlimited") forged several funded, cooperative agreements with the Bureau of Sports Fisheries and Wildlife and the DFG, to propagate specific game fish. Clineschmidt, like Pelnar, was a significant force in northern California fisheries circles, and together, they made formidable advocates. Clineschmidt and Pelnar's plan was simply to introduce Kamloops trout into Shasta (and later Whiskeytown) reservoirs, to be followed by kokanee salmon (Hallock, personal communication, see "Notes"). They hoped to mirror ecological conditions found in Idaho's lake Pend Oreille, in which legendary forty pound Kamloops trout fed off an established kokanee population. Anticipation of landing a forty pound Kamloops trout on light tackle went a long way toward explaining why "Kamloops, Incorporated" and "Steelhead, Unlimited" were founded by the same individual and consisted of complimentary memberships.

In 1955, Coleman's production was drafted by the US Air Force. The Commander at Beale Air Force Base (near Marysville) sought advice and assistance in stocking waters adjacent to his geographically-isolated personnel. Beale's base population would soon swell to over 15,000 individuals as it became a Strategic Air Command base.⁴⁵ Rainbow trout as well as some warm water fishes were planted. A subsequent agreement signed between the Service and the Air Force directed Coleman to stock waters near two northern California bases (CAR 1955, p 5). Some rainbow trout were reared at Coleman while the majority came from State of California hatcheries.

In March 1956, 43,025 yearling coho salmon were introduced into the Sacramento River basin from Washington's Lewis River (Hallock and Fry 1967, p 15). In late September 1957, Coleman Hatchery trapped 910 coho salmon for the continuing experiment in artificial propagation (CAR 1957, p 5).⁴⁶ Cohos were promoted by Jim Baucum, President of the Sacramento River Resort Owners Association. Baucum, himself a resort owner (in Los Molinos), saw an opportunity in introducing these prized sports fish into the Sacramento's mainstem. Resort owners sought to convince biologists that cohos might fill a seasonal recreational fishing "gap" without unfairly competing with other anadromous fish.⁴⁷ The Resort Owner's Association promised to foot the bill

45. In 1960, Congress passed the Sikes Act which institutionalized cooperative arrangements between the US Fish and Wildlife Service and other federal agencies which were interested in stocking and managing, among others holdings, Indian and military reservations (USFWS and Hamelberg 1997, p 7).

46. Of this total, 125 were females, yielding a total of 386,971 eggs (CAR 1957, p 5).

47. Richard Hallock, personal communication, see "Notes." DFG biologists presumed that coho would come upriver after steelhead and remain within the mainstem Sacramento rather than proceed on into upriver tributaries and compete with other salmon.

if Leo Shapovalov of DFG and John Pelnar of Coleman Hatchery were agreeable. Coho salmon trapped at Coleman were part of a three year study conducted by Richard Hallock of the DFG (Hallock, personal communication, see "Notes"; Hallock and Fry 1967, p 15-16).

Over the next three years, Coleman and Darrah Springs hatcheries sought to establish a run of coho in the Sacramento River basin. Hatchery personnel later discovered that eggs taken from returning fish were unsuitable for artificial propagation. The eggs themselves were soft and failed to fertilize properly. The experiment seemed to have been quietly discontinued in 1960 when 63 coho were released into Battle Creek (CAR 1960, p 6). Superintendent John Pelnar was pleased to be rid of the project because, in the words of biologist Richard Hallock, "it made his numbers look bad" (Hallock, personal communication, see "Notes"). By the fall of 1963, Hallock and Fry reported that cohos were as scarce in the Sacramento River as they had been before this recreational experiment (Fry and Hallock 1967, p 16).

Throughout the 1950s, the DFG reported a general increase in steelhead populations throughout the remaining mainstem Sacramento River. By 1958, artificial propagation of steelhead at Coleman Hatchery shifted from its prior experimental status to becoming a more fully established program. Collaboration with members of Steelhead Unlimited and the DFG helped solidify Coleman's steelhead production objectives. Azevedo and Parkhurst reported that roughly 5,000 chinook salmon and 2,500 steelhead were caught by sportfishers in the upper Sacramento River between 1952 and 1954 (Azevedo and Parkhurst 1958, p 70). These biologists also noted that Sacramento River fishing resorts "...increased from eight in 1951 to twenty in 1954" (Azevedo and Parkhurst 1958, p 70). Kamloops, kokanee and steelhead production at Coleman was bolstered by outside recreational interests who shared a sizable economic stake in the hatchery's recreational production.

Throughout the 1950s, disease remained a serious problem at Coleman Hatchery. In 1953 through 1955, biologists believed a filterable virus of unknown origin hit hatchery salmon stocks.⁴⁸ Heaviest losses occurred during March, April, and May of 1955 when almost 17 percent of the salmon stock affected died (CAR 1955, p 5). Biologists observed the disease outbreak diminishing when water temperatures rose in late Spring. Again during 1958 and 1959, the station was hit by considerable losses among salmon fingerlings, prompting personnel to write: "Since the advent of this station's fish operations a steadily increasing loss was suffered by all age groups of chinook salmon, various

48. Biologists believed that with sufficient filtration, they could prevent the onset of this disease. The disease was probably Infectious Hematopoietic Necrosis (IHN) which was finally identified in 1962 after several years of study.

remedies were made use of but to no avail" (CAR 1959, p 7). Scientists from Seattle's Western Fish Disease Laboratory were called in to study the problem.

As hatchery personnel busily contained disease outbreaks, Coleman's director observed there was growing public interest in hatchery activities and production. A steady stream of visitors prompted Superintendent Pelnar to write:

Considerable interest has been shown by commercial and sport fishermen in the station's work, due to the general down trend of the chinook run in California. Many feel that the natural reproduction is no longer practical and far too much loss occurs from natural spawning (CAR 1957, p 3).

Throughout the 1950s, Coleman National Fish Station's diversification strategy appears to have been opportunistically motivated. Saddled as it was with running a very expensive facility, the Service had little choice but to continually seek sympathetic outside constituencies, external funding, and broad-based public support. By 1960, the sole remaining formal piece of the Bureau's original "Sacramento River Migratory Fish Control Program" was booming production of predominantly lower-river, fall-run chinook salmon. In 1960, Coleman hatchery combined the stripped eggs of 6,849 female salmon with the milt of 2,225 males to yield 41,612,640 fertilized eggs. Of this total, 96 percent survived to become fingerlings (CAR 1960, p 26). Although not originally part of the Bureau's upriver mitigation efforts, steelhead production continued at Coleman where 357 females and 207 males were stripped yielding a total of 791,000 fertilized eggs. Almost 79 percent survived to the fingerling stage (CAR 1960, p 26). Meanwhile, due to increasing habitat degradation, water exports, and stock hybridization, among other causes, naturally-reproducing Sacramento River salmon and steelhead populations continued their long, steady decline.

V. Coleman Hatchery Production: The 1960s

Well established production patterns originating in the late 1940s and early 1950s continued at Coleman National Fish Hatchery through the 1960s with a few notable exceptions. In 1961, a small number of Kamloops trout was produced for stocking Shasta reservoir and fall-run chinook salmon and steelhead trout remained the primary fish reared at Coleman.⁴⁹ The DFG supplied Coleman with catchable rainbow trout for stocking Beale Air Force Base (CAR 1962, p 3) and the following year, brown trout were imported from Massachu-

49. In 1961, Donald Fry identified a separate late fall-run of chinook salmon on the Sacramento River when substantial numbers of spawning fish were captured at Keswick Fishtrap and hauled to the Coleman National Fish Hatchery (Fisher 1994, p 871; Fry 1961).

setts to stock California sites (CAR 1962). Twelve coho salmon made their way back upstream to the Battle Creek hatchery while the Keswick Fishtrap was used to trap 2,625 winter-run salmon for re-release below the ACID dam.⁵⁰ One hundred fifty-five winter-run salmon were also trapped and hauled to Coleman's ponds for ongoing experimentation.

Biologists at the DFG cooperatively marked one half million hatchery chinook salmon fingerlings for the third year in a row. A third of the fish was released into adjacent Battle Creek and a third was trucked to Rio Vista. The final third was hauled to Rio Vista and then transported downstream by boat for eventual release at 50 percent salinity (CAR 1961, p 13). By planting fingerlings within different parts of the river basin, scientists sought to understand issues like optimal escapement size, straying effects, and eventual upriver recruitment of mature fish. Those fish released at Rio Vista "contributed significantly more [1.5 times]...to the fisheries than those released at the hatchery," while downstream transplants "strayed considerably [more] from the parent stream when returning to spawn" (Hallock and Reisenbichler 1979, p 3). DFG also conducted a jointly run Kamloops marking program.

Outbreaks of the "Sacramento River Chinook Salmon Disease" (Infectious Hematopoietic Necrosis) continued at Coleman Hatchery. During 1960, fish disease specialist Tom Parisot substantiated prior observations that a subtle increase in hatchery water temperatures to between 54 and 56 degrees "rendered the virus agent inactive" (CAR 1961, p 13). Biologists constructed a system capable of blending, then re-using, warmer temperature well water with cooler Battle Creek waters to obtain the desired 54 degree temperature. Unfortunately, the experimental system easily clogged up with mud, silt, or debris, causing high mortalities among fry. Various parasitic and bacterial invasions continued to dog production efforts at Coleman National Fish Hatchery as it had throughout the 1950s.

In 1966, Coleman's disease specialist Elmo Barney prescribed "antibiotic therapy" to nullify the ill effects of disease on Coleman's fish stocks (CAR 1966, p 9).⁵¹ It was not until February 1967, that an experimental water rehabilitation system existed for regulating water temperatures. Hatchery personnel pinned high hopes on temperature stabilization, calling it "The first real breakthrough in the control of the Sacramento River Chinook Salmon Disease..." (CAR 1968, p 4). That optimism was dashed the following season

50. Biologists believed that winter-run below Keswick Dam could become entrained in irrigation canals upstream from ACID (CAR 1961, p 11).

51. To quote from the annual report, "Healthy and diseased fish were challenged with new parasiticides and bactericides for fish toxicity and biological control. Satisfactory control of Myxobacterial infections in juvenile fish populations has been attained through antibiotic therapy" (CAR 1966, p 9).

when three times the normal precipitation fell upon the Battle Creek watershed, keeping water temperatures well below normal for over six weeks. Sacramento River Chinook Salmon Disease “ran rampant” through the chinook salmon stocks, save for those few enjoying elevated temperatures within a Burrows water re-use system (CAR 1969, p 6).

Throughout the early 1960s, Coleman Hatchery personnel continued cooperating with other federal agencies including the US Bureau of Reclamation and the US Army Corps of Engineers. The Bureau continued operating the Keswick Fishtrap and attempted to control, as best they could, for toxic mining leachate harmful to anadromous fish (CAR 1962, p 8).⁵² When pulses of heavy metal contamination exited Spring Creek, Bureau personnel trapped, then hauled, downstream winter-run salmon for re-release below the ACID dam. Members of the Army Corps of Engineers used Coleman fish in a lengthy series of elaborate studies of fish passage through Shasta Dam’s turbines.

Winter-run Salmon

During 1962, 140 winter-run chinook were hauled to Coleman for experimental holding and propagation. The first full length report on the occurrence of the Sacramento River winter run occurred the following year, when Service biologist Dan Slater published a seminal article on the salmon. Slater observed that, historically, winter-run were “...uniquely adapted to streams fed largely by the flow of constant-temperature springs arising from the lavas around Mount Shasta and Mount Lassen” (Slater 1963, p 8). In 1884, Livingston Stone identified the winter run (he also called them “black salmon”) as one of three major stocks inhabiting the upper Sacramento River (Stone 1874; Fisher 1994, p 871). In its 1888–1889 Biennial Report, the State Board of Fish Commissioners records that, “it is a fact well known to fish culturalists that winter and spring run salmon, during the high cold winters, go to the extreme headwaters of the rivers if no obstructions prevent, into the highest mountains” (SBFC 1890, p 33; Hallock and Rectenwald 1989, p 4) Ironically, mention of the winter run also occurred among early biological investigators charged with creating Shasta Salmon Mitigation Plan proposals (Hanson and others 1940). Although never included among the Board of Consultants mitigation obligations, the winter-run waited until the late 1960s before its life history details were fully understood.

Combining life history traits common to both “stream-” and “ocean-type-” salmon, the winter-run was something of a behavioral anomaly (Healey, as cited in Groot and Margolis 1991, p 319). Mike Healey observes,

52. Bureau personnel sought to remove mature fish from the river when Spring Creek’s pollution was present (CAR 1962, p 8).

[winter-run fish] enter the river green and migrate far upstream. Spawning is delayed for some time after river entry. Young winter-run chinook, however, migrate to sea in November or December, after only four to seven months of river life (Healey, as cited in Groot and Margolis 1991, p 319).

Biologists Slater and Richard Hallock combined their talents to estimate inland catch and population. Concomitantly, Slater approached Pacific Coast fisheries agencies to determine if there were other similar stocks. When that answer came back “no,” it became clear winter-run were uniquely adapted to the Sacramento River (Hallock, personal communication, see “Notes”).

Independently of Slater’s work, questions about the winter run continued to pique Hallock’s interest. Hallock questioned whether the winter-run constituted a truly distinctive population. Over the course of three years, and working together with five assistants, Hallock seined, fin-clipped, and released several hundred thousand juveniles along the shores formed by Red Bluff Diversion Dam. Seining occurred “almost entirely in September” when the juveniles were 35 to 45 mm in length (Hallock, personal communication, see “Notes”). Adult returns allowed Hallock and his colleagues to construct the first life history profile on where the fish went in the ocean, age at spawning, eggs per female, catch to escapement ratio, and migration timing (Hallock, personal communication, see “Notes”; Hallock and Reisenbichler 1980; Hallock and Fisher 1985).

Red Bluff Diversion Dam

In 1987, Richard Hallock identified the Bureau of Reclamation’s Red Bluff Diversion Dam (RBDD) as “One of the major causes, and perhaps the single most important recent cause of the decline of salmon and steelhead in the Sacramento River...” (Hallock 1987, p 33). Originally promoted as a “fish-enhancer,” the structure was located two miles downstream from Red Bluff and it diverted water into the Tehama-Colusa Canal and to the Corning Canal Pumping Plant. During average water years, each canal shunted 700,000 and 50,000 acre feet, respectively (Hallock 1987, p 33).

Completed in 1964 (it became fully operational in 1966), the dam included elaborate fish protection measures. Closed circuit television monitored fish passage through separate fishways. A built-in trap assured biologists access to incoming adult fish. Louver-type fish screens sought to limit fish losses within canals while a (never-used) Service hatchery was eventually constructed on site to harvest roe and milt from excessively ripe fish.⁵³ The 3,000 salmon which once occupied RBDD's immediate upstream spawning riffles were to be more than compensated by newly engineered downstream spawning channels suitable for holding 30,000 fish (Hallock 1987, p 58).⁵⁴ Jack Savage of the Fish and Wildlife Service promoted the idea of spawning channel enhancements (Hallock, personal communication, see "Notes"). The mitigation strategy partially stemmed from Washington State and British Columbia precedents with considerable help provided by Columbia River-based engineering and hatchery staffs (Grover, personal communication, see "Notes").⁵⁵ There were just two problems: it never worked, and, to make matters worse, it required 20 years to discover that fact.⁵⁶

Richard Hallock observes that the Red Bluff Diversion Dam radically altered the existing distribution of fish within the lower and remaining reaches of the Sacramento River. Before its full operation, 90 percent of the fall-run spawned upriver from the damsite. After operating for a decade, less than 40 percent of the fall-run chinook salmon spawned above and greater than 60 percent were distributed below the dam site (Hallock, as cited in Lufkin 1991, p 100).

53. Female salmon were considered ripe upon losing eggs when handled. The Service constructed the temporary 3 million-egg incubation station near the dam's left bank fishway. Fish were released back into the river in the hope that they would spawn naturally. The facility became fully operational in 1979, but due to a "...lack of personnel and management interest," the 7 million egg hatchery was never used (Hallock 1987, p 33). Within a subsequent cooperative study, biologists demonstrated that "...an average of almost 2,500 (3.4%) of those [fish] passing the dam were ready to spawn immediately..." (Hallock and others 1982, p 17).

54. Tehama-Colusa Fish Facilities enhancements were calculated at 27,000 fish, a hypothetical number which "...made the entire [diversion dam] water project much more feasible" (Hallock 1987, p 58).

55. In 1950, Harold Gangmark operated a federally sponsored artificial spawning channel in Mill Creek at the site of the old abandoned hatchery at Los Molinas (Hallock, personal communication, see "Notes"). Dale Schoeneman was brought in to manage the newly constructed RBDD spawning channels from Washington State where he oversaw a similar spawning channel venture.

56. Cost for building the Tehama-Colusa Canal "salmon enhancement facilities" was \$23 million dollars. Engineers originally called for building a "dual-purpose" irrigation-spawning canal, including water turn-outs, for spawning fish at Thomes and Stony creeks. For a particularly biting assessment, read Zeke Grader's commentary (Grader 1988a).

Although historical information was lacking, declines among other races of anadromous fish followed these same disturbing trend lines. Hallock reported:

Between 1969 and 1982,...RBDD has caused an estimated loss in the upper Sacramento River system's adult salmon population of 114,000 fish: 57,000 fall run, 17,000 late fall run, and 40,000 winter run. These losses have deprived the fisheries of about 228,000 salmon a year at a catch-to-escapement ratio of two-to-one...In addition, an estimated decline of 6,000 sea-run steelhead...has been attributed to RBDD (Hallock, as cited in Lufkin 1991, p 101).

Biological investigations document upstream salmon passage delays of one to forty days, while an additional 26 percent never even made it past the dam (Hallock 1987, p 36). Particularly hard hit were winter-run salmon which remained ill-suited to spawning within the warmer lower river. Downstream from Red Bluff Diversion Dam, Hallock reports that "...water temperatures were suitable for winter-run spawning and incubation...only four out of eighteen years (only 22 percent of the time) between 1967 and 1984" (Hallock 1987, p 55). By comparing the 1967-1969 average salmon counts passing RBDD with those between 1970-1982, Hallock and Fisher demonstrated a decline of 58 percent (or 40,364) among winter-run salmon. If records from the three drought years of 1979-1980 and 1982 were included, the percent winter-run decline was 79 percent (79,289 fish), or a 52 percent decline in each successive generation (Hallock and Fisher 1984, p 9).

Hallock observes that upstream dam passage delays increased with river flow, for mature fish experienced greater difficulty finding fishways under higher than lower water conditions (Hallock, as cited in Lufkin 1991, p 100). Downstream passage by juvenile fish was equally problematic, as excessive downstream dam turbulence disoriented emigrating fish and forced them toward the river's surface. Whereas adult fish held their own against predators like Sacramento pike minnow, striped bass, steelhead and shad, younger fish often were eaten. Among juvenile salmon, 1974 Service studies estimated downstream migratory salmon losses at between 55 to 60 percent during daylight hours (Hallock, as cited in Lufkin 1991, p 100). Within another document, ocean sampling data among marked Coleman salmon indicated that fingerlings freed below RBDD "...survived better than those released upstream from the dam...Losses among those released upstream from the dam ranged between 29 percent and 77 percent (Hallock 1983, p 5). To this day, many fish conservationists still consider the Bureau's Red Bluff Diversion Dam to be a "fish killer."

Quite unlike the once proposed Iron Canyon or Table Mountain dams, however, the Red Bluff Diversion Dam did not "nullify" the attempted Shasta Salmon Salvage Plan of the 1940s. Serious delays in upstream fish passage did

render remaining spawning grounds inaccessible to a quarter of the fall run alone. Excessive dangers accompanying downstream fish passage further undermined escapement, and, among Coleman managers at least, raised the size, distribution and age of fish at release. If the original "Foster Plan" sought to balance natural propagation within the mainstem Sacramento with artificial propagation at Coleman National Fish Hatchery, then RBDD hurt the former while selecting for the latter. Coleman's personnel could plan rearing fish to larger sizes, and release these same cohorts below the offending structure. Naturally spawning spring- and winter-run salmon did not enjoy these same artificial advantages and were left as they were to fend for themselves within the river's mainstem. Yearling steelhead, which were released below Red Bluff Diversion Dam enjoyed twice the rate of return to the Coleman Hatchery as those released directly into Battle Creek (Hallock 1976, p 2). Declining numbers of returning migratory fish began to worry biologists who became aware of a troubling portrait of irreversible declines.

Diminishing Anadromous Fisheries

Within a July 11, 1968 memorandum, Walter T. Shannon, Director of the DFG, called for severe cutbacks in commercial and recreational salmon harvests (Shannon July 1968). King salmon populations, he noted, were at historically "low levels," as reflected by falling ocean harvests and depleted Central Valley spawning populations. Department of Fish and Game biologists singled out "...a reduced survival rate of young fish" as the primary factor in the crisis. Shannon said that the "emergency situation" nevertheless warranted "...placing some restrictions on both the river and ocean sports fisheries" (Shannon July 1968).

DFG biologists observed in an accompanying report that ocean caught king salmon dropped from about 800,000 in 1964 to a low of 400,000 in 1967 (Fry and others 1968, p 1). The report noted that ocean harvested fall-run chinook had diminished since 1959 while, for the moment at least, record numbers of returning winter-run fish masked the severity of the crisis. Propelling the emergency was

Increased predation, partly from a larger steelhead population, losses in unscreened irrigation diversions, water quality and quantity problems in the San Joaquin and its tributaries, diseases, or unknown changes in the ocean environment (Fry and others 1968, p 1).

No specific mention was made of the Central Valley Project Tracy pumps, nor of the Bureau's Red Bluff Diversion Dam. The report highlighted (and quite literally underlined) that,

The Fishermen are not to blame for the decline, but the survival rates of young fish have become so low that the adult population has been unable to support both good catches and a good spawning population returning to the rivers (Fry and others 1968, p 2).

DFG sought to bolster escapement and adult salmon recruitment by implementing a “small reduction” in the size of the sports and commercial catches between 1969 and 1972 (Fry and others 1968, p 5).

On the evening of July 23, 1968, DFG Director Walter Shannon and Fish and Game Commission President Henry Clineschmidt convened a public meeting to discuss matters (Kier 1998). Clineschmidt had already solicited support for the shut-down among sympathetic sportsmen. What DFG required was a buy-in by commercial fishermen. Fishermen appeared grudgingly compliant with a fishing ban except for Fort Bragg fishbuyer Bill Grader who staunchly opposed any reduced catch (Kier 1998). Grader’s fervent opposition, together with that of many others, marked a watershed point in the fisheries debate: simply shutting down the fisheries was no longer deemed sufficient to save salmon.

The following day Bill Grader visited Senate aide William M. Kier in his Sacramento office with proposals for at least fifteen separate pieces of fisheries legislation. In Kier’s words,

One created the Citizen’s Advisory [Committee] on Salmon and Steelhead; another attempted State fish protections at federal water projects; another sought tightening of fish screen laws; another [an] extension of the spawning gravel protections (Kier 1998).

Subsequently, Grader became chair of the Advisory Committee and he funded the entire project himself. DFG provided clerical and biological assistance to the committee.

It would require a full decade to attribute serious migratory fish declines to a largely-impassable Red Bluff Diversion Dam. In addition, the full impact of the Delta’s combined federal and State water projects constituted, in the words of retired DFG biologist Frank Fisher, a literal “black hole” (Fisher, personal communication, see “Notes”). Between 1967 and 1983, members of the Upper Sacramento River Salmon and Steelhead Advisory Committee wrote that fish counts past RBDD “...indicate[d] substantial declines in the fall and late fall runs, a serious decline in the spring run and the almost complete loss of the unique winter run.” (Frost and others 1984, p 5), The report also singled out steelhead as having all but “disappeared,” save for Coleman Hatchery’s Battle Creek production.

The man-made origins of the fishery collapse were eerily reminiscent of conclusions reached in 1944 by Willis Rich, Paul Needham, A. C. Taft, and Richard Van Cleve, who wrote:

It has been relatively recent that recognition has been given to the importance of dams and diversions to the continued existence of the salmon runs in many of our western rivers. As the ultimate plan for water development is approached, the effect is cumulative and the present proposed postwar projects bring the problem to the acute stage (Rich and others 1944, p 5).

What was more, many of these water projects hinged upon massive and continuing governmental intervention. In 1962, a Bureau of Sports Fisheries and Wildlife report complained that it was man's activities in California which have,

...generally proceeded counter to the best interests of the anadromous salmon and trout resources. In fact, they have destroyed substantial segments of these resources while employing only token efforts to ameliorate the damage. Activities conducted, sanctioned, sponsored and supported by the Federal Government have been prominent in the history. The [following] dam list...documents the major harmful results of direct federal activity (USFWS 1962, p 5).

No wonder this unattributed Fish and Wildlife Service document bore this prominent stamp on its cover: "Official Use Only: Not for Public Release."

Coleman Summary

Throughout the 1960s, several "limiting factors" were identified at the Coleman National Fish Hatchery including an insufficient availability of fresh water necessary to sustain high levels of production (USFWS 1963, p 33). While new rearing ponds constructed in 1962 did boost capabilities, concerns about excessive crowding among fish and disease limited production to about 250,000 pounds a year (USFWS 1963, p 33).⁵⁷ The Coleman Master Plan of 1963 explicitly called for a new hatchery facility to be constructed near Keswick to accommodate incoming fall- and winter-run fish. Diversification would permit the Coleman Hatchery to focus on rearing Battle Creek chinooks to a larger size while concentrating on producing incoming winter-run fish (USFWS 1963, p 34).

57. Within Coleman's 1963 Master Plan, annual production objectives were reassessed at 40 million chinook salmon, steelhead trout and Kamloops trout eggs, fingerlings, and yearling fish weighing 250,000 pounds" (USFWS 1963).

Throughout the 1960s, hatchery personnel continued experimenting with new fish foods. Rather than grinding up spawned out salmon carcasses, Sidney Campbell constructed an automatic fish feeder for delivering moist pellets into several raceways in 1962 (CAR 1963, p 3). Additional mechanical fish feeders followed, coincident with an ongoing debate over which pelleted fish foods to use: Abernathy dry diet versus Oregon Moist Pellets (CAR 1967). During 1967, chinook salmon eating the Abernathy pellets "...suffered a severe mortality" and, during that year at least, the tests were halted (CAR 1968, p 7). Refinements in feeding strategies continued throughout the ensuing decade.

Additional experimentation occurred as Coleman Hatchery sought to produce other kinds of fish. In addition to their Kamloops, rainbow and brown trout stocking programs, coho salmon were again brought into the Sacramento River Basin. In 1967, 550,000 eggs were imported to Coleman Hatchery from Eagle Creek, Oregon. Of these numbers, 390,000 coho salmon were released into the Sacramento River during July, 1968, at a weight of 25 fish per pound (CAR 1971, p 24). During 1970, 81 coho returned to the hatchery. As had occurred during the previous decade, poor quality eggs deposited by returning adults were deemed a total loss before the eyed stage. Consulting DFG found evidence of Sacramento River virus (CAR 1970, p 9). The following year, the coho stocking program was discontinued as 226 unspawned coho were transported and released into an upriver Shasta Reservoir (CAR 1971, p 7).

VI. Coleman Hatchery Production: The 1970s

Throughout the 1970s, fish production at Coleman National Fish Hatchery followed 1950s and 1960s precedents. Fall chinook salmon and steelhead production remained Coleman's bread and butter objectives. In 1969, the Service co-signed a "Salmon-Steelhead Accelerated Production Program" with the DFG. The agreement paved the way for Coleman to accept more fall-run chinook salmon and steelhead eggs (or stocks) from state hatcheries like Nimbus on the American River. The program was designed to maximize primary production at Coleman in exchange for fulfilling certain state restoration priorities (in other words, stocking steelhead on the Yuba river). A second, continuing, cooperative federal-State stocking and fish exchange program required Coleman to produce, rear and/or stock Kamloops trout, brown trout, rainbow trout, coho salmon, and hybridized Kamloops and rainbow trout in designated state waters. In 1978, trout production was suspended and much of the federal-State exchange program was discontinued or substantially renegotiated.

Late in the decade, severe drought exacerbated an established pattern of anadromous fisheries decline. A 1978 drought reduced salmon and steelhead returns to Coleman Hatchery to one of their lowest on record. In 1977, William Sweeney, Area Manager for the Fish and Wildlife Service, became increasingly alarmed by steadily diminishing numbers of returning fall-, winter- and spring-run chinook salmon and steelhead (Sweeney, personal communication, see "Notes"). Sweeney sought, and obtained, DFG's cooperation in redirecting Coleman's activities back to its original 1940s mandate – salmon and steelhead production. Coleman's trout production was curtailed in fiscal year 1978, but not before the epizootic IHN infected the hatchery's state-supplied Kamloops population. As Coleman responded to the growing anadromous fisheries problem, 795,000 Kamloops were buried (CAR 1978, p 2).

Coleman Hatchery began with a series of crises in the 1970s. The initial fall chinook salmon harvest on Battle Creek looked promising until January freshets flooded out many of Coleman's holding ponds (CAR 1970, p 8). High water not only made Battle Creek's winter harvests difficult, it also wreaked havoc on the Keswick Fishtrap. In addition, the previous year's stream "rehabilitation" along lower Battle Creek by the US Army Corps of Engineers had transformed a natural stream into "an ideal spawning channel." Unfortunately, the paltry numbers of incoming fish belied this ideal. The remains of lower Battle Creek were no exception. Biologists believed that homogenization of the stream bed significantly undermined returning spring steelhead and chinook salmon stocks to Coleman Hatchery (CAR 1970, p 8 and 13).

During 1970, Coleman's steelhead and trout rearing programs suffered a 50 percent reduction in funding. Concomitantly, poor quality Kamloops eggs were "...believed to be the result of accidental introduction of steelhead and rainbow trout into the brood lot over the past years" (CAR 1970, p 9). New, "pure," disease-free Kamloops broodstock would be obtained from Idaho's Clark's Fork Hatchery. While Sacramento River Chinook Salmon virus remained the most serious disease at Coleman, coagulated yolk, columnaris, bacterial gill, and external parasites also caused considerable headaches. William Waldsdorf, the hatchery's Supervisory Fishery Biologist, was also assigned to Nevada's Lahontan National Fish Hatchery. That hatchery's discovery of "Whirling Disease" required emergency measures and Coleman⁵⁸ was called upon to provide diagnostic expertise for several years to come (CAR 1970, p 11).⁵⁹ For a matter of months, biologist Waldsdorf would even

58. Concern over Nevada's nearly extinct Lahontan trout is Coleman's first attempt at returning a threatened fish species from altogether disappearing.

59. The Environmental Protection Agency also cited Coleman for being in violation of its pollution discharge permits. Emergency pollution abatement measures were taken until longer term abatement facilities could be constructed.

relocate his family to Nevada as he dedicated his time to resolving Lahontan fisheries emergency.

Within the 1970s, ongoing cooperative agreements between the Service and the DFG bore real benefits. Coleman relied on the State to stock southern California reservations and military bases in exchange for rearing rainbow trout for Whiskeytown and Shasta reservoirs. A 76-mile commute in a tank truck beat a 1400 mile round trip to stocking sites east of San Diego (CAR 1970, p 12). Previously cited cooperative marking programs for salmon and steelhead also paid biological dividends as scientists could better track what became of ocean-bound and incoming fish.

In 1973, Keswick Fishtrap's fall-run chinook never materialized. Since Keswick contributed 50 percent of the spawn to Coleman's production, what accounted for the lowest return of adult fish on record? (403 adults were taken). Biologists attributed the loss to December 1969's deadly overflow from Spring Creek's Debris Dam (CAR 1973, p 4). Scientists believed that copper, zinc, cadmium, and other heavy metal contaminants killed eggs and young fish immediately downstream from Keswick Dam. Other possible contributors included downriver plants at Rio Vista in which 30 percent of the salmon fingerlings returned to stray up the American or Feather rivers (CAR 1973, p 6). DFG biologists also speculated that "unknown changes in the ocean environment" may have further undermined returning numbers of fish (CAR 1973, p 6).

Throughout the 1970s, Coleman Hatchery constructed more and more temperature-controlled rearing ponds to contain Sacramento River Chinook Salmon virus. In February 1974, five new temperature-controlled raceways were added bringing the total available to 20 (CAR 1974, p 6). These ponds, however, were only as reliable as the technological systems serving them. In 1975, the station's water recirculation system failed on two occasions, causing mortalities among greater than six million fish (CAR 1975, p 4). That year unusually cool winter and spring water temperatures compounded the virus problem and Coleman Hatchery suffered heavy fingerling salmon losses. Fish losses also stemmed from high ammonia and nitrite levels in holding ponds.⁶⁰ Coleman simply lacked an efficient water reuse and filtration system capable of keeping pace with the high levels of production being sought (CAR 1976, p 6).

Between 1976 and 1978, chronic disease among trout populations, persistent drought, and declining salmon populations, forced a reconsideration of Coleman's fundamental mission. The combination of poor rainfall (below 50 per-

60. Concern over Nevada's nearly extinct Lahontan trout is Coleman's first attempt at returning a threatened fish species from altogether disappearing.

cent of normal), poor instream flows, and dangerously elevated water temperatures, spelled trouble ahead. By 1977, 18,000 fall-run salmon were blocked at the Red Bluff Diversion Dam and hauled "...to tributaries above and below Red Bluff and to Coleman and the Tehama-Colusa [S]pawning Channel" (CAR 1977, p 3).⁶¹ That year's fall steelhead populations also stood at one-quarter their normal size, casting doubt on even achieving the coming year's propagation requirements. To bolster escapement, all of Coleman's salmon and steelhead plants occurred below Red Bluff Diversion Dam.

Watching the crisis unfold was recently arrived USFWS Area Manager, William Sweeney. In a letter dated March 28, 1978, Sweeney wrote DFG Director E. C. Fullerton that the Service wanted to substantially renegotiate its long standing joint stocking agreement with the State (USFWS 1978, p 1). Sweeney identified producing fall- and spring-run chinook salmon at Coleman Hatchery as his highest priority and he expected that water chillers would be "on-line" within the year. Sweeney proposed that during summer 1978, Coleman start harvesting incoming spring-run fish for an artificial propagation program. Due to space limitations, Sweeney suggested replacing Coleman's entire Kamloops rearing program by focusing instead on spring-run production. He wanted to eliminate any disparities in the federal-State exchange agreement "...by rearing 55,000 pounds of 10-15 [per pound] spring chinook salmon instead of Kamloops trout (USFWS 1978, p 1). Sweeney asked that as part of the exchange, DFG consider picking up Coleman's military program obligations.⁶² (Footnote on next page.)

61. By June 1975, members of the DFG's Sacramento River Task Force had reported that "...the numbers of fall-run king salmon spawning above Red Bluff [Diversion Dam] have declined from an average of about 118,000 per year (1964-69) to an average of 51,000 per year (1970-74)" (Burns and others 1975, p 8). Speculations as to why ranged from the design and operation of the Bureau's Red Bluff Diversion Dam to the deterioration of spawning beds below Keswick Dam.

In 1978, Coleman's disease plagued Kamloops "...was discontinued and the production program redirected to include Winter and Spring Chinook salmon rearing" (CAR 1978, p 1). Winter-run salmon were dry-spawned at the Keswick Fishtrap and transferred to Coleman hatchery. Eighty-four percent of the eggs "eyed-up" yielding 102,000 eggs: but all but 12,500 perished when Coleman's water chiller broke down (CAR 1978, p 2). The same season that Sweeney advocated a return to spring-run production, no spring-run fish entered the Keswick Fishtrap.

During 1978-1979, migration of salmon and steelhead into Coleman Hatchery was one of the lowest on record. Slightly over 2.1 million Battle Creek fall chinook salmon eggs and just under a million steelhead eggs were harvested at Coleman Hatchery (CAR 1979, p 1). To bolster its flagging salmon production, Coleman obtained an additional 3.7 million fall chinook salmon eggs from the State's Nimbus hatchery and 816,000 fingerlings arrived from the Mad River Fish Hatchery (CAR 1979, p 1). The first season that Coleman consciously separated out late fall-run chinook salmon stocks (1.7 million eggs were harvested) arriving at the Keswick Fishtrap from those of the earlier Battle Creek run occurred in 1979.

In late spring 1979, IHN virus was finally isolated from coastal fall chinook salmon stocks at the Mad River Fish Hatchery. Due to their lengthy struggle with the disease, Coleman's superintendent was comfortable importing diseased fish from the Mad River Hatchery for rearing within Coleman's temperature-regulated 58 degree waters (CAR 1979, p 2). Unbeknownst to Coleman's

62. William Sweeney also closed his letter with a significant managerial shift. Sweeney proposed that ever hereafter, all DFG "...requests received for stocking and/or transfer of fish and eggs..." be referred through the Service's Sacramento Area Office (USFWS, Coleman files, Sweeney, March 1978, p 1). Historically, Coleman Hatchery enjoyed an unusually high degree of managerial autonomy. John Pelnar's long and distinguished tenure as Coleman's Superintendent greatly insulated the hatchery from excessive meddling, either by the State of California or by Washington, D.C. As many have observed, Pelnar's colleagues deferentially treated him as something of a "God" when it came to California's fisheries matters (Kier, personal communication, see "Notes"; Black, personal communication, see "Notes"). Lou Garlic, the Service's former Washington Hatcheries Program Administrator confirmed that historically, the Service had never dictated fish policies among its various hatcheries. Specific programs, Garlic insisted, derived from hatchery superintendents making decisions on site in accordance with budgetary constraints. "Whatever gave [Michael Black] the idea," Garlic wondered, "[that hatchery] policy was dictated from Washington" (Garlic interview conducted by George Black, see "Notes"). Occasional exceptions, like the Sikes Act, simply formalized what had once been handled informally among discrete hatcheries and other federal agencies. Former Coleman Hatchery Superintendent Jerry Grover remarked that it was not until 1984, when Donald Hodel was President Ronald Reagan's Secretary of the Interior, that a comprehensive policy on hatchery programs was finally spelled out (Grover, personal communication, see "Notes"). It was at this point that modern management substantially reshaped policy formulation at the hatchery level.

personnel, however, Mad River's cohort of fall-run salmon bore Enteric Red Mouth Disease (ERM). In early August of 1979, mortality among transferred fish increased sharply and during 1981–1982, ERM again infected Coleman juvenile steelhead and late fall chinook salmon. As an anonymous Coleman memorandum explained, "This was the first recorded outbreak of ERM in either species" (USFWS 1988, p 1).

Coleman National Fish Hatchery continued its production of fall-run chinook salmon and steelhead rainbow trout throughout the 1970s. A cooperative rearing arrangement with the DFG assured maximizing production at Coleman even as disease and overcrowding plagued the hatchery. While a substantially modified water reuse system was completed in December 1979, the hatchery remained saddled with inadequate funding, a decaying infrastructure, soaring power charges for new equipment (like chillers), and remained marginally able to tackle new artificial propagation objectives like spring- and winter-run salmon. Plummeting numbers of salmon reminded some that a long awaited reckoning had come due.

VII. Coleman Hatchery Production: The 1980s and The Richardson Reports

Coleman Hatchery returns of 1980 marked a significant improvement over the previous several years. Over 15.5 million fall chinook salmon eggs were harvested at Coleman and a record number of steelhead arrived during fall 1979, culminating in a 3.2 million egg harvest (CAR 1980, p 1). One hundred fifty-thousand late fall chinook salmon were held over for spring stocking in 1981, but no mention is made of attempts to rear either winter- or spring-run chinook salmon (CAR 1980, p 1).

Throughout the early 1980s, Coleman continued focusing on fall and late fall salmon and steelhead production. In 1982, experimentation resumed with 57 winter-run salmon which were captured at Keswick Fishtrap and hauled to Coleman Hatchery. A total of seven females was spawned. By the close of the spawning cycle, however, water temperatures peaked at 60 degrees. Two power outages interfered with the hatchery's water chilling systems. Coleman's Superintendent wrote that: "The eggs from two females were no good. The rest of the winter chinook salmon adults died before spawning." By the late September 1982, 14,700 of the 15,000 surviving eggs hatched successfully (CAR 1982, p 1).

Nineteen eighty-three's fall chinook salmon run was the largest in Coleman's history. Just shy of 20,000 fish made the upriver journey, yielding a total of 26,624,000 green eggs (21,137,000 eyed-up). Of this total, in October 1982, 4,856 fish died due to low dissolved oxygen in Coleman's ponds. Mortalities were blamed on PG&E's water operations just upriver from Coleman's water

intakes (CAR 1983, p 2). A total of 11,548 winter-run salmon was released into the Sacramento River Basin. In addition to the fall run, 958 late fall fish yielded 1,888,000 green eggs, 1,629,000 of which eyed-up. Steelhead numbered 958 this year, yielding 1.4 million eggs (a half million of these were imported from the State's Feather River Hatchery).

Coleman Hatchery's Operational Plan (1981)

In 1981, Coleman Hatchery manager Thomas B. Luken co-authored (with Terrence Merkel and Richard Navarre) an "Operational Plan" for rebuilding and greatly expanding Coleman National Fish Hatchery (Luken and others 1981). A subheading titled "Authorization and History" trails its brief introduction. As though to remind readers, the subsection's opening lines read:

The Coleman hatchery was built under the authority of the Federal Reclamation Laws-Act of June 17, 1902, 32 state. 388, and acts amendatory thereof or supplementary thereto. The Coleman station and its many associated facilities were included in the reimbursable costs of the Central Valley Project (Luken and others 1981, p 1).

A two-page history underscores that the Service assumed the "operational costs" and "responsibility" for Coleman during fiscal year 1950. A detailed description of Coleman's infrastructure comes next, followed by a summary of current and proposed production capabilities. Winter- and spring-run salmon receive passing mention as do Coleman's water chilling capabilities. "At this time [the reports authors concede, Coleman's] production program does not include the [winter and spring] runs" (Luken and others 1981, p 16). The authors also attribute 40 percent of the Sacramento River's steelhead production to Coleman's "hatchery sustained run" (Luken and others 1981, p 16).

Coleman's production objectives include rearing chinook salmon for sport and commercial fisheries and steelhead for sport fisheries (Luken and others 1981, p 21). Under the draft Central Valley Strategy Plan, targeted current and long-term salmon hatchery objectives (catch plus escapement) are 68,000 and 314,000 adults, respectively. Short- and long-term steelhead production is pinned at 13,000 and 19,000 adults, respectively (Luken and others 1981, p 21). With sufficient help from DFG hatcheries, a substantially expanded Coleman Hatchery should be able to meet various proposed long-term goals.

Ambitious future objectives, however, contrast sharply with 1982's declining abundance figures. Based upon a ten year cycle (adjusted) of fish counts at Red Bluff Diversion Dam, we learn that "...the relative abundance of the various runs since 1971 have been approximately 53 percent, 15 percent, 23 percent, and 9 percent for the fall, late-fall, winter, and spring runs, respectively" (Luken and others 1981, p 22). During the 1953-1960 period, fall chinook

salmon averaged 257,000 spawners. Between 1961 and 1976, that number fell by greater than 50 percent to stabilize near 121,000 adult spawners (Luken and others 1981, p 22). Between 1953 and 1976, spring-run chinook salmon averaged 9,000 spawners. Throughout the 1970s, late fall- and winter-run salmon averaged roughly 50,000 fish. The winter-run returns were profoundly affected by the drought of 1976–1977, however, and 1978–1979 counts past Red Bluff Diversion Dam numbered a mere 2,242 fish, dropping to 1,156 fish in 1979–1980 (Luken and others 1981, p 22–23). Steelhead counts in 1977–1978 were approximately 13 percent of those counted in 1967 (Luken and others 1981, p 25).

Coleman's "Operational Plan" closes by identifying hatchery strategies to arrest and reverse serious anadromous fisheries declines. Specific problems cited include finding sources for obtaining sufficient milt and eggs for winter- and spring-run salmon. Holding facilities for these stream-type fish must also be constructed, necessitating running chillers 24 hours a day. In 1981 dollars, power costs to operate Coleman's existing chillers would be \$27,000 per month (Luken and others 1981, p 26). For some spring-run salmon, this would require continuously operating chillers for four months or more, resulting in very expensive power bills. Studies would identify Coleman's optimal fish release timing, escapement sizes, and release sites, for steelhead and all four salmon runs. Specific tagging studies would determine the percentage of hatchery contributions to commercial and sports fisheries.

Luken, Merkel and Navarre argue that achieving Coleman's future operational objectives required an infusion of roughly \$5.5 million. Under the sub-heading of "Future Development," a four-phase program prioritizes strategies for substantially rebuilding and expanding the hatchery's production capacities. Personnel services, utilities, and fish food are singled out as the hatchery's three main expenditures. In view of the high cost of running chillers, means of reducing power costs required immediate consideration (Luken and others 1981, p 26). The Coleman Hatchery could either generate its own power on site or seek to obtain Department of Energy Central Valley Project power at "preferred rates." It was up to USFWS policy makers to select among four production options, thereby bolstering the Sacramento River's plummeting anadromous fish populations (Luken and others 1981, p 29–30).

USFWS Report on Problem A-6 (1982)

In May 1982, a second Service report built from Coleman's previous "Operational Plan" to argue for a substantial expansion and rehabilitation of the Sacramento River's salmon and steelhead mitigation program. This sophisticated document (entitled *Report of the US Fish and Wildlife Service on Problem A-6 of the Central Valley Fish and Wildlife Management Study*, or referred to simply as "A-6")⁶³ embeds activities and future expansion at Coleman Hatchery and the

Keswick Fishtrap within a historical narrative and a comprehensive policy framework (USFWS 1982).

The document notes that hatchery objectives at Coleman have been recently expanded to increase chinook salmon contributions to commercial fisheries (USFWS 1982, p 3). Improved hatchery escapement is to be bolstered by "...increasing survival of juveniles by releasing them at size;" releasing smolts at optimum time and location (while assuring proper imprinting); and making certain hatchery production reinforces these prior objectives (USFWS 1982, p 2-3). Primary production of winter- and spring-run chinook salmon are made pivotal among Coleman's formal objectives.

The A-6 document argued that expansion and modernization of the Coleman National Fish Hatchery required the implementation of a five year development program initiated in 1977 (Luken and others 1981). Construction priorities necessitated investigating additional sources for groundwater, increasing fish rearing capacity, and, for disease-containment, achieving effective temperature control (by completing the partially constructed water reuse systems) (USFWS 1982, p 4). For an additional \$5.487 million, Coleman Hatchery could rear 12 million chinook salmon fingerlings annually, weighing 115,000 pounds (USFWS 1982, p 4). The report further specified that, due to severe spawning gravel losses below Keswick dam, the Keswick Fishtrap must capture as many incoming salmon as possible for relocation to suitable substitute habitats or for artificial propagation at Coleman Hatchery.

Following this general statement of objectives, the document circled back to the historic 1949 MOA between the US Bureau of Reclamation and the US Fish and Wildlife Service. A precedent-setting disclaimer followed a general restatement of that document:

This agreement, while recognizing that salmon were successfully spawning in the Sacramento River downstream from Shasta Dam, should not be construed as a concession on behalf of the Service that the Bureau had satisfied its mitigation obligation for the Shasta Dam Project (USFWS 1982, p 6).

This may have been the first time in 33 years that Service personnel sought to consciously extricate themselves from the myth of a successful Shasta Salmon Salvage Plan. For heightened dramatic effect, Service biologists took language from the 1949 MOA and inverted its originally intended meaning:

63. "A-6" referred to an anadromous fisheries team assigned to "Determine the need for additional support for ongoing evaluation of Coleman National Fish Hatchery and Keswick Fishtrap operations, and providing this support if necessary" (USBR 1985, p 8).

Despite the now obvious failure of the Sacramento River-Butte Creek-Deer Creek Plan...to fully mitigate for pre-project salmon resources, and the inability of the Central Valley Project to maintain salmon runs below Shasta Dam in numbers equal to the numbers existing before the dam was built, operation of the Coleman NFH is still funded entirely by the Service (USFWS 1982, p 7).

In spite of substantial Service improvements made at Coleman National Fish Hatchery over the previous four decades, the A-6 document repeats that runs of chinook salmon and steelhead continue to decline. It noted that gravel degradation, heavy metal toxicity, unfavorable flow patterns, the Red Bluff Diversion Dam, predation, increased Delta pumping, unscreened diversions, and over-fishing, were all factors contributing to overall fisheries decline (USFWS 1982, p 27). Despite these problems, Coleman nevertheless continued producing 10 percent of the fall chinook salmon run and 70 percent of the steelhead run left below Keswick Dam (USFWS 1979; Hallock as cited in USFWS 1982, p 32). "Because of declining runs of all four races of chinook and steelhead trout to the upper Sacramento River," the document concludes that "the Service is committed to improving efficiency of the Coleman NFH" (USFWS 1982, p 32).

Before a summary statement of "problems" and "recommendations" was made, biologists identified the winter- and spring-runs as being particularly deserving of study for artificial propagation. Additional loss of natural habitats (for example, suitable spawning gravel, favorable seasonal flows, and suitable water temperatures), "may eventually necessitate" artificially propagating winter- and spring-run stocks (USFWS 1982, p 33). The report concluded that heightened hatchery efficiency is the best means of sustaining these badly depleted populations of fish.

Redefining Coleman Hatchery's mission, the report asserts, departs from these two fundamental premises. First the Bureau and the Service must:

Assess the need for revising the 1949 Memorandum of Agreement...pertaining to the operation and maintenance of Coleman National Fish Hatchery in view of the deterioration of salmon and steelhead runs resulting from long-term impacts of Keswick and Shasta Dams (USFWS 1982, p 35).

Second, redefining Coleman's mission hinges upon successfully receiving Central Valley Project electrical power at preferred rates.

Electrical water chiller operation is necessary to initiate production of and [to] provide protection [for]...the depressed run of winter chinook salmon in the Sacramento River. Estimated annual cost of operating chillers on [the] existing rate schedule is \$129,600 (USFWS 1982, p 35).

The Service basically invites the Bureau of Reclamation to reexamine that agency's historic and future salmon mitigation obligations by using the precarious status of winter-run salmon.

Coleman Station Development Plan (1984)

During October 1984, a second Coleman report was issued by the Service on the status of Battle Creek's antiquated Coleman National Fish Hatchery (USFWS 1984). The Coleman Station Development Plan called for a significant hatchery upgrade

To restore chinook salmon stocks of the upper Sacramento drainage to levels of the 1950s (adult contribution 673,000 fall chinook, 50,000 late fall chinook, 80,000 winter chinook and 130,000 spring chinook (USFWS 1984, p 9).⁶⁴

Hatchery goals ranged from energy-efficient means of controlling disease to increased hatchery size to accommodate winter-run chinook. A historical subsection underscores that "Construction of the facility was authorized as an integral part of the Central Valley Project" (USFWS 1984, p 5). Within yet another subsection on water rights, Coleman Hatchery's legal entitlement to Battle Creek's waters "...are [called] the lowest priority known on Battle Creek" (USFWS 1984, p 15).

Coleman's Station Development Plan specifies a three phase development program in which the term "rehabilitate" figures prominently. Initial priorities included rebuilding the hatchery's badly undercut diversion dam, expansion of pollution abatement facilities, installation of an ozone generator for water treatment, installation of emergency power generators, and the digging of several wells (USFWS 1984, p 26-28). Intermediate priorities included replacing the original redwood incubation troughs installed in 1942, replacing the deteriorating hatchery building's badly leaking roof, repairing chillers for water temperature control, and constructing new broodstock holding ponds for adult winter- and spring-run salmon (USFWS 1984, p 30-32). Costs for accomplishing the whole development program (in extrapolated 1986 dollars) are \$6,524,800 (USFWS 1984, p 25).

Petitions to List the Winter-run Chinook Salmon

Driving this latest Coleman document was a litany of woes contained in 1981's Coleman Report. Also disturbing were winter-run stocks which had plunged from 1969's estimated high of 117,808 to a 1983 figure of 1,381 fish (USBR and Richardson 1985, p 13). Within the same time frame, spring-run

64. This objective was taken verbatim from the Regional Resource Plan. Hoped for production figures included catch plus escapement.

chinooks also fared poorly, falling from 26,471 to 3,491 fish (USBR and Richardson 1985, p 13). Similarly, steelhead diminished from 10,995 to 1,968 fish (USBR and Richardson 1985, p 13). With the sole exception of hatchery-driven fall- and late fall-run stocks, the Sacramento River's anadromous fisheries were in trouble and the Service, the National Marine Fisheries Service (NMFS), and the DFG needed to formulate credible responses.

Tension was heightened by the potential listing of winter-run chinook salmon under the State and federal endangered species acts. The threats of a "listing" carried significant political muscle, as it focused statewide and national political attention-desired or not-on a regulatory agency's rationales and performance. Considerable opposition would be triggered by this State and federal action and the DFG, the Service, and NMFS exhibited reluctance to act. Meanwhile, independent advocates concerned with diminishing anadromous fisheries were clamoring to have the fish listed.

Partial justification for both State and federal ESA winter-run listings derived from the status report prepared by Richard Hallock and Frank Fisher and by subsequent counts (Hallock and Fisher 1985). The Tehama Fly Fishers (the Sacramento River Preservation Trust later joined them) petitioned the State of California for a listing, while, in October 1985, the California-Nevada Chapter of the American Fisheries Society (AFS) petitioned NMFS to list the winter-run as "threatened" under the federal Endangered Species Act (16, USC 1531, et. seq.). The Sierra Club Legal Defense Fund handled court proceedings against the federal government (Hallock, personal communication, see "Notes"). Annual winter-run counts between 1982 and 1988 averaged 2,334 fish, a 97 percent decline from prior levels (Williams and Williams, as cited in Lufkin 1991, p 107).

In 1986, NMFS responded with a non-binding, ten point action plan:

1. Resolving the fish passage problems at Red Bluff Diversion Dam.
2. Instituting a hatchery program for winter-run at the Coleman Hatchery.
3. Restoring spawning habitat in the Redding Area.
4. Developing measures to control Sacramento pike minnow at Red Bluff Diversion Dam.
5. Restricting in-river sport fishing.
6. Developing water temperature control for drought years.

7. Correcting Spring Creek pollution problems.
8. Correcting the problem at the Anderson-Cottonwood Irrigation District Dam (due to flow fluctuations and an inadequate fish ladder).
9. Correcting the spilling basin problem at the Keswick Fishtrap.
10. Continuing to expand studies on winter-run chinook salmon (after Grader 1988, p 2).⁶⁵

Pacific Coast Federation of Fishermen's Associations General Manager Zeke Grader observed that AFS and NMFS staff were in agreement that "...the problem facing the winter run [was] from water temperature and diversions and not fishery pressure..." (Grader 1988, p 2).⁶⁶ The sole permanent step taken was a restriction of the in-river sport fishery. The Bureau of Reclamation did open the gates at Red Bluff Diversion Dam but closed them again without notifying NMFS (Grader 1988, p 2). Without a "threatened" listing, many, including Grader himself, believed it "...may be impossible to force agencies such as the Bureau of Reclamation to make the necessary changes in their [water] operations to protect the winter run" (Grader 1988, p 3).

With their ten point recovery plan in place, NMFS determined in February 1987 that a winter-run listing was "not warranted" (Williams and Williams, as cited in Lufkin 1991, p 110). A year later, the Sierra Club Legal Defense Fund filed suit on behalf of AFS and others against the federal government, arguing that under the Endangered Species Act, the federal government had a "non-discretionary obligation" to list the nearly extinct fish (Williams and Williams, as cited in Lufkin 1991, p 111). All it would take were additional droughts or accelerated habitat losses accompanying new water projects to undermine the precarious status quo. "Threatened" ESA status for the winter-run fish would not be forthcoming until August 4, 1989 (Williams and Williams, as cited in Lufkin 1991, p 113).

65. Wally Steucke asked the Service's FAO-Red Bluff Project Leader to develop the preceding "Suggested Management Actions" which were intended to benefit the beleaguered winter-run salmon. On June 16, 1986, DFG's John Hayes participated in formulating these recommendations. Tellingly, a final eleventh suggestion was dropped from the list. It called for "Oppos[ing] any new [water] projects that would adversely impact winter-run chinook. With current severely depressed run sizes, winter-run cannot sustain additional adverse impacts." (USFWS 1986).

66. Grader clearly spelled out the PCFFA's interest in the winter-run case. "If listed as a threatened species," Grader wrote, "NMFS would be required to declare critical habitat, and to develop, adopt and implement a [fish] recovery plan. All federal agencies would be obligated, by law, to assure that their actions would not jeopardize the winter run. A threatened listing would not require restrictions on [ocean] fisheries, [however] an "endangered" listing would..." (Grader 1988, p 2)

Initially, the DFG withheld listing the winter-run under the state's ESA. Managers at DFG believed that the non-binding NMFS ten point conservation program would prove sufficient to reverse winter-run declines. Legal wrangling, mounting political pressures and declining numbers of fish eventually overwhelmed opposition to a listing. On August 7, 1986, the petition to list the winter-run as endangered was submitted to the California Fish and Game Commission (pursuant to subdivision (a) (2) of Section 2074.2 of the Fish and Game Code, as a candidate species defined in Section 2068 of the Fish and Game Code). The State Commission eventually accepted the petition at their February 4, 1988 meeting (Grader 1988, p 2). Implementation, however, still required a written report by DFG indicating that the petitioned action was warranted. In February 1989 the DFG had not yet completed its recommendation on winter run listing, so the Fish and Game Commission delayed action until its March 1989 meeting. At the March meeting the Commission accepted the DFG recommended to not list winter run but required the DFG to provide 60-day updates on the status of the resource and adherence to the 10-point plan. At the May 1989 meeting, the DFG changed its recommendation in favor of listing the winter run and the Commission made a finding at that meeting to list the species as Endangered. At its August 3-4, 1989 meeting, the Commission added winter-run chinook salmon to Section 670.5, Title 14, California Code of Regulations as an Endangered Species (Robert R. Treanor, Executive Director, Fish and Game Commission, personal communication).

Problem A-6 and the Bureau's Coleman Hatchery Action Plan (1984)

As State and federal fisheries agencies mobilized to stave off diminution of winter-run salmon stocks, the Bureau of Reclamation began responding with new programs of their own. Throughout the 1970s and into the 1980s, the Bureau funded collaborative, coded-wire tagging studies to determine optimal fish size at release and solve fish passage problems stemming from Red Bluff Diversion Dam. The Bureau also pumped resources into resurrecting the ill-fated Tehama-Colusa Fish Facilities. It also sought to overcome long-standing problems surrounding the Keswick Fishtrap. Resolution of issues arising from Red Bluff Diversion Dam and its compensatory spawning channels fell under a Bureau program termed "Interim Action Measures" (USBR and Richardson 1985, p 32). In November, 1984, the Bureau initiated the Coleman Hatchery Action Plan (CHAP) which was intended to "...assist the US Fish and Wildlife Service...in the fishery mitigation effort at the Keswick Dam fish-trap and the Coleman [National Fish Hatchery]" (USBR and Richardson 1985, p 32).

CHAP's objectives included identifying problems at Coleman Hatchery and Keswick Fishtrap, selecting cost-effective alternative solutions, determining which agencies had the ultimate authority and responsibility to implement solutions, prioritizing effective solutions by using cost/benefit analysis, and

setting a reasonable timetable for achieving desired results (USBR, Richardson 1985, p 32-33). As Service biologist Thomas Richardson stated, CHAP's main goal was for the Bureau "...to offer the technical expertise, resources, and equipment which could provide immediate solutions to ongoing problems that [adversely] affected hatchery production (CHAP, as cited in USBR and Richardson 1985, p 33).

CHAP's recommendations derived from a steering committee composed of representatives from the Bureau, the Service, NMFS, DFG, and the Department of Water Resources. While most of Coleman's and Keswick Fishtrap's problems and resolutions lay well beyond CHAP's scope, interagency participants insisted that their entire priorities list be presented to the Bureau's Regional Director for identification and eventual funding consideration (USBR and Richardson 1985, p 34). At the top of their wish list was new broodstock facilities capable of handling the beleaguered winter-run chinook salmon. There was also the matter of legally obtaining Central Valley Project power at "preferred rates" to run Coleman's power-hungry chillers (USBR and Richardson 1985, p 35).⁶⁷

CHAP suggestions included increasing Bureau water releases from the Shasta-Keswick complex "...to 14,000 cubic feet per second for a 3-day period from May 13-16, 1985" (USBR and Richardson 1985, p 34). This pulse of water would help flush Coleman's 6 million salmon smolts downstream into the Delta and Suisun and San Pablo bays. To help Sacramento River fish migration, the Bureau also agreed to operate its Red Bluff Diversion Dam to minimize fish losses due to irrigation. CHAP's steering committee also recommended that the Keswick Fishtrap be modified to remain usable at flows between 16,000 and 20,000 cubic feet per second, when not yet higher water conditions (USBR and Richardson 1985, p 56).

CHAP recommendations were imbedded within two subsequent, Bureau-commissioned versions of 1992's A-6 Service document which sought to identify and resolve nagging problems at Coleman Hatchery and Keswick Fishtrap (USBR and Richardson 1985; USBR 1985). Within the first report, Richardson wrote that Sacramento River salmon declines stemmed from a variety of factors

67. As to Coleman Hatchery's eligibility for CVP power at "preferred rates," the Service sought out the Solicitor General's legal determination. On the issue of "...free mitigation water with respect to the FWS facilities in the Grasslands area, one part of the overall Central Valley Project," Donald J. Barry, the Department of the Interior's Assistant Solicitor wrote: "Agreement was reached in the Solicitor's Office among the Divisions of Conservation and Wildlife and Energy and Resources that, with respect to the Coleman National Fish Hatchery, there was ample legal authority for the Bureau of Reclamation to provide water and power to operate the Hatchery, the cost for which must be borne by the project users" (USDI and Barry 1985, p 2).

...including gravel degradation, heavy metal toxicity, unfavorable flow patterns, the Red Bluff Diversion Dam, predation, increased delta pumping, unscreened diversions and over-fishing (USBR and Richardson 1985, p 52).

From the Service's point of view, insufficient returning broodstock simply underscored the importance of improving efficiency at Coleman and the Keswick Fishtrap. A second Bureau-funded report concluded:

The [Bureau] should endorse the efforts of the [Service] and assist in securing funding for facilities modifications required to meet mitigation responsibilities at both Coleman NFH and the Keswick Fishtrap (USBR 1985, p 84).

Achieving these ends would be best obtained by revisiting the 1949 MOA between the Bureau and the Service. The report continues:

...operation and maintenance of Coleman NFH should be assessed in view of the deterioration of salmon and steelhead runs resulting from long-term impacts of Keswick and Shasta dams (USBR 1985, p 84).

The three phase resurrection of a dilapidated Coleman National Fish Hatchery carried a projected price tag of \$6,524,800 (USBR 1985, p 58).

Whirling Disease (*Myxosoma cerebralis*) at Coleman Hatchery

Coleman Hatchery's propagation activities followed somewhat predictable patterns during most of fiscal year 1985. A total of 21,543 fall chinook salmon was spawned yielding 27,814,636 green eggs (25,430,879 eyed up). A total of over 24.1 million fall-run chinook salmon was stocked. A total of 388 late fall-run chinook salmon was harvested, yielding 597,378 eggs (492,029 eyed up). Over 374,000 late fall-run salmon were stocked (CAR 1985, p 3).

Success at propagating winter-run salmon remained as elusive a goal as ever. Lack of fish prevented obtaining adequate broodstock at Keswick Fishtrap and insufficient State and federal fish personnel precluded much fish capture at Red Bluff Diversion Dam. Only one of the 32 winter-run salmon obtained survived. That lone fish was released into Battle Creek. As Coleman's Superintendent wrote: "The bottom line is that with current Coleman facilities and funding, [winter chinook salmon] holding and spawning at CNFH is impossible" (CAR 1985, p 3).

This same year 1078 steelhead were spawned yielding 2,723,830 eggs (2,281,269 eyed up). However, in June 1985, an outbreak of Whirling Disease (*Myxosoma cerebralis*) was detected among steelhead trout fingerlings. In compliance with the Service's Fish Health Protection Plan, the "Class A" infected fish were destroyed in February 1986 (CAR 1985, p 2-3; USFWS, Coleman

Files, "Whirling Disease," Decision Paper, 1987). The destruction of 1.3 million juvenile steelhead was hardly welcome news in any quarters. However, since the DFG classified the *Myxosoma cerebralis* organism as a far less catastrophic affliction than did the Service, State biologists pleaded that the fish be released into Battle Creek. The Service's Class A designation held sway, however, and Coleman Hatchery destroyed its entire steelhead production for one year, amounting to a 70 percent in-river decline among returning 1988-1989 Sacramento River runs.

Amidst a hail of criticism, Service personnel responded that Coleman's history of disease and parasitism necessitated significant facilities upgrades. The previous year, members of the Upper Sacramento River Salmon and Steelhead Advisory Committee had argued that chronic underfunding and inefficiencies produced a substandard Coleman Hatchery rife with disease problems (Payton and Coakley 1985; Frost and others 1984). Writing in August 1984, that Committee's members argued that Coleman's operation should be increased to \$1.5 million a year and "recommended operating the hatchery as part of the federal Central Valley Project, with funding from the US Bureau of Reclamation instead of [the Fish and Wildlife Service] (Payton and Coakley 1985).

Service spokesman Bill Meyer of the Portland Regional Office believed that significant Coleman funding should derive from the Bureau of Reclamation. Bureau officials, however, were more circumspect. They responded that Coleman remains the sole responsibility of the Service.

'They've assumed full jurisdiction and we've been out of it for years,' said David Houston, mid-Pacific regional director for the Bureau. Still, Houston said his agency is committed to doing what it can to rehabilitate Coleman (Payton and Coakley 1985, p A-14).

The discovery of whirling disease at Coleman Hatchery intensified discussions as to the ultimate responsibility for salmon and steelhead mitigations throughout the Sacramento River Basin. For some it was only a dress rehearsal before the Bureau accepted full financial responsibility for a failed Shasta Salmon Salvage Plan.

Coleman Hatchery's Revised Station Development Plan (1987)

In 1987, a new Coleman Station Development Plan was released "...to upgrade or develop sound, practical station development plans for future budget requests" (USFWS 1987b, p 1). The major addition to this proposal was a comprehensive, nine phase construction program which bore a total price tag of \$22,104,800 (USFWS 1987b, p 27-28). An ozone generator for water treatment topped priorities while visitor facilities closed out the list. One nagging ques-

tion remained. Who would provide the funding for such an ambitious anadromous fish recovery effort? The agency or agencies willing to fund that dramatically increased budget remained unspecified. However, it appears as though the Service pinned their hopes on the Bureau of Reclamation and a failed Shasta Salmon Salvage Plan.

It would require an additional five years before the issue of agency responsibility was resolved by an Inspector General's inquiry. Numbers of Sacramento River salmon populations requiring formal mitigation derived from Needham and others' (1943) study, which argued that a minimum of 60,000 (but probably many more) Sacramento River salmon required mitigation. Recall that Needham had called for 10,000 spring-run chinook to be hauled to Deer Creek for natural propagation; 2,000 spring-run fish to be transferred to Battle Creek for artificial propagation; 18,000 summer and early fall-chinook to be transferred for artificial propagation; and distribution of 30,000 fall-run chinook by means of instream racks (Needham and others 1943).

In a series of Service- and Bureau- commissioned reports, Thomas H. Richardson best argued that the Bureau had an outstanding unmet mitigation obligation. Time and time again he returned to historic themes to build his case (USBR and Richardson 1985). In blunt language, Richardson wrote:

...It appears that the proper [Bureau of Reclamation] mitigation goals [of the Sacramento River Migratory Fish Control Program] were not established for the loss of habitat and fish runs upstream from Keswick and Shasta Dams (USFWS and Richardson 1987a p, 32).

Using original spawning survey data, Richardson calculated that 118,048 salmon were cut off as a result of Shasta Dam (USFWS and Richardson 1987, p 12). Particularly hard hit were the spring-run for access to 187 miles of their upriver spawning habitat (consisting of 2,360,000 square feet of spawning beds) were blocked while below-dam, spring-run mitigations failed entirely (Hanson and others 1940). Richardson cited Needham's 1943 revised population estimates of 60,000 salmon as being much closer to true population size lost as a result of Shasta and Keswick dams (Needham and others 1943).

As one crude measure of what was missing, Richardson suggested the Service (and the Bureau) take current production goals and subtract them from Needham's far more plausible estimate of 60,000 fish. Since Coleman's 1984 production goals specified 18,650 return spawners, Richardson deducted this figure from Needham's preceding estimate to arrive at an unmet mitigation of 41,350 fish (USFWS and Richardson 1987, p 32). The Service biologist concluded that "...any hoped for [Bureau sponsored post-Shasta enhancement] was never realized" (USFWS and Richardson 1987, p 33).⁶⁸ Richardson advised the Bureau of Reclamation that "...the loss of anadromous fish runs (but not habitat) may be compensated by artificial propagation" (USFWS and Richardson 1987, p 31).

VIII. The Inspector General's Report and the CVPIA

Initially the Bureau of Reclamation resisted accepting Richardson's invitation to reimburse the Service for ongoing unmet mitigation obligations. Sometimes the Service funded mitigation costs which agency personnel believed "...were properly assessable to water project beneficiaries," and Coleman Hatchery was no exception (Audit Report 1991, p 3). Service policy sought to promote "cost assumption," a term connoting recovery from water project beneficiaries of unmet mitigation costs. Discussions on this and other points continued between the two agencies and culminated in a November 1988 interagency agreement (Audit Report 1991, p 3). However that MOA failed to resolve the controversial cost-assumption issue. Additional progress was also hampered by interagency bickering over who retained formal "operational control" over mitigation facilities like hatcheries. Tiring of the impasse, Service directors eventually sought and obtained a formal audit by the Office of the Inspector General. If the Service could not resolve this by means of direct negotiations with the Bureau, then they would try another approach.⁶⁹

The Auditor General's report concluded that the Service continued "...to underwrite almost \$1.5 million a year in [hatchery] mitigation costs on behalf of the beneficiaries of the two Bureau water projects [Coleman was specifically singled out]" (Audit Report 1991, p 4). Throughout the 1950-1989 period,

68. In a separate 1987 report, biologist Richard J. Hallock summarized the results of the "Shasta Salvage Plan" this way: "The plan included only mitigation for fall- and spring-run salmon, none for late fall and winter-run salmon or steelhead. Only part of the plan was ever implemented. As each element of the salvage plan failed, it was simply abandoned and those particular groups of fish to be salvaged were just "written off" (Hallock 1987, p 30).

69. Service eligibility for project power was the first in several legal steps taken to force the Bureau's hand at reinstating funding to achieve mitigation compliance.

the Service spent \$8 million in operating costs for Coleman National Fish Hatchery which should have been properly assumed by project beneficiaries.⁷⁰ Auditors also observed that a 1949 MOA between the Bureau and the Service omitted a critical “...provision for cost recovery or user assumption” as part of the project’s reimbursable costs (USDI 1991, p 4). Auditors found no justification for omitting this provision upon transfer of the facility (Audit Report 1991, p 4).

The Inspector General’s report helped break through an interagency logjam. The Bureau generally agreed that “...mitigation costs were legally assessable to project beneficiaries” and that they could logically recover these mitigation costs through its water service contracts (USDI 1991, p 5). The final point rested on “operation control,” over who would actually run these facilities and receive assessed costs. As the chief protector and conservator of the nation’s fish and wildlife resources, the Service continued insisting it was best suited to run the nation’s hatcheries.

On January 11, 1991, Harold Bloom of the Inspector General’s office ordered the Service to negotiate with the Bureau to establish procedures for recovering costs stemming from future CVP and other mitigations. He also advised that the Service seek a separate opinion from the Solicitor “...concerning recoverability [from the Bureau and CVP beneficiaries] of [historic] mitigation expenditures” at the Coleman Hatchery. Although Service compensation on this point was never forthcoming, a new institutional arrangement meant funding for CVP salmon and steelhead mitigations was back on track as never before.

The Central Valley Project Improvement Act (1992)

A second institutional transformation in attitudes and policies toward Western water politics, development, and its beneficiaries began in 1992. Passage of the Central Valley Project Improvement Act (CVPIA) assured that for the first time, fish and wildlife resources would have legitimate standing as a serious “beneficial use” (CVPIA 1992). The act provided specifically for the protection, restoration, and enhancement of fish, wildlife habitats in California’s Central Valley and Trinity River basins (CVPIA 1992, p 1). The CVPIA included protection of both the Sacramento-San Joaquin Delta Estuary and downstream San Francisco Bay. CVPIA specified achieving a

...reasonable balance among competing demands for use of Central Valley Project water, including the requirements of fish and wildlife, agricultural, municipal and industrial and power contractors (CVPIA 1992, p 1).

70. The Service had spent \$11 million dollars funding operations at Coleman since 1950. Of this total, the Bureau advised as 76.4 percent of this total cost was reimbursable from agricultural, industrial, and municipal water users (USDI 1991, p 5).

Section 3406 of the CVPIA focuses on fish, wildlife and habitat restoration. It specifies that environmental "... mitigation, protection, and restoration of fish and wildlife" are its top priorities. This section specifies:

The mitigation for fish and wildlife losses incurred as a result of construction, operation, or maintenance of the Central Valley Project shall be based on the replacement of ecologically equivalent habitat and shall take place in accordance with the provisions of this title and concurrent with any future actions which adversely affect fish and wildlife populations or their habitat but shall have no priority over them (CVPIA 1992, p 11).

The CVPIA proposes by the year 2002, that "...natural production of anadromous fish in Central Valley rivers and streams will be sustainable, on a long-term basis, at levels not less than twice the average levels attained during the period of 1967-1991" (CVPIA 1992, p 12). The legislation also directs the Secretary of the Interior to "...address other identified adverse environmental impacts of the Central Valley Project..." without exactly specifying what they are (CVPIA 1992, p 12). First priority goes to "...measures which protect and restore natural channel and riparian habitat values..." through ecological restoration. To achieve this objective Central Valley Project operations like insufficient instream flows can be modified to benefit anadromous fish (CVPIA 1992, p 12).

Implementing Coleman National Fish Hatchery's Development Plan received special mention as did the Keswick Fishtrap. Additional hatchery production may mitigate for fish losses provided that it is only used to "...supplement or to re-establish natural production while avoiding adverse effects on remaining wild stocks" (CVPIA 1992, p 24). The act also calls for "...eliminating barriers to upstream and downstream migration of salmonids in the Central Valley..." including other measures deemed appropriate to "...protect, restore, and enhance natural production of salmon and steelhead trout in tributary streams of the Sacramento [River] (like Battle, Butte, Deer and Mill creeks)" (CVPIA 1992, p 25).

The intent of Central Valley Project Improvement Act legislation regarding anadromous fisheries is clear. With the recognition of fish as a legitimate interest, the act favors:

- Natural spawning over artificial propagation as a reproductive strategy.
- Restoration of certain "critical habitats" capable of supporting threatened or endangered anadromous fish stocks. (Battle, Butte, Deer and Mill creeks are singled out for their restoration promise).

- Elimination of instream fish barriers which hamper passage of returning migratory fish stocks (including Coleman Hatchery).⁷¹

Under the CVPIA's legislative umbrella, artificial propagation was relegated to last on the list of priorities. First-order priorities included restoration of riparian stream corridors capable of supporting regenerative stocks of (remaining) wild salmon. The satisfaction of "public trust" values were best accomplished by allowing nature to heal itself with minimal human interference.

Concluding Remarks

Several conclusions stem from the historical review presented within this paper.

Coleman Hatchery should seek a more balanced role in attempting to mitigate anadromous fish losses incurred above the Shasta-Keswick complex. Hanson, Needham, and Smith originally argued that a combination of artificial and natural propagation was required to achieve a balanced fish rescue strategy on the Sacramento River. These Bureau of Fisheries biologists sought a combination of reproductive paths so that each could serve as a "buffer" for the other (Hanson and others 1940, p 17). Neither Coleman Hatchery nor the Keswick Fishtrap should be faulted for becoming the sole surviving pieces of the Bureau's original fish salvage plan. Nor should we forget the hatchery's decisive failure to raise spring-run salmon. Almost by default, Coleman produced predominantly lower river fall-run chinook.

Today's CVPIA legislation calls for natural propagation within restored rivers and streams. Battle, Butte, Deer and Mill creeks, among others, should be set aside, to the greatest extent possible, as refugia for naturally propagating salmonids. Historically, spring-run and winter-run fish also spawned within some east-side Sacramento River tributaries like Battle Creek. Good faith negotiations must occur among all those affected to remove instream obstacles and "rewater" critical habitats like Battle Creek. Given the opportunity, resilient fish should be able to hold their own within surviving, remnant watersheds.

71. I recognize that Coleman's wider barrier is essential to the hatchery's broodstock collection operations (USFWS and Hamelberg 1999, p 2). However, a seasonally removable structure would provide the hatchery with their broodstock requirements while eliminating yet another obstacle for upmigrating Battle Creek stocks during most months of the year. Technologies such as weirs should be redesigned to suit the biological requirements of naturally spawning fish within restored river basins.

The idea of using tributaries as salmon refugia is hardly a recent one. In 1938, the Bureau considered designating four tributaries below Grand Coulee Dam as protected anadromous fish corridors. The Bureau sponsored considerable stream restoration on the Wenatchee, Methow, Okanogan, and Entiat rivers in the hopes of bringing newly transplanted salmon populations back up to their historic levels. The Bureau, however, soon abandoned the idea of reining-in (or buying out) competing and often harmful water development. Within the intervening decades, we have paid dearly for the Bureau's understandable but regrettable failure to set aside tributaries located downstream from dams as experimental refugia.

Water for fish is a "beneficial use". Some argue that fish conservationists can have anything they want in California, as long as it is not water. Competing riparian and appropriative water claims make salmon and steelhead restoration within their southernmost ranges all the more difficult. Salmon salvage efforts in the Sacramento River Basin are fraught with examples where biologists were required to place competing water claims above fish and wildlife habitat requirements. Under the Stillwater plan of 1940, Bureau of Fisheries biologists sought to export McCloud River water (by flume, suspended pipeline and tunnel) to a stream which was typically dry nine months of the year. There were no other competing water claims along Stillwater's dry streambed. In a second example, biologists sought to import water from the mainstem Sacramento River to supply riparian and appropriative users who seasonally dewatered Deer Creek. Money for the water substitution scheme never materialized, however, and, by 1946, the spring-run transplants to Deer Creek were abandoned. The history of fish rescue in California contains similar stories of biologists attempting to cobble together fish restoration plans with insufficient water. Sufficient, guaranteed instream flows are required to have suitable habitats for healthy runs of anadromous fish. In the end, there is no substitution for enough, clean, fresh water dedicated for fisheries.

Mitigating for salmon biodiversity on the Sacramento River. The Sacramento River (including Battle Creek) is North America's only river basin with four phenotypically unique stocks of chinook salmon. Dispersed, both temporally and spatially, one race of salmon was vacating a stretch of river just as their mature replacements (given suitable conditions) were headed upstream to spawn. This co-evolutionary example is all the more eloquent because emigrating fry and smolts feed along their downriver journey while migrating upriver salmon cease eating long before moving upstream to their natal spawning waters.

Sacramento River salmon still constitute an unequalled biodiversity treasure. With the loss of their upriver habitats, gone, too, was the opportunity for fish to mature in the upper river's high canyons. Also

missing was the possibility of over-wintering or summering in protective, upper riverine pools. After construction of the Shasta-Keswick complex, salmon stocks headed for the few remaining spawning grounds along the mainstem Sacramento. This included a stretch of river extending from Red Bluff to Keswick Reservoir. Upriver stocks remain casualties of a historically failed mitigation effort. Thus far, we have failed to mitigate for salmon biodiversity loss on a dramatically altered river, thereby placing at risk a national biodiversity treasure.

Acknowledgments

Many individuals have given freely of their time, knowledge and advice to strengthen this document. My thanks extend to: Laurie Aumack, Nat Bingham, George Black, Michael Borrus, Ron Brockman, Jim Buell, Bill Davoren, Frank Fisher, Ed Forner, Dan Free, Lou Garlic, Jerry Grover, Dick Hallock, Scott Hamelberg, Colleen Harvey-Arrison, Joel Hedgpeth, Patrick Higgins, Will Hobart, Buford Holt, Mark Jennings, Bill Kier, Susan Kitchell, Jim Lichatowitch, Tom Luken, Erik Merrill, Barry Mortimeyer, Peter Moyle, Willa Nehlsen, Tom Nelson, Kevin Niemela, Patricia Parker, Roger Patterson, Paula Peterson, Harry Rectenwald, Felix Smith, Jim Smith, Gary Stern, Ted Steinberg, Bill Sweeney, Joseph Taylor, Paul Ward, Ed Whitsel, Rick Worthington, Ronald Yoshiyama, and members of the Battle Creek Technical Advisory/Work Group. I would also like to thank the many archivists or fish historians (and their assistants) who have provided invaluable materials necessary to complete this study. Specific thanks go to Roy Wingate of the Bureau of Reclamation's Denver Regional Office; archivists located at the Bureau's Sacramento Office; Gretta Siegel at "Streamnet," of the Columbia River Inter-Tribal Fish Commission in Portland; Frank Fisher and Zeral Twitchell of the DFG's Red Bluff office; Scott Hamelberg, Patricia Parker, and Kevin Niemela of the Service's Red Bluff Northern Central Valley Fish and Wildlife Office; Ed Forner and Mary Brubaker of the Service's Portland Regional Office; Linda Vida at UC Berkeley's Water Resources Center Archives, archivists at UC Berkeley's Science Library, and cartographers Brian Lasagna and Chuck Nelson at Chico State University's Geographical Information Center.

Contractual Statement

This document was prepared under contract for the Battle Creek Technical Advisory/Work Group by William M. Kier Associates, 207 Second Street, Suite B, Sausalito, California 94965. Original funding stemmed from a subcontract with Kier Associates as part of a Metropolitan Water District of Southern California Category III, Agreement No. 14532, "Battle Creek Chinook Salmon

and Steelhead Restoration Plan Development,” with additional funding provided by the US Department of the Interior, Bureau of Reclamation, Shasta Lake, CA; Contract No. 1425-98-PG-23-00840.

References

- Advisory Council on SB1086. 1989. Upper Sacramento River fisheries and riparian habitat management plan. Prepared for The Resources Agency, State of California. January 1989.
- Azevedo RL, Parkhurst ZE. 1958. The Upper Sacramento River salmon and steelhead maintenance program, 1949-1956 [mimeographed report]. US Fish and Wildlife Service.
- Black M. 1995. Tragic remedies: a century of failed fishery policy on California's Sacramento River. *Pacific Historical Review* LXIV(1):37-70.
- Blote MH. 1946. Water requirements of anadromous fishes: preliminary report of the special committee on water requirements of fish and wildlife in connection with dams. Two sections prepared by the Research Department of the Statewide Water Resources Committee of the California State Chamber of Commerce. 1 March 1946. 217 p + appendices.
- Burns JW. 1975. The upper Sacramento River: its problems and a plan for its protection. California Department of Fish and Game. June 1975. 16 p.
- Cairns John, Jr. 1990. Lack of theoretical basis for predicting rate and pathways of recovery. In: Yount JD, Niemi GJ, editors. *Recovery of lotic communities and ecosystems following disturbance: theory and application*. Springer International. p 517-526.
- Calkins RD, Durand WF, Rich WH. 1939a. Report of the Board of Consultants on the fish problems of the Upper Columbia River [mimeograph]. Section I. 8 February 1939. Palo Alto (CA): Stanford University. p 1-19.
- Calkins RD, Durand WF, Rich WH. 1939b. Report of the Board of Consultants on the fish problems of the Upper Columbia River [mimeograph]. Section II. 7 March 1939. Palo Alto (CA): Stanford University. p 1-82.
- Calkins RD, Durand WF, Rich WH. 1940a. Report of the Board of Consultants on the fish problems of the upper Sacramento River [mimeograph]. 21 July 1940. Palo Alto (CA): Stanford University. p 1-34.
- Calkins RD, Durand WF, Rich WH. 1940b. Supplemental report: salvage of salmon—upper Sacramento River [mimeograph]. 5 October 1940. Palo Alto (CA): Stanford University. p 1-13.

- [CAR] Coleman Station annual reports. 1942-1992 [mimeographs].
- Clark GH. 1929. Sacramento-San Joaquin salmon (*Oncorhynchus tshawytscha*) fishery of California. Fish Bulletin 17. Bureau of Commercial Fisheries. Sacramento (CA): California State Printing Office. 73 p.
- Coots M, Healy T. 1966. Pacific Gas and Electric Company's Battle Creek System Power Project. Minor Part, FERC License nr. 1121, California Department of Fish and Game. 31 p.
- Cope OB, Slater DW. 1957. Role of Coleman Hatchery in maintaining a king salmon run. Research report 47. US Department of the Interior, Fish and Wildlife Service. 22 p.
- Cramer FK, Hammack DF. 1948. Deer Creek operations: Sacramento River salmon maintenance program, 1940-1948 [mimeograph]. US Fish and Wildlife Service. 16 p.
- [CVPIA] Central Valley Project Improvement Act. 1992. HR 429, Title XXXIV. Text downloaded from Westlaw Congressional Record database on 5 October 1992 and formatted for the California Department of Water Resources. p 1-34.
- Engle C. Central Valley Project documents. 1958. Volume II, operating documents. Washington, DC: US Government Printing Office.
- Fisher FW. 1994. Past and present status of Central Valley chinook salmon. Conserv Biol 8(1994):870-3.
- Foster FJ. 1937. Outline of artificial propagation of fish on the lower Columbia River. July 1937. Box 611, fldr. 826.53, entry 269.
- Foster FJ. 1940. A plan for salvaging fish which will be affected by the Shasta Dam. March 1940. Seattle (WA): Division of Fish Culture.
- Forbes GF. 1983. Operation of Coleman National Fish Hatchery. Statement presented to members of the upper Sacramento River Salmon and Steelhead Advisory Committee. 10 p.
- Frost D, Warner G, Lufkin A, Reginato J, Maloney T, Pool D, Moss C, Patten J, Hecht B, Stromsness C, Dodgin M, Ferris W. 1984. Upper Sacramento River Salmon and Steelhead Advisory Committee report number 2. Coleman National Fish Hatchery. 13 p.
- Fry DH Jr. 1961. King salmon spawning stocks of the California Central Valley, 1940-1959. California Fish and Game 47(1).
- Fry DH, Kelly DW, Jensen PT, Hallock R, Iselin R. 1968. Decline of the Central Valley king salmon resource. 11 July 1968. California Fish and Game. p 7.

- Grader Z. 1988a. Saving the Sacramento. Quarterly Newsletter of the Sacramento River Preservation Trust 4(1):4. Spring 1988.
- Grader Z. 1988b. River run. Quarterly Newsletter of the Sacramento River Preservation Trust 4(1):4. Spring 1988.
- Gresh T, Lichatowich J, Schoonmaker P. 2000. An estimation of historic and current levels of salmon production in the Northeast Pacific ecosystem: evidence of a nutrient deficit. Fisheries 25(1):15-21.
- Groot C, Margolis L. 1991. Pacific salmon life histories. Vancouver: UBC Press. p 564.
- Hallock RJ. 1983. Effect of Red Bluff Diversion Dam on chinook salmon, *Oncorhynchus tshawytscha*, fingerlings. 24 January 1983. California Department of Fish and Game administrative report. 8 p.
- Hallock RJ. 1987. Sacramento River system salmon and steelhead problems and enhancement opportunities. Report to the California Advisory Committee on salmon and steelhead. 90 p.
- Hallock RJ, Fisher FW. 1984. Estimated losses of salmon and steelhead attributed to the Red Bluff Diversion Dam [memorandum dated 7 February 1984]. California Department of Fish and Game. 21 p.
- Hallock RJ, Fisher FW. 1985. Status of winter-run chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento River. 25 January 1985. California Department of Fish and Game administrative report. 27 p.
- Hallock RJ, Fry DH. 1967. Five species of salmon, *Oncorhynchus*, in the Sacramento River. California Fish and Game 53(1):5-22.
- Hallock RJ, Rectenwald H. 1989. Environmental factors contributing to the decline of the winter-run chinook salmon on the upper Sacramento River. In: Northwest Pacific chinook and coho salmon workshop proceedings. Bethesda (MD): American Fisheries Society. p 141-5.
- Hallock RJ, Reisenbichler RR. 1979. Evaluation of returns from chinook salmon, *Oncorhynchus tshawytscha*, released as fingerlings at Coleman and Nimbus hatcheries and in the Sacramento River Estuary. 22 August 1979. California Department of Fish and Game administrative report. 5 p.
- Hallock RJ, Reisenbichler RR. 1980. Freshwater and ocean returns of marked winter-run and late fall-run chinook salmon, *Oncorhynchus tshawytscha*, from the Sacramento River. 15 September 1980. California Department of Fish and Game administrative report. 8 p.
- Hallock RJ, Van Woert WF. 1959. A survey of anadromous fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. California Fish and Game 45(4):227-66.

- Hallock RJ, Vogel DA, Reisenbichler RR. 1982. The effect of Red Bluff Diversion Dam on the migration of adult salmon, *Oncorhynchus tshawytscha*, as indicated by radio tagged fish. Administrative report nr. 82-8. California Department of Fish and Game. 47 p.
- Hankin DG. 1991. Interaction of hatchery and naturally-spawning chinook salmon stocks in Battle Creek, Shasta and Tehama counties [unpublished draft report dated 1 February 1991]. Redding (CA): California Department of Fish and Game.
- Hanson HA, Smith O, Needham PR. 1940. An investigation of fish-salvage problems in relation to Shasta Dam. Special scientific report nr. 10. Washington. p 200.
- Hatton SR. 1939. Progress report on the Central Valley fisheries investigations. California Fish and Game 26(4):334-73.
- Hazel C. 1976. Assessment of effects of altered stream flow characteristics on fish and wildlife. Part B: California. December 1976. US Fish and Wildlife Service.
- Hedgpeth JW. 1941. Livingston Stone and fish culture in California. California Fish and Game 27(3):126-48.
- Hedgpeth JW. 1943. California's forgotten salmon. Reprinted from Outdoor America. January 1943.
- Hedgpeth JW. 1944. The passing of the salmon. In: Moulton FR, Campbell FL, editors. Scientific Monthly LXI(1944):370-8. December 1944. AAAS.
- Hilborn R. 1992. Can fisheries agencies learn from experience? Fisheries 17(4):6-14.
- Hopson EG, Means TH. 1915. Report on Lower Pit River Project. Cooperative Investigations in California, US Reclamation Service in cooperation with the Northern California Irrigation Association. Washington, DC: US Government Printing Office. 55 p.
- Jennings MR. 1996. A biography of Cloudsley Louis Rutter (1867-1903), pioneer salmon biologist and curator of ichthyology at the California Academy of Sciences [unpublished manuscript]. 81 p.
- Kano RM, Reavis R. 1997. Annual report: chinook salmon spawner stocks in California's Central Valley, 1987. California Department of Fish and Game Inland Fisheries administrative report nr. 97-4.
- Kier WM. 1998. Memorandum dated 11 April 1998. Sausalito (CA): William M. Kier Assoc.
- Lee KN. 1993. Compass and gyroscope: integrating science and politics for the environment. Covelo (CA): Island Pr. 243 p.

- Leitritz E. 1970. A history of California's fish hatcheries: 1870-1960. Fish Bulletin 150. Sacramento (CA): California Department of Fish and Game. 92 p.
- Lufkin A, editor. 1991. California's salmon and steelhead: the struggle to restore an imperiled resource. Berkeley (CA): University of California Press.
- Luken TB, Merkel TJ, Navarre RJ. 1981. Coleman National Fish Hatchery operational plan. Shasta County (CA): US Fish and Wildlife Service. 35 p.
- McEvoy AF. 1990. The fisherman's problem: ecology and law in the California fisheries, 1850-1980. New York (NY): Cambridge Univ Pr. p 368.
- Mills TJ, Fisher F. 1993. Central Valley anadromous sport fish annual run-size, harvest, and population estimates, 1967 through 1991. Third Draft, Inland Fisheries Technical Report. Sacramento (CA): California Department of Fish and Game.
- Mills TJ, McEwan DR, Jennings M. 1997. California salmon and steelhead: beyond the crossroads. In: Stouder DJ, Bisson PA, Naiman RJ, editors. Pacific salmon and their ecosystems: status and future options. London (UK): Chapman & Hill.
- Moffett JW. 1949. The first four years of king salmon maintenance below Shasta Dam, Sacramento River, California. April 1949. Reprinted from California Fish and Game 35(3).
- Mullan JW. 1987. Status and propagation of chinook salmon in the mid-Columbia River through 1985. US Fish and Wildlife Service Biological Report 87(3). April 1987. Washington, DC: US Fish and Wildlife Service. 111 p.
- Mullan JW, Williams KR, Rhodus G, Hillman TW, McIntyre JD. 1992. Production and habitat of salmonids in mid-Columbia River tributary streams. US Fish and Wildlife Service Monograph I. 273 p.
- Needham PR, Hanson HA, Parker LP. 1943. Supplementary report on investigations of fish-salvage problems in relation to Shasta Dam. US Fish and Wildlife Service special scientific report nr. 26. 30 June 1943.
- Needham PR, Smith OR, Hanson HA. 1941. Salmon salvage problems in relation to Shasta Dam, California and notes on the biology of the Sacramento River salmon. Proceedings of the Transactions of the American Fisheries Society; 1940 Sep 5-6, Toronto, Canada. p 55-69.
- Payton K, Coakley T. 1985 Dec 21. Disaster for Sacramento River steelhead. The Sacramento Bee; A:1 and 14.
- Reiger JF. 1986. American sportsmen and the origins of conservation. Norman (OK): University of Oklahoma Pr. 316 p.
- Reisner M. 1986. Cadillac desert: the American West and its disappearing water. New York (NY): Viking. 582 p.

- Reynolds TS, Scott C. 1980. The historic American engineering record, the Battle Creek hydroelectric system: an historical study. Washington, DC. 181 p.
- Rich WH. 1939. The present state of the Columbia River salmon resources. Proceedings of the Sixth Pacific Science Congress. Volume 3. p 425-430.
- Rich WH, Needham PR, Taft AC, Van Cleve R. 1944. A preliminary report of the fishery resources of California in relation to the Central Valley Project. Manuscript nr. 48064. Stanford (CA): Stanford University. 20 p + appendix.
- Rieser DW, Bjorn TC. 1979. Habitat requirements of anadromous salmonids. In: US Forest Service. General technical report PNW-96. p 54.
- Rutter C. 1902. Natural history of the Quinнат salmon: a report of investigations in the Sacramento River, 1896-1901. Bull US Fish Comm 22:65-141.
- Rutter C. 1903. Natural history of the Quinнат salmon: a report on investigations in the Sacramento River, 1896-1901. Extracted from the Bulletin of the United States Fish Commission for 1902, 1903, p 86-131, plates 10 to 18.
- Rutter C. 1904. Artificial propagation of salmon in the Sacramento River. Reproduced from the San Francisco Trade Journal. In: State Board of Fish Commissioners. 18th biennial report, 1903-1904. p 103-106.
- [SBFC] State of California Board of Fish Commissioners. 1872. Biennial reports 1870-1871 (first report) to 1946 (fortieth report).
- [SBFC] State Board of Fish Commissioners. 1890. Biennial report 1888-1890. AJ Johnson, Superintendent. Sacramento (CA): State Printing Office.
- [SBFC] State Board of Fish Commissioners. 1896. Biennial report 1895-1896. AJ Johnson, Superintendent. Sacramento (CA): State Printing Office.
- [SBFC] State Board of Fish Commissioners. 1900. Biennial report 1897-1898. AJ Johnson, Superintendent. Sacramento (CA): State Printing Office.
- [SBFC] State Board of Fish Commissioners. 1904. Biennial report 1903-1904. AJ Johnson, Superintendent. Sacramento (CA): State Printing Office.
- Schofield NB. 1900. Notes on an investigation of the movement and rate of growth of the Quinнат salmon fry in the Sacramento River. In: Vogelson A, Gould CB, editors. Fifteenth biennial report of the State Board of Fish Commissioners of the State of California for the years 1897-1898. Sacramento (CA): State Printing Office. p 75.
- Slater DW. 1963. Winter-run chinook salmon in the Sacramento River, California with notes on water temperature requirements at spawning. Special scientific report: Fisheries nr. 461. Washington, DC: US Department of the Interior. p iii-9.

- Smith FE. Central Valley dams: salmon, steelhead and trout at risk [undated mimeograph].
- Smith FE. 1992. California's riverine ecosystems and associated fish resources [draft mimeograph]. p 1-16.
- Smith FE. 1994. Headwaters to the Pacific Ocean and fair ecological share [mimeograph]. p 1-5.
- Stubblefield G. 1948. Comments on preliminary report: water requirements of anadromous fishes. June 1948. Research Department, California State Chamber of Commerce.
- Sweeney WL. 1978. Whirling disease [Letter to E. C. Fullerton, California Department of Fish and Game, dated 26 March 1978]. Available from USFWS Coleman Files. 3 p with responses.
- Taylor JE, III. 1996. Making salmon: economy, culture, and science in the Oregon fisheries, precontact to 1960 [PhD dissertation]. Department of History, University of Washington. Available from University Microfilms, Ann Arbor, MI. 441 p.
- Thomas R. Payne & Associates. 1998. A 1989 instream flow study: 1 of 8 components. Prepared for the California Department of Fish and Game.
- [USBR] US Bureau of Reclamation. 1985. Central Valley Fish and Wildlife Management Study, Coleman National Fish Hatchery and Keswick Fish Trap Operations. November 1985. 89 p + appendices.
- [USBR] US Bureau of Reclamation. 1991. Planning report/final Environmental Impact Statement: Shasta outflow temperature control. Sacramento (CA): US Bureau of Reclamation. p vi-39.
- [USBR and Richardson] US Bureau of Reclamation, Richardson TH. 1985. Coleman National Fish Hatchery and Keswick Fish Trap: report of the USFWS on problem A-6 of the Central Valley fish and wildlife management study. October 1985. Prepared for the US Bureau of Reclamation. 59 p + appendices.
- [USDI] US Department of the Interior, Office of the Inspector General. 1991. Audit report: recovery of costs incurred for mitigation of fishery damages attributable to Bureau of Reclamation water projects. Report Number 91-I-284. Office of Inspector General. January 1991. Washington, DC: US Department of Interior.
- [USDI and Barry] US Department of Interior, Barry DJ. 1985. Central Valley Project power and water for the Coleman National Fish Hatchery [memorandum dated 13 December 1985]. 2 p.
- [USFWS] US Fish and Wildlife Service. Mortality of juvenile steelhead trout and late fall chinook salmon at Coleman National Fish Hatchery 1981 to 1987 [undated memorandum]. 3 p.

- [USFWS] US Fish and Wildlife Service. 1948a. Coleman agreements [memorandum dated 11 August 1948]. Portland Regional Office. Available from USFWS Coleman files.
- [USFWS] US Fish and Wildlife Service. 1948b. Coleman agreements [memorandum dated September 8, 1948]. Portland Regional Office. Available from USFWS Coleman files.
- [USFWS] US Fish and Wildlife Service. 1956. Coleman agreements [Henry Cline-schmidt letter dated 18 September 1956]. Portland Regional Office. Available from USFWS Coleman files.
- [USFWS] US Fish and Wildlife Service. 1962. A proposed development program for anadromous fishes in California. Portland (OR): Bureau of Sports Fisheries and Wildlife. 36 p + appendices.
- [USFWS] US Fish and Wildlife Service. 1963. Coleman National Fish Hatchery master plan. June 1963. 54 p.
- [USFWS] US Fish and Wildlife Service. 1979. Proposal to evaluate time and size at release for steelhead trout and four races of chinook salmon reared at Coleman NFH. Office Report. Red Bluff (CA): California Fisheries Assistance Office.
- [USFWS] US Fish and Wildlife Service. 1982. Report of the US Fish and Wildlife Service on problem no. A-6 of the Central Valley fish and wildlife management study, Coleman National Fish Hatchery and trap. 39 p + appendices.
- [USFWS] US Fish and Wildlife Service. 1984. Coleman National Fish Hatchery: station development plan. March 1984. US Fish and Wildlife Service Region 1. 48 p + appendices.
- [USFWS] US Fish and Wildlife Service. 1986. Coleman NFH, 5 reports [memorandum dated 19 June 1986]. Portland Regional Office. Available from USFWS Coleman files.
- [USFWS] US Fish and Wildlife Service. 1987a. Coleman National Fish Hatchery: station development plan. 9 November 1987.
- [USFWS] US Fish and Wildlife Service. 1987b. Whirling disease decision paper [memorandum dated 25 June 1987]. Portland Regional Office. Available from USFWS Coleman files.
- [USFWS] US Fish and Wildlife Service. 1992. Use of growth data to determine the spatial and temporal distribution of four runs of juvenile chinook salmon in the Sacramento River. 17 p.
- [USFWS] US Fish and Wildlife Service. 1997. A review of steelhead *Oncorhynchus mykiss* in the upper Sacramento River; life history and propagation at Coleman National Fish Hatchery [draft report]. Red Bluff (CA): Northern Central Valley Fish and Wildlife Office.

- [USFWS] US Fish and Wildlife Service. 1998. Coleman National Fish Hatchery barrier trap summary [draft report]. Presented to the Battle Creek Working Group.
- [USFWS and Hamelberg] US Fish and Wildlife Service, Hamelberg S. 1997. Comments on the history of Coleman National Fish Hatchery mitigation efforts as reconstructed by Dr. Michael Black. 11 December 1997. Red Bluff (CA): Northern Central Valley Fish and Wildlife Office. 17 p.
- [USFWS and Hamelberg] US Fish and Wildlife Service, Hamelberg S. 1999. Comments on the final draft of the history of Coleman National Fish Hatchery mitigation efforts reconstructed by Dr. Michael Black. February 4, 1999. Red Bluff (CA): Northern Central Valley Fish and Wildlife Office. 3 p.
- [USFWS and Richardson] US Fish and Wildlife Service, Richardson T. 1987a. An overview of the mitigation plan for Shasta and Keswick dams [mimeograph]. July 1987. Sacramento (CA): Division of Ecological Services. 29 p + appendix.
- [USFWS and Richardson] US Fish and Wildlife Service, Richardson T. 1987b. An analysis of the effectiveness of the mitigation plan for Shasta and Keswick dams. September 1987. US Fish and Wildlife Service. 36 p + appendix.
- [USFWS and USBR] US Fish and Wildlife Service, US Bureau of Reclamation. 1948. Coleman agreements [memorandum from the Commissioner of Reclamation dated 25 August 1948]. Portland Regional Office. Available from USFWS Coleman Files.
- [USFWS and USBR] US Fish and Wildlife Service, US Bureau of Reclamation. 1984. Evaluation report of the potential impacts of the proposed Lake Red Bluff Water Power Project on the fishery resources of the Sacramento River. Division of Ecological Services, Sacramento, and the Bureau of Reclamation, Mid-Pacific Region. 89 p with appendices.
- Ward MB, Kier WM. 1999. Battle Creek salmon and steelhead restoration plan. Prepared for the Battle Creek Working Group. January 1999. Sausalito (CA): Kier Assoc. 110 p + appendices.
- Williams JE, Williams CD. 1991. The Sacramento River winter chinook salmon: threatened with extinction. In: Lufkin A, editor. California's salmon and steelhead. p 105-15.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Sierra Nevada ecosystem project: final report to Congress. Volume III: assessments, commissioned reports, and background information. Davis (CA): University of California, Centers for Water and Wildlife Resources. p 309-61.
- Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. *N Am J Fish Manage* 18(1998):487-521.

Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 2001. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1. Sacramento (CA): California Department of Fish and Game.

Notes

George O. Black. NOAA and USFWS biologist, retired. Personal communication in August 1998.

Ron Brockman. USDI, Bureau of Reclamation, Sacramento Bureau. Phone interview on 14 August 1998.

Frank W. Fisher. Personal communication in August 1998.

Lou Garlic. USFWS Washington-based Hatcheries Administrator, retired. Personal communication with retired biologist George O. Black in August 1998.

Jerry Grover. USFWS Coleman Superintendent, retired. Phone interview on August 21, 1998.

W. L. Hobart. National Marine Fisheries Service, Seattle, Washington. Correspondence dated 28 October 28 1997 and personal communication.

Jim Lichatowitch. Sequim, Washington. Personal communication in July 1998.

William L. Sweeney. USFWS Sacramento Office Area Manager, retired. Personal communication.

Appendix A: Spawning Habitat Analysis for the Sacramento River System Affected by the Keswick Dam and Shasta Dam Projects

Harry Rectenwald
California Dept. of Fish and Game
601 Locus Street, Redding, CA 96001

Introduction

This document was prepared for the Battle Creek Technical Advisory/Work Group in an effort to understand the historic role of Coleman Hatchery.⁷²

Methods

Spawning Habitat Inventories. Spawning habitat estimates were made in 1939 as part of the Shasta Salmon Salvage Program (Hanson and others 1940). The surveyed habitat was divided into habitat considered suitable for spring-run, winter-run, or fall-run chinook salmon. The divisions were made according to recorded occurrence of spawners and available information on the suitability of temperatures in the various spawning zones. The 1939 spawning habitat surveys were compared with modern day surveys on the South Fork of Battle Creek where there have not been any habitat changes since 1939. The modern survey completed by Coots and Healey (Coots and Healey 1966) and Kondolf (Thomas R. Payne & Associates 1989) are within 10% of the 1939 surveys within this reach.

The number of available nest sites or redds available above Shasta Dam was estimated by dividing the average redd size measured in 1939 in to the available habitat. The average redd size for the reaches above Shasta Dam was 40 square feet. Reaches below Shasta Dam used a value of 50 square feet per redd (Rieser and Bjorn 1979). It was assumed the distribution of spawning efforts

72. This "Spawning Habitat Analysis" was discussed in October 1997 at a Santa Rosa meeting of the Battle Creek Technical Advisory/Work Group. The methodology of extrapolating from spawning gravel surveys to arrive at historic Sacramento River salmon populations still requires additional work.

over the three month spawning period allowed the necessary space; especially during the first and last quarter of the spawning period.

It is possible to extrapolate the available nest sites into an estimated population size. A habitat-based method may be as justified as the fish counting effort used during the late 1930s and early 1940s. The counting effort at that time was a partial count and the returning adults were from juveniles produced during the worst drought in recent recorded history. This habitat-based estimate of the population represents carrying capacity of the river system only if spawning habitat is limiting and the long-term average population is stable (1:1 spawner replacement). Each redd is assumed to represent two adults and some jacks. The percentage of jacks in 1939 was reported by the U.S. Bureau of Fisheries in 1940.

Results

Spawning sites available above Shasta Dam:

- Fall run: 24,847 nest sites representing 64,602 salmon at 2 adults per redd and 30% jacks.
- Spring run: 51,377 nest sites representing 133,580 salmon at 2 adults per nest and 30% jacks. In addition, the Pit River habitat lost to PG&E dams is estimated at 7,444 redds representing 19,354 salmon at 2 adults per redd and 30% jacks.
- Winter-run: 34,634 nest sites (including habitat lost to PG&E dams), representing 90,048 salmon at 2 adults per redd and 30% jacks.

Spawning sites available between Keswick and Shasta dams:

- Fall run: 2,286 nest sites representing 5,945 salmon at 2 adults per redd and 30% jacks.
- Spring run and winter run: None – the temperatures were too warm.

Spawning sites available between Keswick Dam and Red Bluff Dam:

- 1939 Ground Survey: 18,413 sites.
- 1964 Generalized Aerial Survey: 145,000 sites.
- 1980 Extensive Ground and Aerial Survey: 96,000 sites.

Significant differences within these surveys are attributable to the following:

- The 1939 survey was conducted during the worst drought in recent history.
- The 1964 survey was not as extensive as the 1980 survey because it only used aerial survey techniques without ground surveys.
- The 1964 and 1980 surveys incorporated aerial observations of spawning fish. The 1980 population was only one-third of the 1964 survey.
- There was less spawning gravel available in 1980 than in 1964 within the upper 15 miles of those reaches due to lost gravel recruitment caused by Shasta Dam.

Spawning sites available between Red Bluff Dam and Woodson Bridge:

- 1939 – No survey was conducted. Biologists characterized the additional 70 miles of spawning habitat to be in a “broad, slow...” and warm river.
- 1964 – Generalize Aerial Survey: 70,906 sites.

Factors Affecting Chinook Salmon Spawning in the Lower Feather River

Ted Sommer, Debbie McEwan, and Randall Brown

Abstract

We review the status of chinook salmon in the lower Feather River and examine factors affecting chinook salmon spawning since the construction of Oroville Dam. Spawning occurred in depths from 0.4 to 4 ft with the central 50% of observations in the 1.6 to 2.6 ft range. Depth used was slightly higher at increased flows. Velocities of 0.4 to 4.8 ft/s (central 50% = 1.5 to 2.7 ft/s) were used at all flows. Redds were constructed in substrate containing less than 60% fines in 0.2- to 1-inch to 6- to 9-inch gravel size classes.

Redd surveys showed that spawning occurred in twice as much area below Thermalito Afterbay Outlet than the low flow channel (LFC). However, in most recent years, about 75% of fish spawned in the LFC. Superimposition indices calculated from these results suggest that there was insufficient spawning area in the LFC to support the number of spawning pairs, but adequate area below Thermalito Afterbay Outlet. Spawning activity was highest in the upper three miles of the LFC, whereas spawning area was relatively evenly distributed below Thermalito Afterbay Outlet. Historical results suggest superimposition significantly reduces egg survival.

Statistical analysis of historical data showed that there has been a highly significant increase in the number of salmon spawning in the LFC. In-channel escapement explained a significant additional portion of the variability in spawning distribution. The significant increase in the proportion of spawners using the LFC over time may be at least partially attributable to an increasing proportion of river flow from this channel. Substrate composition based on Wolman counts and bulk samples do not explain trends in spawning distribution as LFC gravel has become progressively armored over the past 16 years, whereas downstream substrate composition has not changed detectably. Temperature trends were not significantly correlated with spawning distribution. We hypothesize that hatchery stocking location and genetic introgression between fall-run and spring-run chinook stocks also account for spawning activity in the LFC. Spawning simulations using an egg production model based on these statistical analyses yielded very different results than a PHAB-SIM instream flow model.

Introduction

The Feather River supports one of the largest runs of chinook salmon (*Onchorhynchus tshawytscha*) in California's Central Valley. Unfortunately, relatively little information has been published about the status of salmon in the lower Feather River. The river was studied intensively by Painter and others (1977), who examined the effects of the construction of Oroville Dam on Feather River fish. In 1981 the California Department of Water Resources (DWR) conducted gravel studies in the river with emphasis on chinook salmon spawning riffles (DWR 1982). Dettman and Kelly (1987) and Cramer (1992) conducted analyses of the contribution of Central Valley salmon hatcheries (including Feather River) to ocean harvest and escapement. In the mid-1990s, DWR, in cooperation with the California Department of Fish and Game (DFG), conducted several unpublished fish studies that focused on the effects of flow on salmon. These results were later used by Williams (1996) for a theoretical analysis of the effects of variability on instream flow modeling results.

The following paper summarizes our understanding about the status of chinook salmon in the Feather River including a portion of their life history, abundance trends, and physical habitat. This information is used as the basis for detailed analyses of spawning, which we believe is probably more important to in-river salmon production than either adult holding, juvenile rearing, or emigration. Specific objectives were to:

- Describe the physical conditions for chinook salmon spawning in the Feather River.
- Identify the factors that affect spawning distribution and success.
- Develop models to simulate spawning in the Feather River.

Chinook Salmon Life History in the Feather River

The lower Feather River has two runs of chinook salmon, the fall-run and spring-run. Adult fall-run typically return to the river to spawn during September through December, with a peak from mid-October through early December. Spring-run enter the Feather River from March through June and spawn the following autumn (Painter and others 1977). However, the spring-run are genetically uncertain as a result of probable in-breeding with the fall-run (Yoshiyama and others 1996; Brown and Greene 1994; Hedgecock and others, this volume). Genetic studies are presently underway to examine this issue. Fry from both races of salmon emerge from spawning gravels as early as November (Painter and others 1977; DWR unpublished data) and generally rear in the river for at least several weeks. Emigration occurs from December

to June, with a typical peak during the February through April period. The vast majority of these fish emigrates as fry (DWR unpublished data), suggesting that rearing habitat is limiting or that conditions later in the season are less suitable. Risks for late migrating salmon include higher predation rates and high temperatures. The primary location(s) where these fish rear is unknown, however in wetter years it appears that many young salmon rear for weeks to months in the Yolo Bypass floodplain immediately downstream of the Feather River before migrating to the estuary (Sommer and others 2001).

Historical distribution and abundance of chinook salmon in the Feather River is reviewed by Yoshiyama and others (this volume). They note that fall-run historically spawned primarily in the mainstem river downstream of the present site of Lake Oroville, while spring-run ascended all three upstream branches. Fry (1961) reported fall-run escapement estimates of 10,000 to 86,000 for 1940–1959, compared to 1,000 to about 4,000 for spring-run. Recent fall-run population trends continue to show annual variability, but are more stable than before Oroville Dam was completed (Figure 1). Pre-dam escapement levels have averaged approximately 41,000 compared to about 46,000 thereafter (see also Reynolds and others 1993). This increase appears to be a result of hatchery production in the system. The pre- and post-dam levels of spring-run are similar, however the genetically uncertain stock is now dominated by hatchery operations (Figure 2).

Hatchery History and Operations

Feather River Hatchery was opened in 1967 to compensate for the loss of upstream habitat by the construction of Oroville Dam. The facility is operated by the California Department of Fish and Game and typically spawns approximately 10,000 adult salmon each year (see Figure 1). Until the 1980s, the majority of the young hatchery salmon was released into the Feather River (Figure 3). However, the release location was shifted to the Bay-Delta Estuary to improve survival.

Hydrology

The Feather River drainage is located within the Central Valley of California, draining about 3,600 square miles of the western slope of the Sierra Nevada (Figure 4). The reach between Honcut Creek and Oroville Dam is of low gradient. The river has three forks, the North Fork, Middle Fork, and South Fork, which meet at Lake Oroville. Lake Oroville, created by the completion of Oroville Dam in 1967, has a capacity of about 3.5 million acre-feet (maf) of water and is used for flood control, water supply, power generation, and recreation. The Lower Feather River below the reservoir is regulated by Oroville Dam, Thermalito Diversion Dam, and Thermalito Afterbay Outlet. Under normal operations, the majority of the Feather River flow is diverted at Thermalito Diversion Dam into Thermalito Forebay. The remainder of the flow,

typically 600 cubic feet per second (cfs), flows through the historical river channel, the “low flow channel” (LFC). Water released by the forebay is used to generate power before discharge into Thermalito Afterbay. Water is returned to the Feather River through Thermalito Afterbay Outlet, then flows southward through the valley until the confluence with the Sacramento River at Verona. The Feather River is the largest tributary of the Sacramento River.

The primary area of interest for salmon spawning is the low flow channel (see Figure 4), which extends from the Fish Barrier Dam (river mile 67) to Thermalito Afterbay Outlet (river mile 59), and a lower reach from Thermalito Afterbay Outlet to Honcut Creek (river mile 44). There is little or no spawning activity in the Feather River below Honcut Creek.

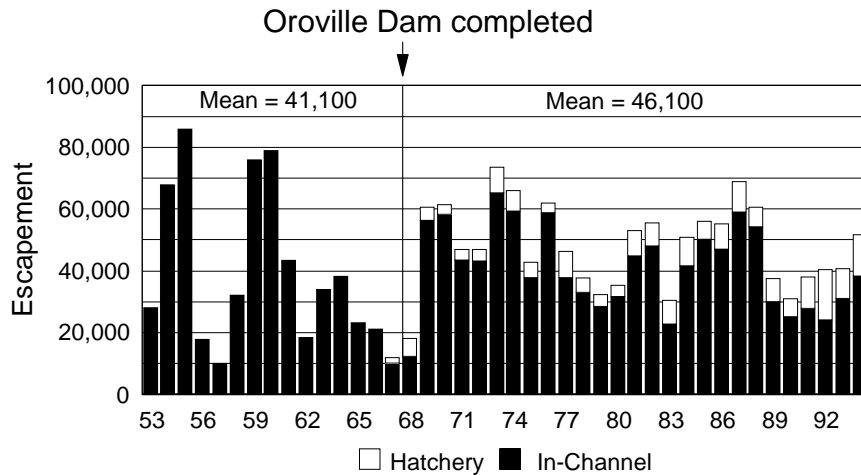


Figure 1 Escapement of fall-run chinook salmon (1953–1994) in the Feather River Hatchery and channel

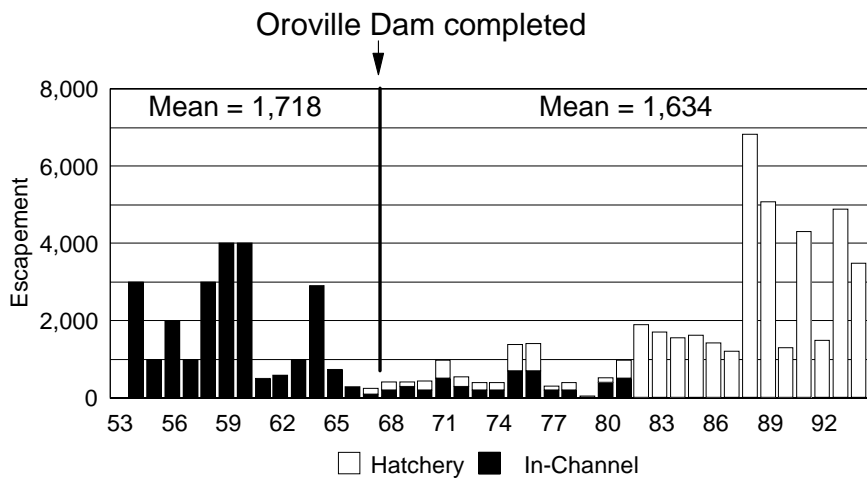


Figure 2 Escapement of spring-run chinook salmon (1953–1994) in the Feather River Hatchery and channel

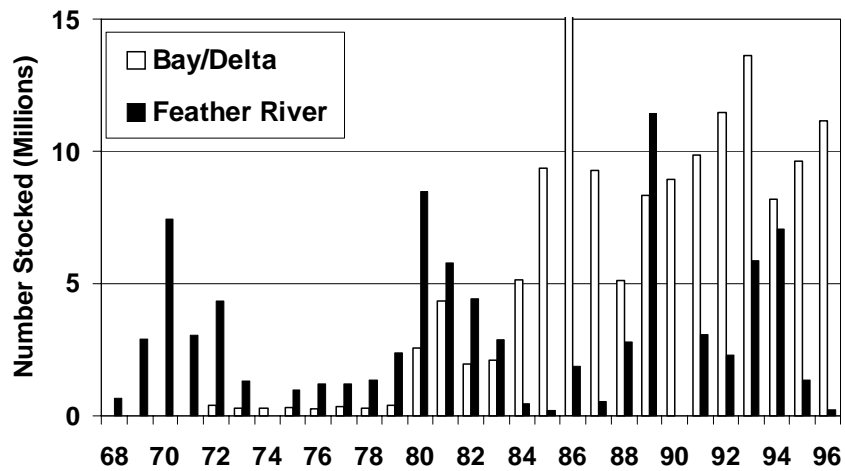


Figure 3 Stocking rates of juvenile salmon from the Feather River Hatchery into river and Bay-Delta locations

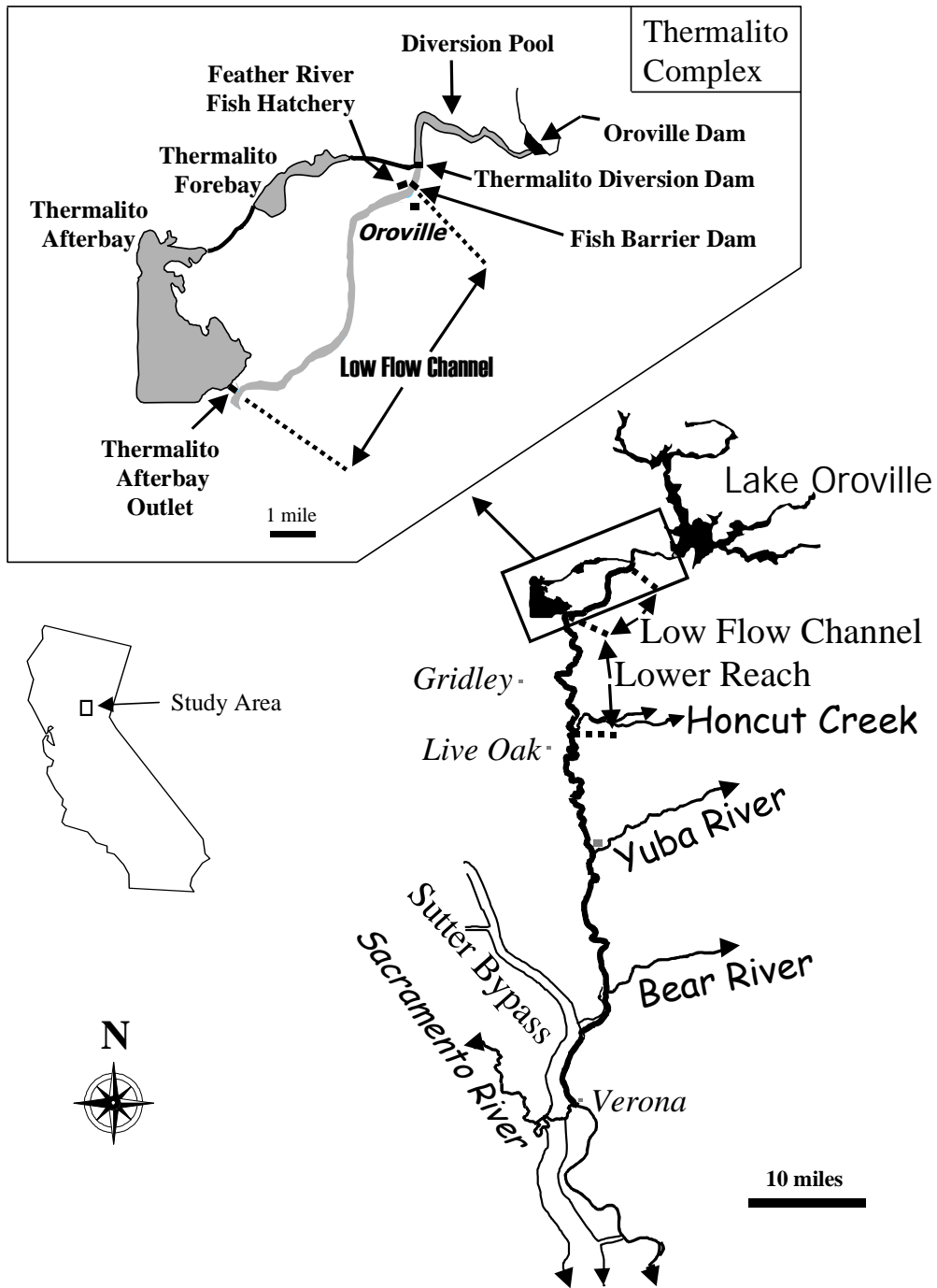


Figure 4 Feather River and vicinity

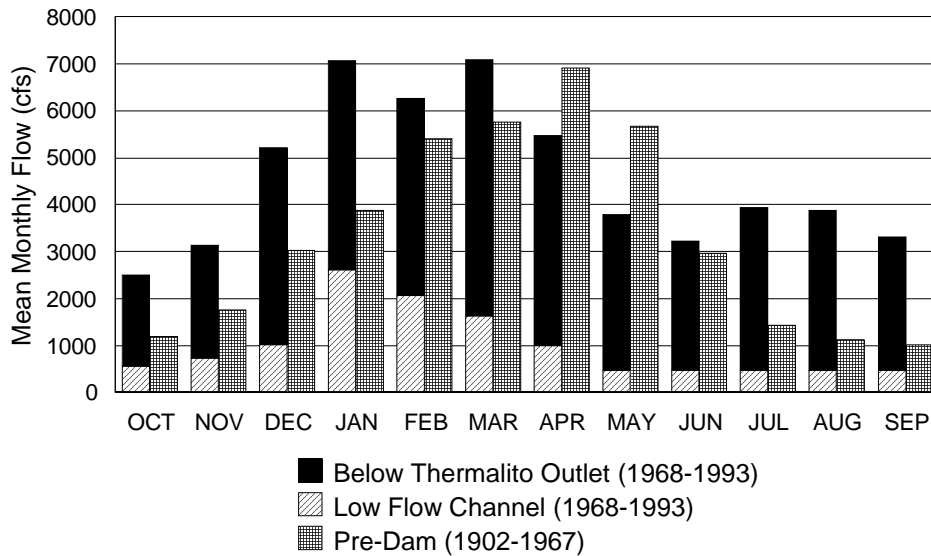


Figure 5 Mean monthly flows (cfs) in the Feather River for the pre-Oroville dam (1902–1967) and post-Oroville dam (1968–1993) periods. Total flow in the post-dam period includes the portion from the low flow channel and the portion diverted through the Thermalito complex.

The hydrology of the river has been considerably altered by the operation of the Oroville complex. The major change is that flow that historically passed through the LFC is now diverted into the Thermalito complex. Mean monthly flows through the LFC are now 5% to 38% of pre-dam levels (Figure 5). Mean total flow is presently lower than historical levels during February through June, but higher during July through January. Project operations have also changed water temperatures in the river. Compared to historical levels, mean monthly water temperatures in the LFC at Oroville are 2 to 14 °F cooler during May through October and 2 to 7 °F warmer during November through April. Pre-project temperature data are not available for the reach below Thermalito Afterbay Outlet, but releases from the broad, shallow Thermalito Afterbay reservoir probably create warmer conditions than historical levels for at least part of the spring and summer.

Methods

Data for the present study were obtained from three sources: annual carcass surveys, instream flow studies conducted during the early 1990s, and recent detailed studies on spawning. The major field measurements are summarized below.

Physical Conditions for Spawning

Our analysis of spawning conditions focused on depth, velocity, and substrate conditions. Initial field measurements were made October 1991, representing early-peak spawning activity. Sampling was concentrated in the vicinity of 36 transects selected to represent historical spawning areas (DWR 1982) and habitat types (see below). Further details about the transects are available in Williams (1996). Individual redds within approximately 100 ft of each transect were located by three field crew by wading or boat observations.

The ground level survey was verified using aerial photography of the area between Fish Barrier Dam and Honcut Creek. Photographs were taken on 16 October 1991 from an elevation of approximately 1000 ft. Comparison of color prints from the flyover with ground-level redd mapping confirmed that the field survey was reasonably comprehensive.

Field measurements of depth, substrate, and velocity were performed using wading methods. Depth and velocity were measured using a Price AA flow meter in undisturbed gravel approximately two feet upstream of each redd at an angle of 45 degrees to the direction of flow. The dominant gravel type was evaluated for the surface substrate using a modified Brusven classification (Platts and others 1983). A visual estimate of the amount of fines in the surface layer was recorded separately as a percentage of the total substrate. A single field observer was used throughout the study to minimize subjective variation.

Additional field measurements were made in 1995 based on concerns that the 1991 data were collected under unusually low flow conditions. Flows in the river during the 1995 spawning season (October to December) were experimentally increased in the low flow channel and reach below Thermalito Afterbay Outlet to 1,600 and 2,500 cfs, respectively, compared to the 600 and 1,000 cfs levels studied in 1991. Similar techniques were used in 1995 sampling, although substrate was not analyzed. Depth and velocity data from 1991 and 1995 were compared using Mann-Whitney U tests.

The quality of gravel in the major spawning riffles was examined in more detail from samples collected in 1982 and 1996. The 1996 samples were taken as close as possible to the original 1982 sites. Bulk samples weighing between 400 and 700 pounds were collected using shovels at the head of point bars adjacent to most of the major salmon spawning riffles. The surface and subsurface portions were sampled separately. Bulk samples were sieved on site and the sand to silt portion was taken to the laboratory for further analysis. The laboratory sieves ranged from 0.019 to 1.2 inches. The results were analyzed based on the geometric mean of the particle size distribution by river mile.

Surface samples were also taken at twenty riffles using a modified Wolman (1954) grid method. Although the Wolman counts do not adequately sample the finer sediments, we selected the technique because of its relative simplicity and common usage. The area sample included or was adjacent to the bulk sample site. Statistical analysis of the Wolman counts was similar to the bulk samples.

Spawning Distribution

Our basic approach to analyzing Feather River spawning distribution was to prepare a map of the available aquatic habitats, then use aerial photographs and ground-based observations to identify the spawning areas.

The major habitat types were classified using a system similar to Beak Consultants, Inc. (1989). Channel features delineated using aerial photographs (1 inch:400 feet) from October 1990 and US Geological Survey topographical maps indicated that the majority of the study area consisted of island bar complex and straight flatwater habitat. Field studies were then conducted to further refine site maps to include specific habitat components: riffles, pools and run-glide areas. Field observations were made at a flow rate of 600 cfs above Thermalito Afterbay Outlet and at approximately 4,500 cfs below the outlet.

The maps were analyzed by recording the linear distance (ft) of each habitat type. In complex areas with overlapping habitats or multiple channels, the relative abundance of each habitat type was estimated as a percentage of the total channel area. Note that actual habitat boundaries for "riffles", "pools" and "run-glide" areas changes relative to flow conditions. However, the maps we prepared provide a useful baseline to identify sampling areas and changes in spawning distribution. Another consideration is that there have been changes to some areas as a result of subsequent high flows in 1993 and 1995. However, site visits in 1995 indicated that there was no major change in the relative proportions of the different habitat types.

Aerial photographs were taken of the entire study reach in November 1995 to examine redd distribution. Ground-based observations were made within 24 hours of the date of the flight to check the accuracy of the methods. However, we were unable to identify individual redds because of the large numbers of fish spawning in relatively few areas. As an alternative, we quantified spawning activity based on the total area disturbed by spawning activity. Because some disturbed areas do not represent redds, we consider the results an estimate of the maximum amount of area used for spawning. The 1:3000 scale photographs were prepared using a yellow filter to minimize glare. The negatives were reviewed before printing to identify the sites containing redds that needed to be enlarged to a scale of 1:600. Total disturbed area, referred to as "total spawning area," was delineated on the prints relative to habitat bound-

aries from the previously described habitat map. The area estimates were calculated by digitizing these maps using AUTOCAD. The results were quantified by river mile, river reach, and habitat type.

We examined carcass count data from Painter and others (1977) to provide a historical perspective on spawning distribution. Carcass recoveries were recorded by river mile for 1971 through 1974. Although these data are biased because many carcasses would have drifted downstream of the riffle or run-glide where spawning occurred, we believe the results are a useful approximation of actual distributions.

Field observations of spawning suggested that superimposition of redds was a major problem in the Feather River. We developed indices from the 1995 data to examine superimposition rates by river reach as follows:

$$\text{Superimposition Index} = \frac{(\text{Escapement Estimate} \times 0.5)(\text{Spawning Area in ft}^2)}{55\text{ft}^2}$$

The escapement estimate is from DFG's fall carcass survey and is multiplied by 0.5 to represent the number of spawning pairs. The 55 ft² value is the average surface area for an average size fall-run chinook salmon (Bell 1986). The spawning area estimate was calculated from previously described aerial photography methods. We emphasize that the result should be considered an index rather than an actual measure of superimposition rates. As described in Healey (1991) there is considerable variability in the surface area of redds, which could have a major effect on the amount of superimposition in the Feather River.

Analysis of Factors Affecting Spawning Distribution

The superimposition and redd distribution analyses showed that there were major differences in the distribution of spawning activity between study reaches. We addressed this issue by examining the proportion of fish that spawned in the LFC relative to different environmental conditions. Historical escapement data were obtained from DFG for the LFC and from Thermalito Afterbay Outlet to Gridley. Data were available for 1969 through 1974, 1977, 1979 through 1987, 1989, and 1991 through 1996. We calculated the percentage of spawners in the low flow channel as:

$$\text{Percent Spawners in Low Flow Channel} = 100 \times \frac{\text{Escapement in Low Flow Channel}}{\text{Total Escapement Oroville to Gridley}}$$

As will be discussed in further detail, we found strong time trend in spawning distribution. We used regression analysis to determine whether total escapement, temperature, flow, and flow distribution had similar time trends that might explain the apparent changes in spawning distribution. In addition, we regressed each variable against the residuals from the spawning distribution-time relationship to determine whether the variable explained a significant additional portion of the variability. We calculated average maximum daily temperature for October and November of each year (1969–1991) using data from US Geological Survey records for Thermalito Afterbay Outlet. USGS data for 1969–1996 were obtained to estimate average October and November flow in the LFC and flow distribution, calculated as the percentage of total river flow that was released through the LFC. The normality of each variable was tested with a Shapiro-Wilks W test and log-transformed where necessary.

Modeling

Two different approaches were used to model spawning in the lower Feather River. The first was to use simulate the effect of flow on spawning using the instream flow model Physical Habitat Simulation System (PHABSIM). As an alternative, we simulated egg production using a simple mechanistic model developed from statistical relationships for factors affecting spawning distribution and egg survival.

Instream Flow Model

PHABSIM methods and models were developed by the US Fish and Wildlife Service Instream Flow Group (Bovee 1982). To summarize briefly, a habitat mapping approach (Morhardt and others 1984) was used to select and model the previously described transects. A hydraulic model was developed based on physical data collected at each transect to simulate depth, velocity, and substrate at a range of river flows for each reach. Weighted Useable Area (WUA), an index of habitat, was simulated by combining the hydraulic model results with binary suitability curves developed from data collected on conditions used for spawning. Details about the modeling approach are provided below and in Williams (1996).

Physical data collection procedures followed the methodology of Trihey and Wegner (1981). Permanent headstakes and benchmarks were established between autumn 1991 and summer 1992 at all transects following surveys of the study reach. Stage-discharge measurements were attempted at three to four different flows between autumn 1991 and spring 1993. For most lower reach transects, stage data were collected at 1,000, 2,500 and 3,000 cfs. In the LFC, stage measurements were performed at 400, 600 and 1,000 cfs.

During July 1992 cross-sectional coordinates and mean column velocity (one to three depths) were collected on at least 15 points across the wetted width of each transect. At pool and glide sites, Price AA flow measurements were made from a ten-foot aluminum boat attached to aircraft cable stretched across the channel. Similar measurements were made at riffle sites by wading using a top-setting rod.

The hydraulic data were calibrated using the methods of Milhous and others (1989). Water surface elevation and velocity data for most transects were calibrated using the IFG4 option of PHABSIM, although MANSQ was used as an alternative to calibrate elevations for some riffle and glide habitats. When at least four stage-discharge measurements were available, calibration was often improved using separate low- and high-flow range models to simulate elevations. Following calibration, water surface elevations and velocities were simulated using IFG4 within the maximum extrapolation range recommended by Stalnaker and Milhous (1983): 200 to 2,500 cfs in the LFC and 500 to 7,500 cfs in the lower reach.

Habitat suitability curves were developed using previously described data on depth, velocity, and substrate. For modeling purposes, the results were simplified into binary curves. The central 50% of observations for each depth, velocity, and dominant substrate were assigned a value of "1" and the remaining observations were assigned a value of "0." In addition, any substrate with greater than 50% fines was assigned a value of "0." Although we also considered modeling suitability based on more complex curve-fitting techniques (Bovee 1982), the resulting curves are often biologically questionable (Bovee, personal communication, see "Notes"). The binary curve approach seems reasonable for the Feather River, where spawning activity is concentrated in suitable gravel on a relatively small number of riffles and glides.

The amount of microhabitat available for different discharge rates was simulated using the PHABSIM program HABTAT (Milhous and others 1989). Habitat availability was calculated in terms of WUA by combining hydraulic simulation data and binary habitat suitability curves. The WUA in each reach was obtained by weighting transects modeled for each habitat type using habitat abundance data collected during site selection.

Egg Production Model

As further described in the results, statistical analyses suggest that flow and escapement have a significant effect on the proportion of salmon that spawn in the LFC. However, egg survival is reduced in the LFC as a result of superimposition. We developed a spreadsheet model which simulates egg survival based on flow and escapement. The basic structure of the model is that spawning distribution between the two river reaches is simulated using a

regression equation based on the proportion of flow from the LFC and escapement. Initial egg production for each reach is calculated from the number of spawning pairs. Egg survival rates are then assigned separately to the two study reaches based on historical observations.

The regression equation for spawning distribution came directly from previously-described analyses of variables affecting the proportion of LFC spawners. Other variables such as hatchery practices that may result in time trends in spawning distribution were assumed to be constant. Total flow was assumed to be constant at 2,500 cfs, which is typical for the spawning period. Total egg production was calculated for each reach by multiplying the number of spawning pairs by an assumed fecundity of 5,000 eggs.

Egg survival was simulated based on the results of Painter and others (1977), who examined the proportion of live and dead eggs for several years over different spawning densities. They found a significant inverse relationship between egg survival (S) and escapement of salmon in the LFC (L): $S = -0.00292L + 111.2$, ($r^2 = 0.575$, $P < 0.05$). We assumed that this regression relationship represented egg survival in the LFC, but set a minimum survival limit of 30%, the lowest rate observed in the Painter and others (1997) study. The upper limit was set at 100% based on maximum survival estimates from Healey (1991). There was no such relationship or strong indication of density dependence for the study reach below Thermalito, so we used the average egg survival rate for 1968 through 1972 (84%) for all simulations.

As evidence that the highest egg survival rates measured by Painter and others (1977) are reasonable, survival estimates for undisturbed chinook salmon eggs to hatching stage range from 82% (Briggs 1953) to 97% (Vronskiy 1972). We also used the method of Tappel and Bjornn (1983) to calculate "ideal" Feather River egg survival rates based on the particle size distribution of several spawning riffles. The key particle sizes needed for the model were estimated by linear interpolation from combined bulk surface and subsurface samples. The survival estimate for gravel in three spawning riffles using the Tappel and Bjornn (1983) method was 83% (SD = 5), close to the 84% average (SD = 8) for below Thermalito Afterbay Outlet, but lower than the highest survival rate observed in the LFC (93%). Although these results suggest that the highest Feather River survival rates measured by Painter and others (1977) are reasonable, we were unable to verify the shape of the inverse relationship with LFC escapement. The Painter and others (1977) results were from observations of eggs pumped from redds using a McNeil sampler, which does not measure mortality of eggs lost to the water column through superimposition. However, Fukushima and others (1998) found that the number of pink salmon eggs lost into the channel was roughly proportional to spawner abundance, indicating that water column losses can at least be expected to follow the same trend as intergravel mortality. For modeling purposes, we assumed that the

slope of the Painter and others (1977) relationship would not change substantially if water column losses were included.

Results

Physical Conditions for Spawning

A total of 205 depth measurements and 198 velocity measurements was made in riffles, pools and glides in the low flow channel. Spawning occurred in depths from 0.4 to 4.0 ft with the central 50% of observations ranging from 1.6 to 2.6 ft (Figure 6). Salmon spawned at velocities of 0.4 to 4.8 ft/s with a range of 1.5 to 2.7 ft/s for the central 50% of observations (Figure 7). The data suggest that the velocities used in 1992 were similar to 1995, but spawning occurred at somewhat greater depths in 1995 (see Figure 6). These hypotheses were confirmed using a Mann-Whitney U test, which showed that there were no significant differences for velocities, but highly significant differences for depth ($P < 0.0001$).

The dominant substrate used by spawners ranged from the 0.2- to 1-inch size class to the 6- to 9-inch class (Figure 8). Spawning was not observed in substrate with greater than 50% fines. The Wolman samples show that the largest substrate was at the top of the LFC, with a trend towards smaller material to Thermalito Afterbay Outlet (Figure 9). Gravel size increased at most sampling sites in the LFC from 1982 to 1996, but decreased below Thermalito Afterbay Outlet, suggesting armoring of the LFC as smaller gravel was transported downstream. Armoring is also evident in the surface bulk samples, with similar spatial trends and changes between the two years in the samples (Figure 10). Subsurface gravel size was somewhat larger in the LFC and showed an increase in size in the uppermost riffles.

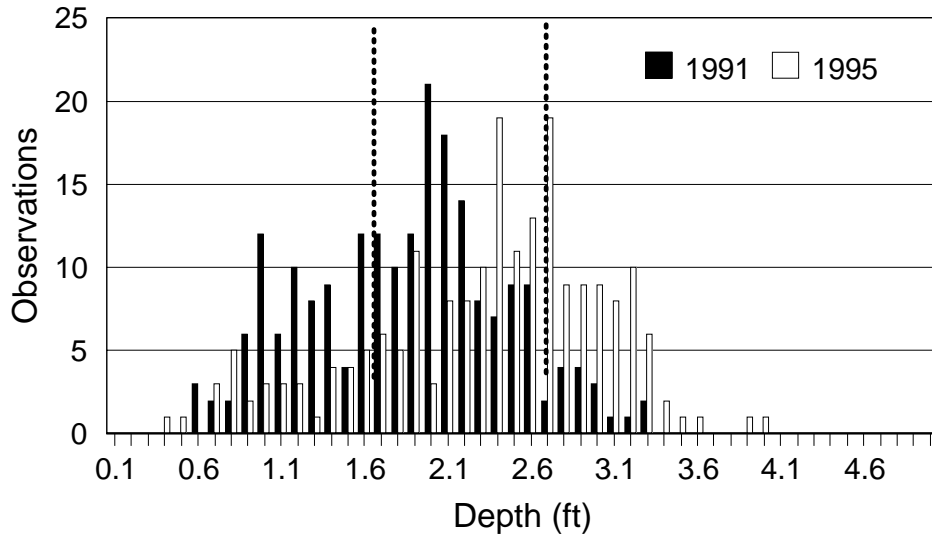


Figure 6 Histogram of spawning observations at different depths for 1991 and 1995, when flows were higher. The central 50% of observations are bracketed by dashed lines.

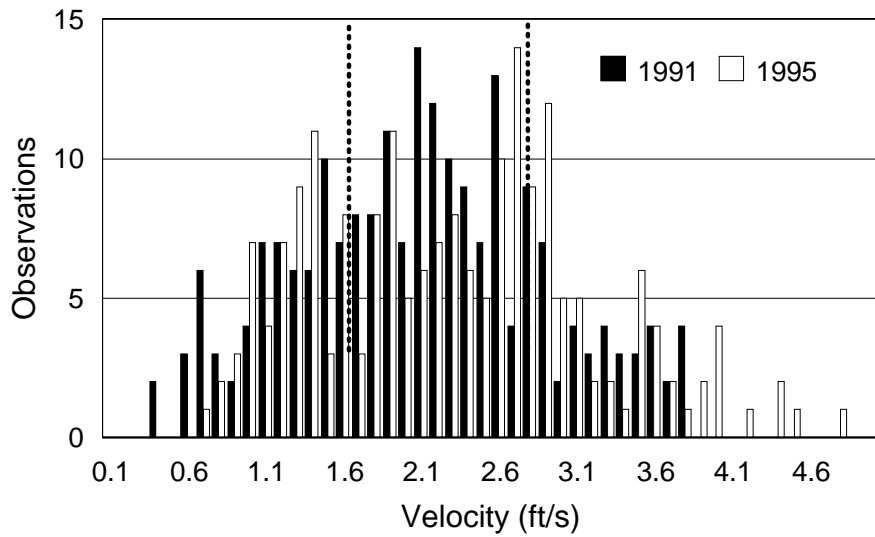


Figure 7 Histogram of spawning observations at different velocities for 1991 and 1995, when flows were higher. The central 50% of observations are bracketed by dashed lines.

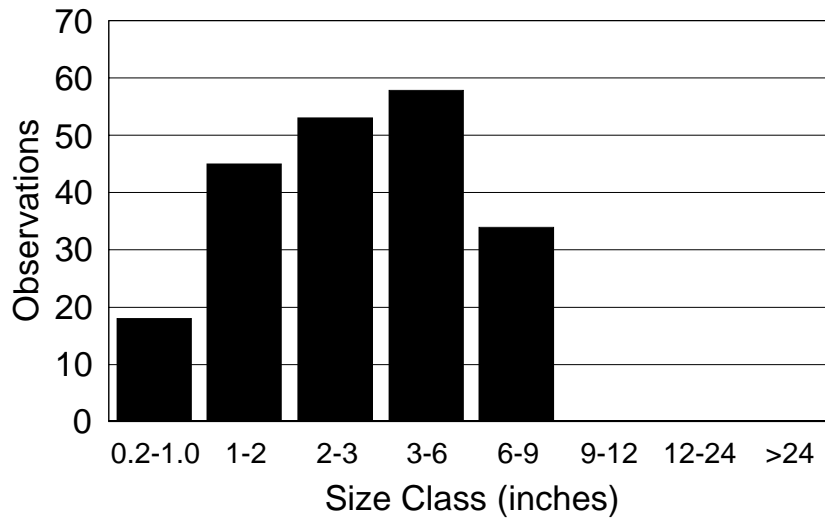


Figure 8 Size classes of spawning gravel used by Feather River salmon

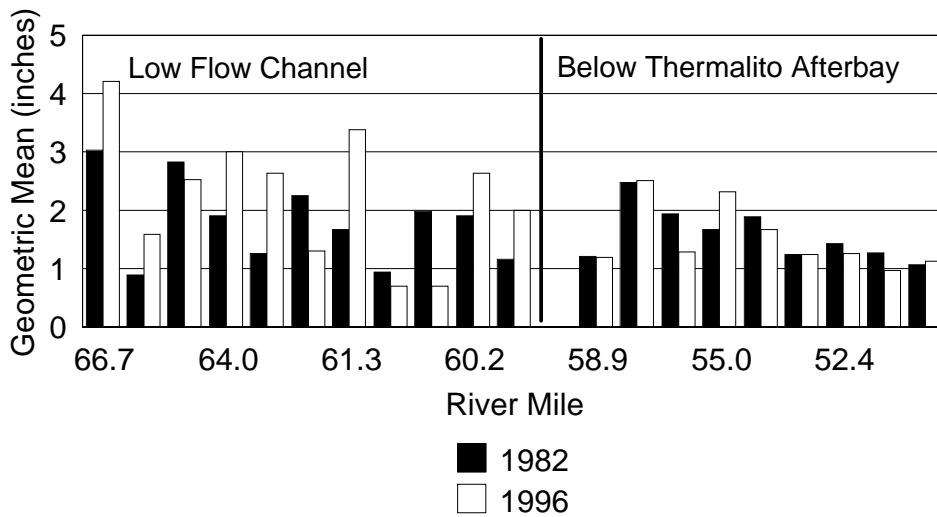


Figure 9 The geometric mean (inches) of Wolman gravel samples collected by river mile for 1982 and 1996

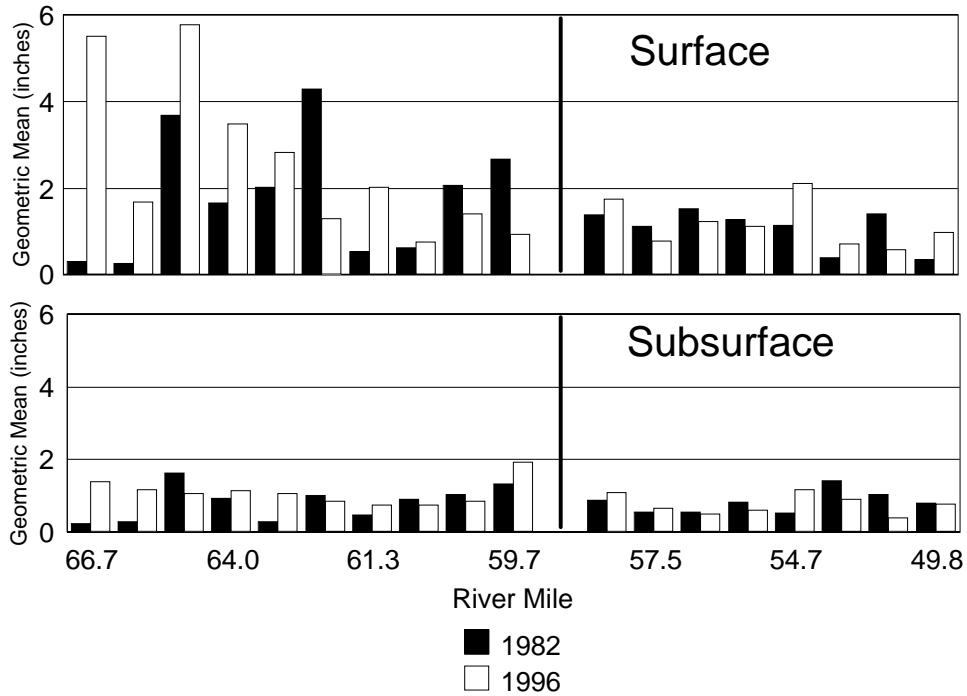


Figure 10 The geometric mean (inches) of bulk surface and subsurface gravel samples collected by river mile for 1982 and 1996

Spawning Distribution: In 1995 a total of 773,732 ft² of the LFC was used for spawning, with the greatest area concentrated in upper few kilometers of the reach (Figure 11). The majority of spawning occurred in the “riffle” and “glide” areas (Table 1). The upper three miles contained more than 60% of the total spawning area. A similar trend for the LFC is also evident in the historical data (Figure 12).

The estimate of total spawning area for the reach below Thermalito Afterbay was 1,480,085 ft² (see Figure 11). The “glide” areas showed the greatest amount of spawning activity and the “riffle” and “pool” areas had approximately equal levels (see Table 1). In contrast to the LFC, spawning area below Thermalito showed no obvious trend by river mile—spawning areas were relatively evenly distributed across the reach. The historical data below Thermalito Afterbay suggest a similar pattern, although there is some indication of increased spawning activity near river mile 57 at the upper end of the reach (see Figure 12).

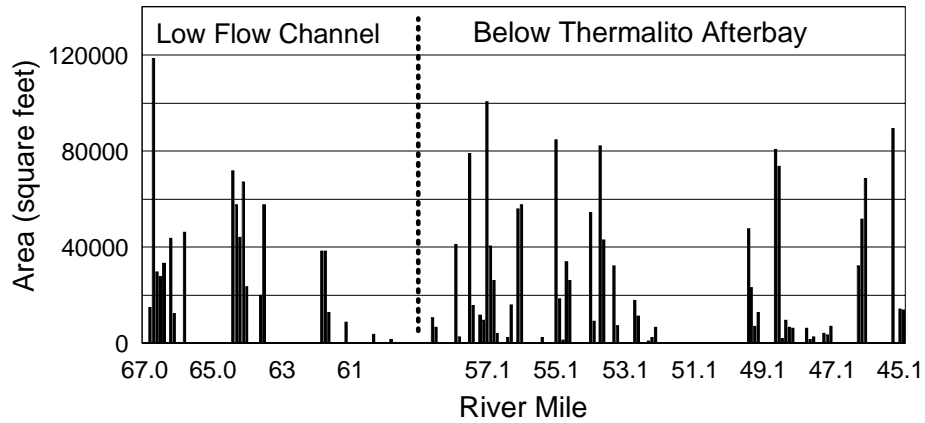


Figure 11 Spawning area (ft²) by river mile for 1995

Table 1 Spawning areas relative to boundaries set in a baseline habitat map

| <i>Habitat</i> | <i>Area (ft²)</i> | <i>Percent</i> |
|---------------------------|------------------------------|----------------|
| Low Flow Channel | | |
| “Riffle” | 276,078 | 40 |
| “Glide” | 141,486 | 20 |
| “Pool” | 280,845 | 40 |
| Total | 698,409 | 100 |
| Below Thermalito Afterbay | | |
| “Riffle” | 508,607 | 34 |
| “Glide” | 517,340 | 35 |
| “Pool” | 468,531 | 31 |
| Total | 1,494,478 | 100 |

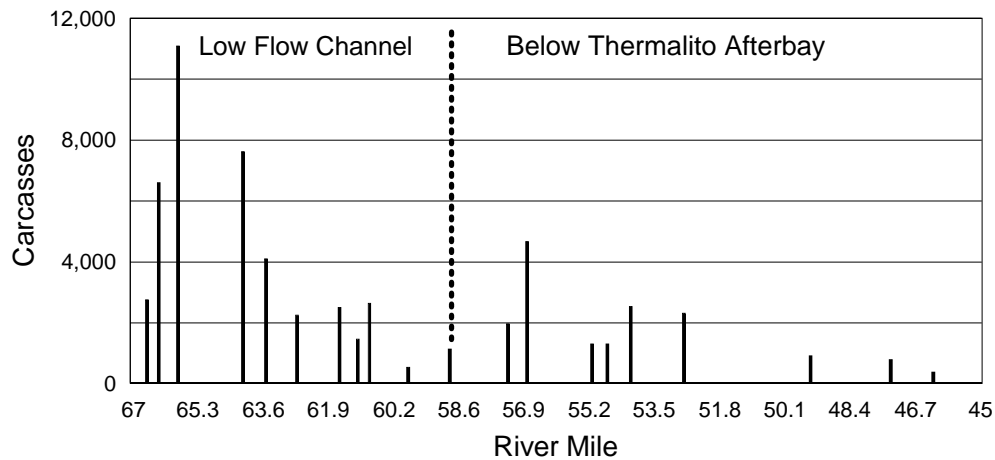


Figure 12 Salmon carcass numbers collected by river mile for 1971–1974

The 1995 DFG carcass surveys estimated that the total number of spawners for the low flow channel and the reach from Thermalito Afterbay Outlet to Gridley (see Figure 1) was 44,111 and 15,572, respectively. However, spawning area showed the opposite trend with estimates of 773,732 ft² and 915,089 ft², respectively. Based on these results, the estimated superimposition index for the LFC was 1.57 and the index for the lower reach was 0.47.

Factors Affecting Spawning Distribution

Time had a highly significant effect on the percentage of fish spawning in the LFC, explaining 72% of the variability (Figure 13). LFC flow ($r^2 = 0.02$, $P > 0.05$), October water temperature ($r^2 = 0.12$, $P > 0.05$), November water temperature ($r^2 = 0.02$, $P > 0.05$) and annual escapement ($r^2 = 0.09$, $P > 0.05$) showed no such time trend. However, flow distribution had a similar significant but weaker trend ($r^2 = 0.33$, $P < 0.001$) (Figure 14). Flow distribution ($r^2 = 0.10$, $P > 0.05$), total LFC flow ($r^2 = 0.02$, $P > 0.05$), October water temperature ($r^2 = 0.15$, $P > 0.05$) and November water temperature ($r^2 = 0.02$, $P > 0.05$) were not significantly related to the residuals from the spawning distribution-time relationship, but escapement had a weak significant relationship ($r^2 = 0.19$, $P < 0.05$) (Figure 15).

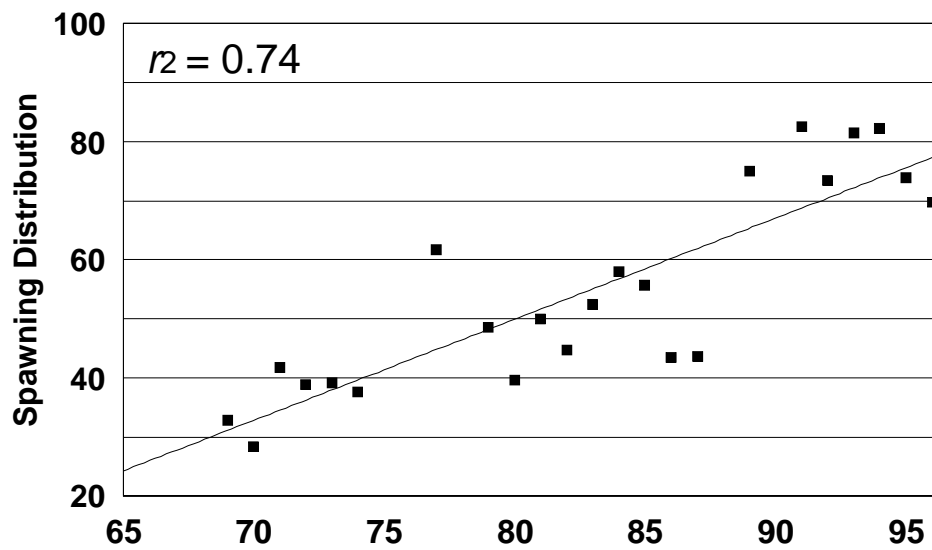


Figure 13 The percentage of salmon spawning in the LFC for 1969–1996. The increase is significant at the $P < 0.001$ level.

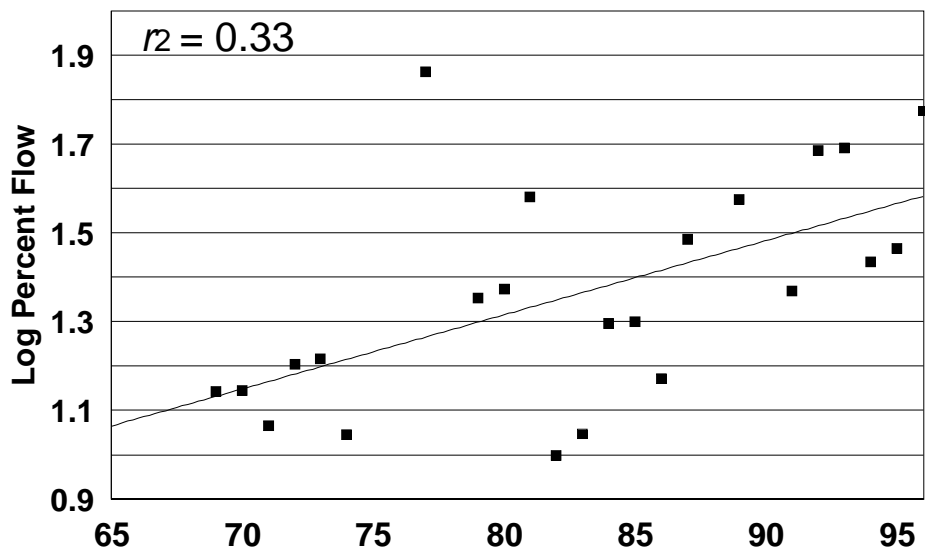


Figure 14 Log percentage of river flow from the LFC for 1969–1996. The increase is significant at the $P < 0.05$ level.

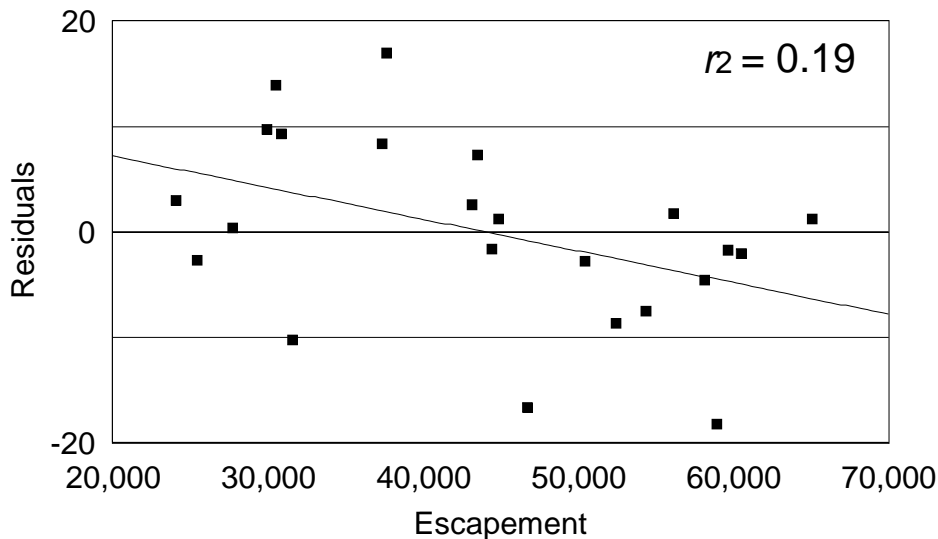


Figure 15 Relationship between in-channel escapement and the residuals from the time-LFC flow distribution relationship (see Figure 11). The decrease is significant at the $P < 0.01$ level.

These results suggested that escapement in the river and flow distribution were the key variables analyzed that could explain trends in spawning distribution. The two variables were combined in a multiple regression analysis, which showed that total escapement in the river and flow distribution explained about 47% of the variability in the percentage of salmon spawning in the LFC. However, the combined effects of flow and escapement explain less variability in spawning distribution than a model using time and escapement (multiple $r^2 = 0.77$, $P < 0.001$).

Modeling

The PHABSIM model predicted that WUA would be maximized in the LFC at 1,000 cfs and at 3,250 cfs in the reach below Thermalito Afterbay Outlet (Figure 16). The results for the egg survival model were quite different (Figure 17). Egg production increased roughly in proportion to the number of spawners. Flow had relatively little effect on predicted egg production at low escapement levels (20,000), but at higher escapement levels total egg production improved with decreasing flow.

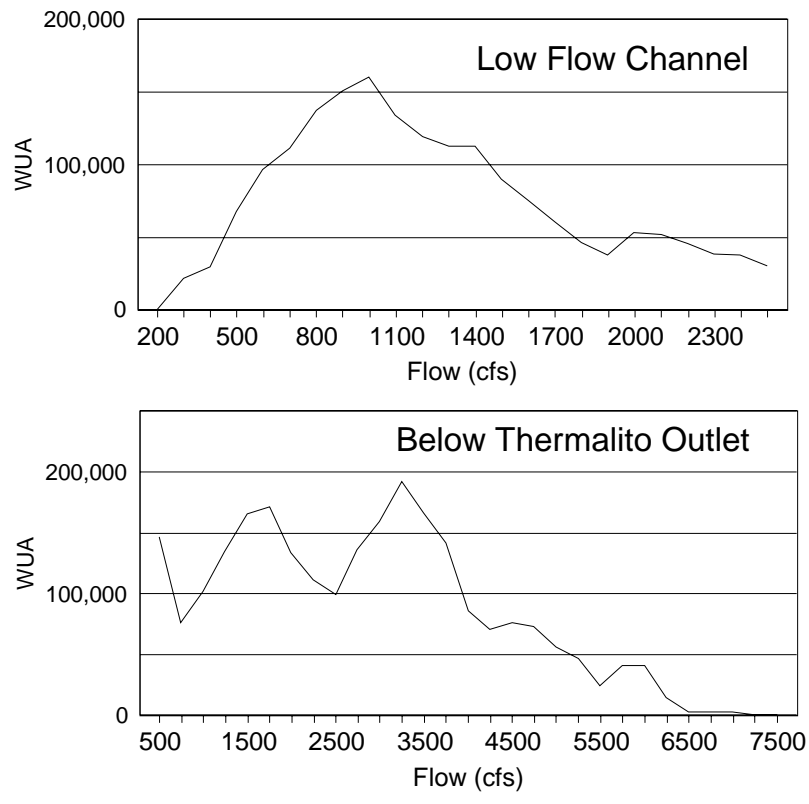


Figure 16 Simulation of spawning Weighted Useable Area (WUA) against flow (cfs) for two reaches of the lower Feather River using a PHABSIM model

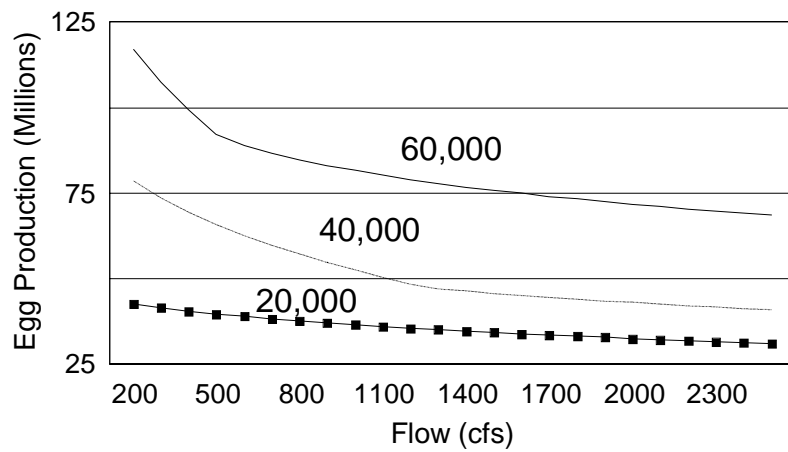


Figure 17 Simulation of egg production against flow (cfs) for three different levels of in-channel escapement

Discussion

This study documents a marked shift in the spawning distribution of chinook salmon in the lower Feather River. Since the construction of Oroville Dam and Feather River Hatchery, salmon have shifted their spawning activity from predominantly in the reach below Thermalito Afterbay Outlet to the LFC (see Figure 13). An average of 75% of spawning activity now occurs in the LFC with the greatest portion crowded in the upper three miles of the LFC (see Figure 11). While there is evidence that this upper section of the LFC was also intensively used after the construction of the dam and hatchery, the shift in the spawning distribution has undoubtedly increased spawning densities. The high superimposition indices we calculated for the LFC suggest that spawning habitat in this reach is limiting. Moreover, the results of Painter and others (1977) indicate that increased escapement will result in high egg mortality from superimposition.

The combined effects of time and escapement explained the greatest proportion of variability in spawning distribution. The effect of run size is biologically reasonable because spawning adults are highly territorial. Increased escapement levels could be expected to “push” more fish into the reach below Thermalito Afterbay Outlet.

Possible factors responsible for the time trend in spawning distribution include changes in total LFC flow, flow distribution, temperature, substrate, escapement, and hatchery practices. Of the first three variables, only flow distribution had a significant time trend. Three reasons may account for the increase in the proportion of flow from the LFC over the past three decades: (1) the minimum required LFC flow increased from 400 to 600 cfs in 1983; (2) drought conditions during 1987–1992, when total river flows were low; and (3) LFC high flow tests in 1995 and 1996. It is biologically reasonable that increasing percentage of flow from the LFC resulted in higher spawning activity in that reach—there is a well documented effect of “attraction flows” on the movements of salmon (Banks 1969).

Although changes in flow distribution explain much of the time trend in spawning distribution, it is likely that other changes may be of equal or greater importance. The combined effects of time and escapement explain 77% of the variability in spawning distribution, whereas flow distribution and escapement explain only 47%. Other potential explanations for increased use of the LFC over time include changes in gravel quality and hatchery operations. If substrate were responsible we would expect to see the greatest decline in gravel quality below Thermalito Afterbay Outlet. Yet our Wolman counts and bulk samples show that the gravel quality has deteriorated to the greatest extent in the LFC, not downstream. The increase in the gravel size at

the surface of the upstream riffles in the LFC shows that substantial armoring has occurred (see Figure 10) as smaller material has been transported downstream. Note, however, that our analyses do not account for possible changes in gravel permeability. It is possible that reduced use of the lower reach is a result of decreased gravel permeability.

Spawners seem most attracted to the heavily armored riffles at the upstream end of the reach, suggesting that hatchery operations may be at least partially responsible. We suggest two possible mechanisms for hatchery effects: (1) changes in stocking location of hatchery salmon and (2) genetic introgression between fall-run and spring-run chinook stocks.

Before 1983, most hatchery fish were stocked in the river, but after most were released downstream in the Sacramento-San Joaquin Estuary (see Figure 3). This change in operations probably increased survival rates of the hatchery fish (Cramer 1992), perhaps increasing the proportion of hatchery salmon in the stock. Salmon of hatchery origin are likely to have a stronger behavioral attraction to the LFC riffles closest to the hatchery than wild fish. Juvenile tagging studies initiated in the 1970s and more intensively in the 1990s may help to address this issue. As an indication that the proportion of hatchery fish has increased in the population, the mean escapement of fall-run at Feather River Hatchery was 4,600 adults during the first ten years of the operation of the hatchery as compared to a mean of 9,200 adults for 1983–1994 (see Figure 1). There is also evidence from other locations that hatchery salmon can displace natural stocks. Unwin and Glova (1997) found that the proportion of naturally produced chinook salmon steadily declined after the construction of a hatchery on a New Zealand stream. Like the Feather River fall-run (see Figure 1), operation of the hatchery resulted in no major change in total run strength. There is also good local evidence that operation of a hatchery can cause major changes in the distribution of chinook salmon stocks. Coleman National Fish Hatchery was built in 1942 on Battle Creek, a small tributary of the Sacramento River, to mitigate for the construction of Shasta Dam (Leitritz 1970; Black, this volume). Data for 1967–1991 show that there has been a major increase in the number of spawners using Battle Creek, while escapement in the mainstem Sacramento River had no obvious trend (Figure 18). The likely cause is that the Battle Creek population has been augmented by, or perhaps even replaced by, salmon from Coleman Fish Hatchery.

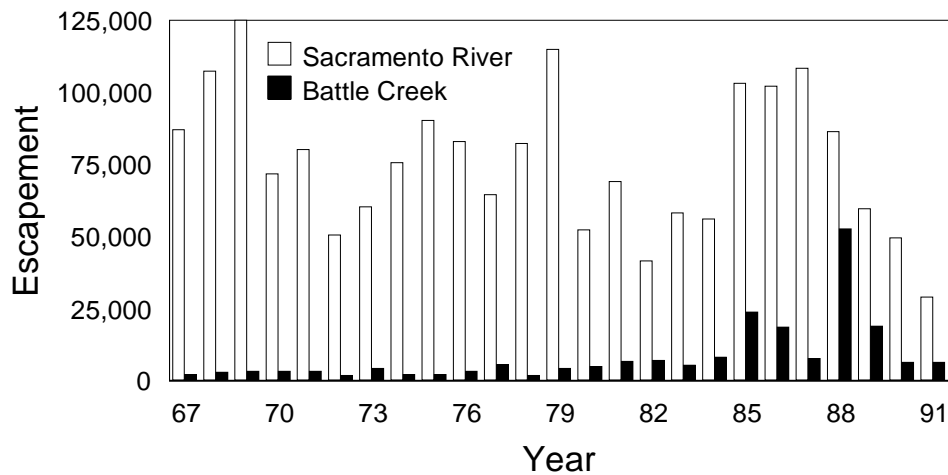


Figure 18 Salmon escapement trends in the Sacramento River compared with Battle Creek, a small tributary where Coleman National Fish Hatchery was constructed

An alternative hypothesis is that genetic introgression between fall-run and spring-run chinook salmon increased spawning in the LFC. The spawning periods for these two races historically overlapped in late summer and early fall. Genetic integrity was maintained by differences in spawning location; fall-run spawned on the valley floor, while spring-run migrated into higher gradient reaches and tributaries (Yoshiyama and others 1996). However, the construction of several dams on the Feather River blocked spring-run access to historical spawning areas. Since the construction of Oroville Dam, DFG staff at the Feather River Hatchery attempted to maintain the genetic integrity of the two races by designating the earliest-arriving spawners as spring-run. Unfortunately, this approach does not appear to have been successful. Brown and Greene (1994) describe coded-wire-tag studies on the progeny of hatchery fish identified as “fall-run” and “spring-run” and found evidence of substantial introgression. They report that significant portions of the offspring of each hatchery race returned as adults during the wrong period. For example, many of the “spring-run” group returned during months when hatchery operators designated all spawners as “fall-run.” Based on historical spawning behavior, gradual introgression of spring-run traits into the Feather River population would be expected to result in an increasing preference for the uppermost riffles of the LFC.

The PHABSIM and egg survival models yielded dramatically different results. Whether either model is a useful management tool is open to debate. The PHABSIM model is based on instream flow methodology, which is the most widely used system to develop flow recommendations (Reiser and others 1989). It predicts that increasing minimum flows in the LFC by 50% should

result in the maximum amount of spawning area (see Figure 16). However, the egg survival model indicates that increasing flow to the LFC could make conditions worse by attracting more spawners, resulting in high egg mortality through superimposition (see Figure 17). Another concern is the PHABSIM model for the reach below Thermalito Afterbay Outlet produced polymodal results, which is biologically questionable (see Figure 16). An advantage of the egg survival model is that it is based on field data collected over many years in the Feather River. While superimposition has been shown to be a major source of mortality in other locations (Fukushima and others 1998), additional studies are needed to determine whether egg supply is actually a limiting factor in the Feather River and to verify the shape of the egg survival-escapement relationship developed by Painter and others (1977). The egg survival model also does not incorporate potentially important effects of hatchery operations and is particularly questionable at low flows in the LFC, when river temperature and egg aeration could result in egg mortality.

We do not recommend either model to manage river flows at this time. Although the models yielded different results, both may reflect actual processes in the river. Given the many additional factors that could affect salmon survival in the river, we recommend the development of a more comprehensive life history model which may include aspects of the PHABSIM and egg survival models, as well as features to describe the effect of hatchery operations. In the absence of a quantitative model of salmon production in the Feather River, the results of this study could still be used as the basis for a conceptual model to test different hypotheses in the river. For example, it is possible that superimposition problems could be reduced by shifting more of the spawning activity to the reach below Thermalito Afterbay, where armoring is low and spawning habitat is more abundant. Testable alternatives to achieve this include varying the proportion of flow from the LFC or reducing the hatchery component of the stock, which are more likely to spawn in the uppermost reach of the LFC close to Feather River Hatchery.

Acknowledgments

This study was conducted with oversight from the Feather River Fisheries Technical Group, whose members include DWR, DFG, and US Fish and Wildlife Service. The Wolman and bulk substrate analyses were performed by Noel Eaves and Koll Buer (DWR). We gratefully acknowledge the assistance of Jeff Scheele, Phil Huckobey, Bill Mendenhall, and Curtis Anderson (all of DWR) with field data collection, Shawn Pike (DWR) and Jeff Thomas (US Fish and Wildlife Service) with PHABSIM model calibration, and Steve Ford, Leo Winternitz and Zachary Hymanson (all of DWR) for logistical support. The manuscript was improved by review comments from Carl Mesick (USFWS) and John Williams.

References

- Banks JW. 1969. A review of the literature on the upstream migration of adult salmonids. *J Fish Biol* 1:85-136.
- Beak Consultants, Inc. 1989. Habitat characterization of the Lower American River. Prepared for State of California Resources Agency, Department of Fish and Game. September 1989. 16 p.
- Bell MC. 1986. Fisheries handbook of engineering requirements and biological criteria. Portland (OR): US Army Corps of Engineers, North Pacific Division.
- Bovee KD. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. US Fish and Wildlife Service Biological Services Program, Cooperative Instream Flow Service Group, Instream Flow Information Paper nr. 12, FWS/OBS-82-26. 248 p.
- Brown R, Greene S. 1994. An evaluation of the Feather River Hatchery as mitigation for the State Water Project's Oroville Dam. In: Environmental enhancement of water projects. Denver (CO): USCID. p 111-23.
- Briggs JC. 1953. The behavior and reproduction of salmonid fishes in a small coastal stream. California Department of Fish and Game. Fish Bulletin 94. 62 p.
- Cramer SP. 1992. Contribution of Sacramento Basin hatcheries to ocean catch and river escapement of fall chinook salmon. Prepared for California Department of Water Resources by S.P. Cramer and Associates. 113 p + appendices.
- Dettman DH, Kelley DW. 1987. The roles of Feather and Nimbus salmon and steelhead hatcheries and natural reproduction in supporting fall-run chinook salmon populations in the Sacramento River Basin. Newcastle (CA): DW Kelley & Assoc.
- [DWR] California Department of Water Resources. 1982. Feather River spawning gravel baseline study. Sacramento (CA): California Department of Water Resources.
- Fry DH, Jr. 1961. King salmon spawning stocks of the California Central Valley, 1940-1959. *California Fish and Game* 47:55-71.
- Fukushima M, Quinn TJ, Smoker WW. 1998. Estimation of eggs lost from superimposed pink salmon (*Oncorhynchus gorbuscha*) redds. *Can J Fish Aquat Sci* 55:618-25.
- Healey MC. 1991. Life history of chinook salmon. In: Groot C, Margolis L, editors. Pacific salmon life histories. Vancouver, BC: University of British Columbia Press. p 311-94.

- Hedgecock D, Banks MA, Rashbrook VK, Dean CA, Blankenship SM. 2001. Applications of population genetics to conservation of chinook salmon diversity in the Central Valley. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids*. Volume 1. Sacramento (CA): California Department of Fish and Game.
- Leitritz E. 1970. A history of California's fish hatcheries, 1870-1960. California Department of Fish and Game. *Fish Bulletin* 150. 86 p.
- Milhous RT, Updike MA, Schneider DM. 1989. Physical habitat simulation system reference manual. Version II. Instream Flow Information Paper Nr. 26. US Fish Wild Serv Biol Rep 89(16):v.
- Morhardt JE, Hanson DF, Coulston PJ. 1984. Instream flow: increased accuracy using habitat mapping. *Proceedings of the International Conference on Hydropower, 1983. Environmental impacts*. Tennessee Valley Authority. p 1294-1304.
- Painter RE, Wixom LH, Taylor SN. 1977. An evaluation of fish populations and fisheries in the post-Oroville project Feather River. California Department of Fish and Game Anadromous Fisheries Branch. Prepared for the California Department of Water Resources. 56 p.
- Platts WS, Megahan WF, Minshall GW. 1983. Methods for evaluating stream, riparian and biotic conditions. Ogden (UT): US Forest Service. General Technical Report INT-138.
- Reiser DW, Wesche TA, Estes C. 1989. Status of instream flow legislation and practices in North America. *Fisheries* 14(2):22-9.
- Reynolds FL, Mills TJ, Benthin R, Low A. 1993. Restoring Central Valley streams: a plan for action. Sacramento (CA): California Department of Fish and Game. 151 p.
- Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. *Can J Fish Aquat Sc* 58(2):325-33.
- Stalnaker CB, Milhous RT. 1983. Responses to general questions compiled by the convensors of the Instream Flow Technology Section of the 1983 Hydropower Conference. Northwest Small Hydroelectric Association. November 29-December 1, 1983.
- Tappel PD, Bjornn TC. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. *N Am J Fish Manage* 3:123-35.
- Trihey EW, Wegner DL. 1981. Field data collection procedures for use with the Physical Habitat Simulation System of the Instream Flow Group [draft]. Fort Collins (CO): Cooperative Instream Flow Service Group, US Fish and Wildlife Service. January 1981. 151 p.

- Unwin MJ, Glova GJ. 1997. Changes in life history parameters in a naturally spawning population of chinook salmon (*Oncorhynchus tshawytscha*) associated with releases of hatchery-reared fish. *Can J Fish Aquat Sci* 54:1235–45.
- Vronskiy BB. 1972. Reproductive biology of the Kamchatka River chinook salmon (*Oncorhynchus tshawytscha* [Walbaum]). *J Ichthyol* 12:259–73.
- Williams JG. 1996. Lost in space: minimum confidence intervals for idealized PHAB-SIM studies. *Trans Am Fish Soc* 125:458–65.
- Wolman MG. 1954. A method of sampling coarse river-bed material. *Trans Am Geophys Uni* 35(6).
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: *Sierra Nevada Ecosystem Project: final report to Congress, volume III, assessments, commissioned reports, and background information*. Davis (CA): University of California, Centers for Water and Wildland Resources.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 2001. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids*. Volume 1. Sacramento (CA): California Department of Fish and Game.

Notes

- Kev Bovee (US Geological Survey, Midcontinental Ecological Science Center, Colorado). In person communication during a class held in 1995.

State of California
The Resources Agency
Department of Fish and Game

FISH BULLETIN 179

CONTRIBUTIONS TO THE BIOLOGY OF CENTRAL VALLEY SALMONIDS

VOLUME 2

Edited by

Randall L. Brown
Department of Water Resources
Sacramento, California



2001

This bulletin is not copyrighted. If reproduced elsewhere, such as by photocopying, the authors, editor, and the DFG would appreciate receiving an appropriate acknowledgment.

The free mailing list is on an exchange basis and is limited by budgetary considerations to libraries, scientific institutions, and conservation agencies. Individuals may obtain copies of this bulletin by submitting a check or money order in the amount of \$25 per copy (includes sales tax and shipping cost) made out to the California Department of Fish and Game and mailing it to:

Department of Fish and Game
Fiscal and Administrative Services
1416 Ninth Street, 12th Floor
Sacramento, California 95814
Telephone: (916) 653-6281
Fax: (916) 653-4645

State of California
The Resources Agency
Department of Fish and Game

FISH BULLETIN 179

CONTRIBUTIONS TO THE BIOLOGY OF CENTRAL VALLEY SALMONIDS

VOLUME 2

Edited by

Randall L. Brown
Department of Water Resources
Sacramento, California



2001

Contents

| | |
|--|-------------|
| Preface | v |
| Dedication | vii |
| In Appreciation | xi |
| Acknowledgements | xiii |
| Foreword | xv |
| Contributing Authors | xvii |
| | |
| Chinook Salmon in the Lower American River, California's Largest Urban Stream | 1 |
| <i>John G. Williams</i> | |
| | |
| Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary | 39 |
| <i>Patricia L. Brandes and Jeffrey S. McLain</i> | |
| | |
| The Effects of San Joaquin River Flows and Delta Export Rates During October on the Number of Adult San Joaquin Chinook Salmon that Stray | 139 |
| <i>Carl Mesick</i> | |
| | |
| Survival of Chinook Salmon Smolts in the Sacramento-San Joaquin Delta and Pacific Ocean | 163 |
| <i>Peter F. Baker and J. Emil Morhardt</i> | |
| | |
| Ocean Salmon Fishery Management | 183 |
| <i>L.B. Boydstun</i> | |

| | |
|--|------------|
| Population Trends and Escapement Estimation of Mokelumne River Fall-run Chinook Salmon (<i>Oncorhynchus tshawytscha</i>) | 197 |
| <i>Joseph J. Miyamoto and Roger D. Hartwell</i> | |
| Studies of Spawning Habitat for Fall-Run Chinook Salmon in the Stanislaus River Between Goodwin Dam and Riverbank from 1994 to 1997 | 217 |
| <i>Carl Mesick</i> | |
| Distribution and Abundance of Chinook Salmon and Resident Fishes of the Lower Tuolumne River, California | 253 |
| <i>Tim Ford and Larry R. Brown</i> | |
| Building Models and Gathering Data: Can We Do This Better? | 305 |
| <i>Wim Kimmerer, Bill Mitchell, and Andy Hamilton</i> | |
| Exploring the Role of Captive Broodstock Programs in Salmon Restoration | 319 |
| <i>Kristen D. Arkush and Paul A. Siri</i> | |
| Are Juvenile Chinook Salmon Entrained at Unscreened Diversions in Direct Proportion to the Volume of Water Diverted? | 331 |
| <i>Charles H. Hanson</i> | |
| Inventory of Water Diversions in Four Geographic Areas in California's Central Valley | 343 |
| <i>Janna R. Herren and Spencer S. Kawasaki</i> | |

Preface

The Salmonid Symposium was organized by an ad hoc committee of state and federal fishery biologists concerned with the management of Central Valley (CV) salmon and steelhead trout (*Oncorhynchus* spp.) populations and their habitats. It was held at Bodega Bay, California on October 22–24, 1997. Topics covered included research on various CV salmon and steelhead populations, ocean fishery management, history of upper Sacramento River hatchery operations, and steelhead management policy.

Any statements or views expressed in these materials are those of the authors and do not necessarily represent those of the California Department of Fish and Game (DFG), which takes no responsibility for any statements or views made herein. No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by the DFG. The materials are for general information only and do not represent a standard of the DFG, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. The DFG makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

Dedication

Fish Bulletin 179 is dedicated to the memory of Nat Bingham. Zeke Grader penned the text, but the feelings and inspiration come from the California community of fishermen, salmon biologists and managers.

It was about 10 years ago, the news had just come out that only 191 winter-run chinook had returned to the Sacramento River that year, when, in a call, Nat said something to the effect: “We’ve got to do something. This run will not go extinct on our watch.” With that pronouncement, he set in motion a whirlwind of activity that, although we weren’t certain in what direction, determined this magnificent run of salmon, spawning in the tributaries of the Upper Sacramento in the heat of the summer, those fish Livingston Stone chronicled more than a century before, would not be lost.

The campaign to save the winter-run began, and the eventual captive broodstock program and all of the products of that effort, was much like FDR’s approach to the depression. That is, try something, do something, but just don’t sit there. Nat Bingham, an ardent student of history may well have thought of that. Nat was going to do something. Initially, he considered a pen-rearing program at the National Marine Fisheries Service’s Tiburon Laboratory, but after gathering the agencies and scientists together an alternate plan began to evolve. The fact that his original concept was rejected didn’t bother him. He cared more that an action plan to save the run was now in motion.

Nat also knew that to save fish—again, as a student of history—the battle had to be engaged on many fronts. A captive broodstock program might prevent extinction of the winter-run, but action had to be taken to correct the problems that had led to the drastic decline of these fish. In a score of years the number of spawners had plummeted from almost 120,000 to less than 200. Litigation, lobbying Congress, cajoling farmers and water districts became Nat’s almost daily activity until he died.

Nat had come from a famous old Connecticut family and started commercial fishing in the Bahamas as a teenager. He arrived in Berkeley in the sixties and shortly after that began commercial fishing salmon and albacore out of the East Bay. A few years later he ended up on California’s north coast where, as a salmon troller, he began to take an interest in the factors affecting salmon productivity. He familiarized himself with the watersheds and the streams and was soon working with groups such as the Salmon Unlimited and the Salmon Trollers Marketing Association. He helped install and operate hatch box programs aimed at jump-starting runs that had nearly been extirpated from damage to the watershed. He saw first hand that logging, road building and a host

of other land use activities were decimating the runs. Unlike most of his contemporaries, he would speak out. And, he railed against what he described as the “code of silence” among those in fisheries who would not actively defend the fish. “No more silence” was his mantra.

Outspoken yes, but Nat was also a gentle person who did not see those across the table as enemies but merely people who needed to be educated about the fish, who needed to understand what the fish needed. He never personalized a fight. He was never anti-logging, anti-grazing, anti-farming, or anti-urban water usage, he was just pro-fish. He never saw winning for the fish as defeating someone else. He was the practitioner of what many now call “win-win.”

He was also tireless. In the early 1980s, at the height of an El Nino, he took over as president of a beleaguered Pacific Coast Federation of Fishermen’s Associations (PCFFA), a more or less coastwide umbrella group of family-based fishing organizations. Ocean conditions associated with El Nino had devastated salmon production and left the group’s coffers nearly empty. Over the next decade he found himself fishing less and spending more time helping with the organization and working on battles to save salmon from the Central Valley to the Columbia. He worked with tribes and ranchers in the Klamath Basin and with the timber industry in coastal watersheds—always trying to save, to rebuild salmon runs. He built alliances with conservation organizations and he looked for opportunities to work with those generally considered his adversaries—from timber industry executives, to power companies, to heads of agricultural and urban water districts. There were few meetings on salmon where Nat was not present.

In the early 1990s seeing no end to the fight for salmon survival, Nat decided to step down as President of PCFFA, a job he could very well have held for life, to sell his boat and dedicate himself exclusively to efforts to restore salmon habitat and rebuild the runs. PCFFA was able to cobble some monies together from government and private foundation contracts and grants and put Nat on the road. For the next seven years his beat-up Toyota pickup, held together it seems by bumper stickers, could be seen up and down the Central Valley, in the Sierra or the Trinity or in some coastal watershed. Nat the salmon disciple, the crusader would be working patiently and in his quiet way to convince people to do things differently so salmon could not only survive, but thrive.

In the spring of 1998, things were looking up for Nat. Quietly working behind the scenes he was able in six-month’s time to help establish a winter chinook conservation hatchery on the mainstem of the Sacramento, just below Shasta Dam. Nat called it the Livingston Stone Hatchery, a name that has stuck. Moreover, negotiations with Pacific Gas & Electric were progressing for the removal of dams on Battle Creek to establish an additional “homestream” for

the winter run. But it was also a tiring period, the Pacific Fishery Management Council meetings (to which Nat was appointed to a few years before) were particularly arduous. At the end of the April Council meeting Nat's wife Kathy was diagnosed with terminal cancer and by the end of the month she was gone. Nat kept his spirits up, but he was exhausted physically and mentally and within a week of Kathy's death, he was gone too.

Nat's life is the stuff of a great book. The important thing, however, for those of us left working for the survival of the salmon to remember what he did and how he did it—and, how he lived his life. With Nat's life as our inspiration, we will win.

Zeke Grader

In Appreciation

With the release of this Fish Bulletin, we extend our appreciation and those of our fellow biologists to its editor, Dr. Randall L. Brown. As local readers are aware, Randy retired last year from State service where he was employed for over 34 years by the California Department of Water Resources.

He will be forever remembered for his great devotion to improving our understanding of salmon biology in the Central Valley and San Francisco Bay-Delta Estuary of California. Randy's professionalism, support, encouragement and friendship to all of us in the salmon community is greatly respected and appreciated. His tireless efforts to enhance salmon monitoring and research as a coordinator in the Interagency Ecological Program, Chief Biologist for the Department, member of numerous committees related to salmon and their management, and as a leader in conducting multiple workshops, meetings, conferences, and symposiums on salmon has greatly improved our knowledge of salmon. Our progress in the area of salmon population genetics, salmon-hydrodynamics interactions, monitoring and evaluation techniques, population dynamics, data management and other fields are directly related to his personal efforts and accomplishments.

We join together to thank Randy as a friend and colleague for his excellent work and wish him the best in his retirement and all future endeavors.

Marty Kjelson
Terry J. Mills

Acknowledgements

Pulling this volume together would not have been possible without the support of Marty Kjelson and Terry Mills. We first discussed the concept over Chinese food a year or so before the Bodega meeting. Periodic meetings before and after Bodega kept me on track – to the extent that is possible.

Special thanks to the symposium presenters for converting their talks to papers. Joe Miyamoto of the East Bay Municipal Utility District receives the award for being, by far, the first to submit a manuscript.

I would also like to acknowledge several authors who did not present papers at Bodega but who were willing to contribute material to help make this a more balanced compendium.

Several anonymous peer reviewers took their valuable time to review the articles and their comments made for a better product.

L.B. Boydstun, of the California Department of Fish and Game, deserves recognition for allowing us to use the Department's Fish Bulletin series and to serve as the DFG sponsor. This is in keeping with L.B.'s long history of working with his agency, NMFS and the commercial and recreational fishing industry to scientifically manage a resource of special significance to California.

Finally, we should all thank Lauren Buffaloe (DWR) for a tremendous job of editing and formatting the articles and to Barbara McDonnell (DWR) and Sam Luoma (CALFED) for funding publication of the Fish Bulletin.

Randall L. Brown

Foreword

The impetus for publication of this Fish Bulletin came from conversations among several biologists working on salmonid issues in the Central Valley and the Sacramento-San Joaquin Estuary. These discussions centered on the idea that more information being developed about these economically, environmentally, and aesthetically important species needed to be available in the open literature. Marty Kjelson, Terry Mills and I developed the concept of a symposium followed by published proceedings. The Interagency Ecological Program's Central Valley Salmonid Team endorsed the concept and a successful symposium was held at the Bodega Marine Laboratory in October 1997.

Originally Marty and Terry agreed to co-edit the proceedings. Due to the press of other work, they were unable to take on much of the day-to-day work on the volume but did provide guidance and suggestions for ways to move the publication from concept to reality. I take responsibility for the final selection of papers and the final technical editing of the papers.

As you will find, I selected papers with varied writing styles. Some papers, such as the ones by Yoshiyama and others and by Black, are longer than would be typically found in journals. I believe they make a significant contribution to our understanding and decided to publish them without major revision. Others are more succinct and could be published in the open literature.

Those readers that attended the Bodega symposium will find that not all the papers presented have been included in this volume and that papers not presented are included. Several of the presenters were unable to find the time to prepare a manuscript. On the other hand, other authors had information of interest. The blend seemed to make the best sense in view of the objective of making a wide variety of information available to salmonid biologists and managers.

This volume also includes some material that could be considered duplicative in that two different papers may discuss the same question—for example, through-Delta survival of juvenile salmonids. I included these papers to provide different perspectives on important questions. I ask the reader to consider the papers, and the data, and reach his or her conclusions as to the interpretations. As with most difficult environmental issues, one must carefully consider all the available data before deciding to accept or reject a hypothesis.

I do recommend that you consider recommendations, made specifically by L.B. Boydstun, Peter Baker, Emil Morhardt, Wim Kimmerer and others, and John Williams about the need to (1) better coordinate salmonid related work in the Valley, the estuary and the ocean; (2) focus more on collecting and analyzing data that can be used to validate conceptual and mechanistic models; and (3) make the information more readily available in the open literature. Along those lines I suggest that symposium such as this be held every two to three years, including publication of the proceedings. Authors should not stop with publication in proceedings but should also publish in appropriate journals. Hopefully the next symposium will have more than one paper dealing with steelhead.

Randall L. Brown
Fair Oaks, California
September 1, 2001

Contributing Authors

Kristen D. Arkush
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Peter F. Baker
Stillwater Ecosystem, Watershed and
Riverine Sciences
2532 Durant Avenue
Berkeley, CA 94577

Michael A. Banks
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Michael Black
756 20th Avenue
San Francisco, CA 94121

Scott M. Blankenship
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

L.B. Boydston
California Department of Fish and Game
1416 Ninth Street
Sacramento, CA 95814

Patricia L. Brandes
U.S. Fish and Wildlife Service
4001 N. Wilson Way
Stockton, CA 95205

Larry R. Brown
5083 Veranda Terrace
Davis, CA 95616

Randall L. Brown
4258 Brookhill Drive
Fair Oaks, CA 95628

Cheryl A. Dean
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Frank W. Fisher
California Dept. of Fish and Game, retired
Inland Fisheries Division
2440 N. Main Street
Red Bluff, CA 96080

Tim Ford
Turlock Irrigation District
P.O. Box 949
Turlock, CA 95380

Eric R. Gerstung
California Dept. of Fish and Game
Native Anadromous Fish and
Watershed Branch
1807 13th Street, Suite 104
Sacramento, CA 95814

Andy Hamilton
U.S. Fish and Wildlife Service
2800 Cottage Way, W-2605
Sacramento, CA 95825

Charles H. Hanson
Hanson Environmental, Inc.
132 Cottage Lane
Walnut Creek, CA 94595

Dennis Hedgecock
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Janna R. Herren
California Dept. of Fish and Game
Sacramento Valley Central Sierra Region,
Environmental Services
1701 Nimbus Road
Rancho Cordova, CA 95670-4599

Spencer S. Kawasaki
formerly with the California Dept. of
Fish and Game
Sacramento Valley Central Sierra Region
8169 Alpine Avenue, Suite B
Sacramento, CA 95826

Wim Kimmerer
Romberg Tiburon Center
San Francisco State University
P.O. Box 855, 3152 Paradise Drive
Tiburon, CA 94920

Dennis R. McEwan
California Department of Fish and Game
Native Anadromous Fish and
Watershed Branch
1807 13th Street, Suite 104
Sacramento, CA 95814

Debbie McEwan
California Dept. of Transportation
Environmental Program
1120 N Street, Room 4301, MS27
Sacramento, CA 95814

Jeffrey S. McLain
U.S. Fish and Wildlife Service
4001 N. Wilson Way
Stockton, CA 95205

Carl Mesick
Carl Mesick Consultants
7981 Crystal Boulevard
El Dorado, CA 95623

Bill Mitchell
Jones and Stokes Associates
2600 V Street, Suite 100
Sacramento, CA 95818-1914

Joseph J. Miyamoto
East Bay Municipal Utility District
500 San Pablo Dam Road
Orinda, CA 94563

J. Emil Morhardt
Claremont McKenna College
925 N. Mills Avenue
Claremont, CA 91711-5916

Peter B. Moyle
University of California, Davis
One Shields Avenue
Davis, CA 95616-8751

Vanessa K. Rashbrook
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Paul A. Siri
Bodega Bay Marine Laboratory
University of California, Davis
P.O. Box 247
Bodega Bay, CA 94923-0247

Ted Sommer
California Dept. of Water Resources
Environmental Services Office
3251 S Street
Sacramento, CA 95816-7017

John G. Williams
Environmental Hydrology, Inc.
875 Linden Lane
Davis, CA 95616

Ronald M. Yoshiyama
University of California, Davis
One Shields Avenue
Davis, CA 95616-8751

Chinook Salmon in the Lower American River, California's Largest Urban Stream

John G. Williams

Abstract

The American River now supports a mixed run of hatchery and naturally-produced fall-run chinook averaging about 30,000 spawners; the spring-run was lost to dams. Salmon in the river have been much studied over the last 20 years, largely because of litigation over proposed diversions, but much uncertainty remains about various aspects of their biology and about the environmental conditions needed to support them. This paper briefly reviews what is known and not known about salmon in the American River and makes recommendations for future work.

Introduction

The American River is the second largest tributary of the Sacramento and supports a mixed run of hatchery and naturally produced fall-run chinook salmon. Salmon in the American River have been intensively studied, largely because of litigation challenging a proposed diversion of water, but much remains to be learned. Here I review what is known about chinook salmon in the American River and give suggestions for future work.

Folsom Dam, a Central Valley Project facility completed in 1955 about 30 miles upstream from the Sacramento River, creates a 975,000 acre-foot reservoir and regulates flows in the reach now accessible to salmon. Salmon migration is blocked at river mile 23 by Nimbus Dam, a regulating facility for Folsom hydropower operations that also diverts a small amount of water into the Folsom-South Canal. Below Nimbus Dam, the lower American River flows through a parkway, surrounded by urban development and is a major recreational area for the Sacramento region. The American River is designated as a recreational river in the state and federal wild and scenic river systems. On average, tens of thousands of hatchery or naturally produced chinook salmon return each year to spawn in California's largest urban stream.

In natural conditions the American River supported spring, fall, and perhaps late fall chinook. Historical data on the upstream extent of salmon migrations are summarized in Yoshiyama and others (Volume 1). Salmon runs were devastated by hydraulic gold mining, and in 1886 the California Fish Commission reported that:

The American River is a shallow, muddy stream and empties into the Sacramento River at Sacramento City. But few fish are found in the lower parts of the stream. Trout are found in some of its branches above the mining districts – notably Silver River and the Rubicon. This river, prior to placer mining, was one of the best salmon streams in the state. Of late years no salmon have ascended it.

Salmon can be resilient, however; 44 years later, G. H. Clark (1929) wrote that although the old Folsom Dam blocked passage for salmon the area downstream supported a large run.

The run of salmon into the American River has always been a late fall migration¹ and like the other rivers has known great runs. In 1927–1928 there was a very good run in the river, which has shown the inhabitants no noticeable decrease in the last twenty years. It was reported that the run of salmon in this river had been destroyed by the early mining operations. Such may have been the case, but since then the run has returned and has remained fairly constant, according to the observations of local residents.

Clark reported that the old Folsom Dam, constructed in the late 1890s, effectively blocked salmon passage although it had a ladder that passed steelhead. Subsequent ladder counts showed a few spring-run chinook, but any prospect for restoring that run were dimmed considerably by construction of Folsom and Nimbus dams.

Physical Setting

The American River drains a roughly triangular watershed of about 1,900 square miles that is widest at the crest of the Sierra and narrows almost to the width of the river at its confluence with the Sacramento River at Sacramento. As described in USACE (1991):

The American River drainage basin above Folsom Dam is very rugged, with rocky slopes, V-shaped canyons, and little flat valley or plateau area. Elevations range from 10,400 feet at the headwaters to about 200 ft at Folsom Dam, with an average basin slope of 80 feet per mile. The upper third of the basin has been intensely glaciated and is alpine in character, with bare peaks and ridges, considerable areas of granite pavement, and only scattered areas of timber. The middle third is dissected by profound canyons, which have reduced the inter-stream areas to narrow ribbons of relatively flat land. The lower third consists of low rolling mountains and foothills.

Below Folsom, the watershed flattens into the Central Valley, but the river remains confined or semi-confined by resistant Pleistocene fan deposits or by

1. Presumably these were fall-run chinook that spawned later than runs in some other rivers, like the current run, rather than late fall-run fish.

levees and has only a narrow flood plain that has been aggraded by debris from hydraulic mining. The channel of the lower American River is described in Snider and others (1992), and Beak Consultants and others (1992). Generally, the gradient of the river decreases over the 23 miles between Nimbus Dam and the Sacramento River, and the size of the particles making up the bed decreases from cobble and gravel to sand. This transition is not smooth, however, and there are large pools separated by steeper reaches along much of the lower river.

Snider and others (1992) divided the lower American River into three reaches (Figure 1). Reach 1, the 4.9 miles from the Sacramento confluence to Paradise Beach, has a very low gradient and sand bed. Depth is normally controlled by the stage in the Sacramento River, rather than discharge, and varies with the tide. Reach 2 includes the 6.7 miles of channel from Paradise Beach to Gristmill, with some slope (average gradient about 0.0005). The bed is mainly sand, but includes some gravel riffles. Reach 3 covers 11.1 miles from Gristmill to the weir at Nimbus Hatchery with more slope (average gradient about 0.001). The bed is mainly gravel, but the river is still characterized by long pools separated by riffles. The average width of the river at a flow of 1,000 cfs in the three reaches is 350, 375, and 275 feet.

The annual discharge in the river averages about 3,750 cfs, or about 2,710,000 acre-feet per year, but has varied from 730 to 7,900 cfs. Runoff comes from winter rains at lower elevations and from spring snowmelt at higher elevations, but very high flows all result from winter storms. Discharge is regulated by various dams, of which Folsom is the largest, with past and present direct diversions being relatively minor. The main hydrological effect of the dams has been to dampen variance in winter runoff and to store snowmelt for release in the spring to meet irrigation demand, mainly in the San Joaquin Valley, with the variance and timing of runoff being changed more than the total amount.

“Natural” mean monthly flows have been estimated by the Bureau of Reclamation (Figure 2A), and on average rise to a peak in May and drop to low levels in August through October. Flows reflecting diversions, regulations, and operating practices in effect in 1993 have been estimated by the Sacramento Area Flood Control Agency (Figure 2B) and show less variation over the year and within winter and spring months, but more variation within summer and early fall months. Comparison of daily flows from the moderately dry years 1908 and 1992 shows these effects in more detail (Figure 3). Because Folsom Reservoir is relatively small compared to the mean annual flow in the river; however, reductions in peak flows in wet years have been moderate (Figure 4), and geomorphically effective flows still occur with some frequency.

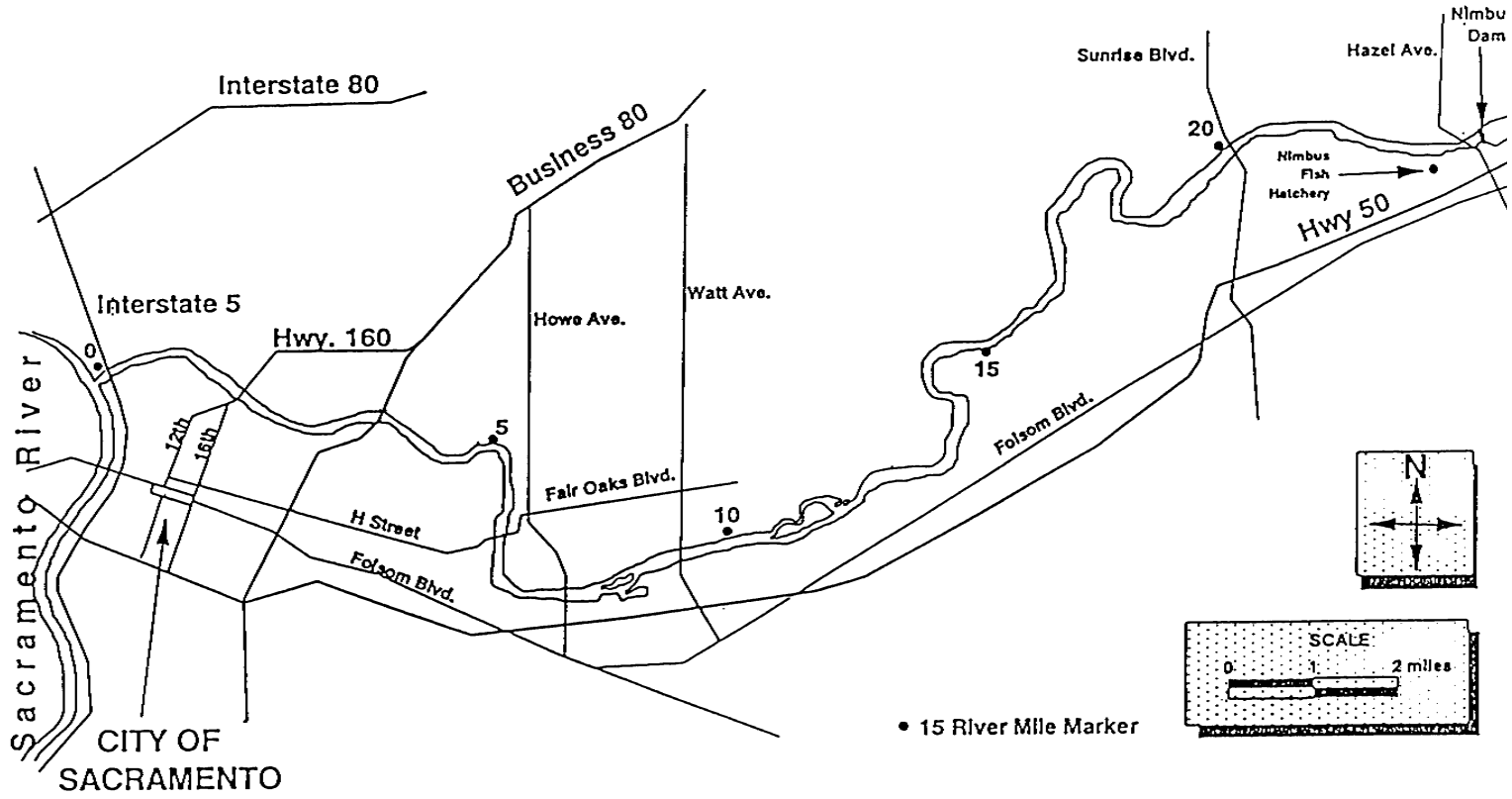


Figure 1 Map of the lower American River taken from Snider and others (1992)

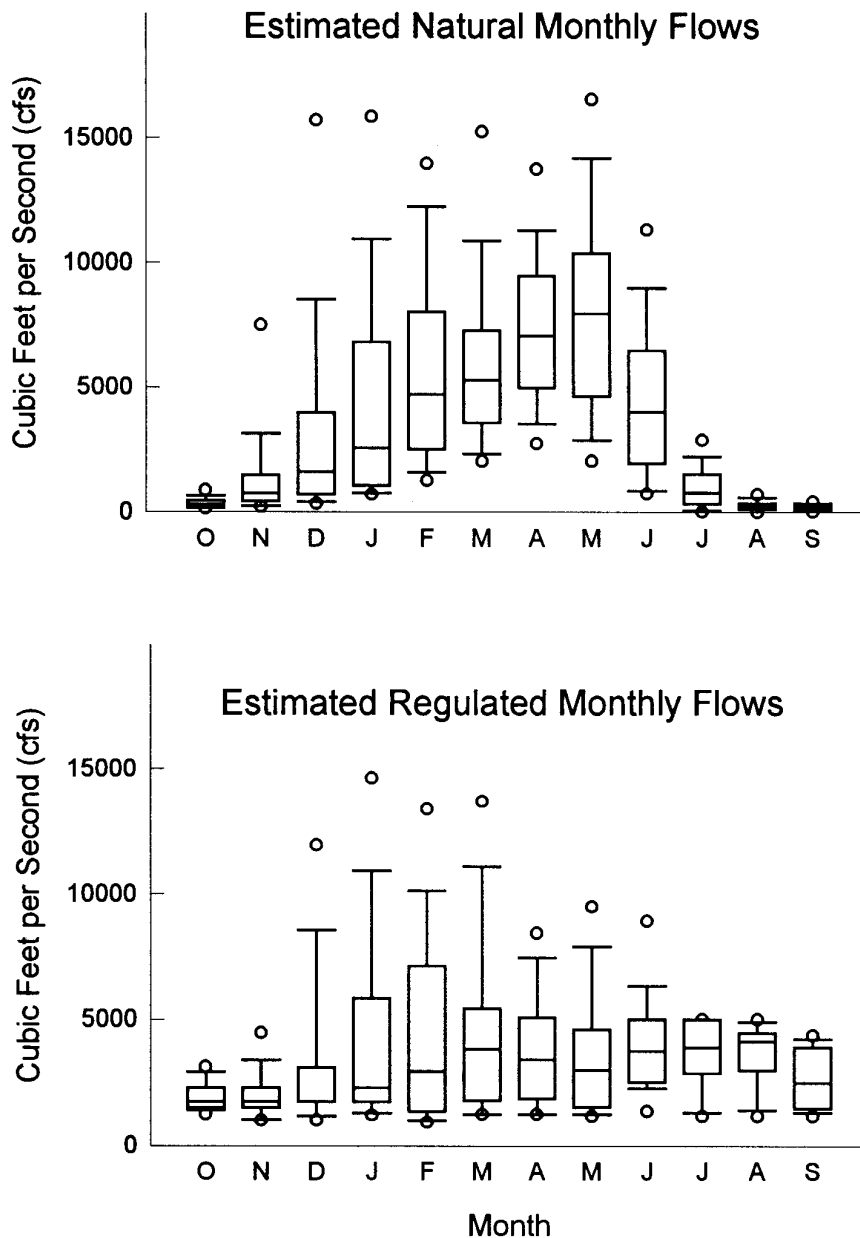


Figure 2 Comparison of the distributions of mean monthly flows in the lower American River for natural conditions (upper panel) and simulated 1993 conditions, assuming the same climatic conditions (lower panel). In the box plots for each month, the “box” covers the central 50% of the data, from the 25th to the 75th percentiles, the solid line across the box shows the median, and the dashed line shows the mean. The “whiskers” extend to the 10th and 90th percentiles, and the circles show the 5th and 95th percentiles. Note that the 1993 simulated flows do not reflect recent corrections to PROSIM, the operations model used for the simulations, or recent changes in CVP operations.

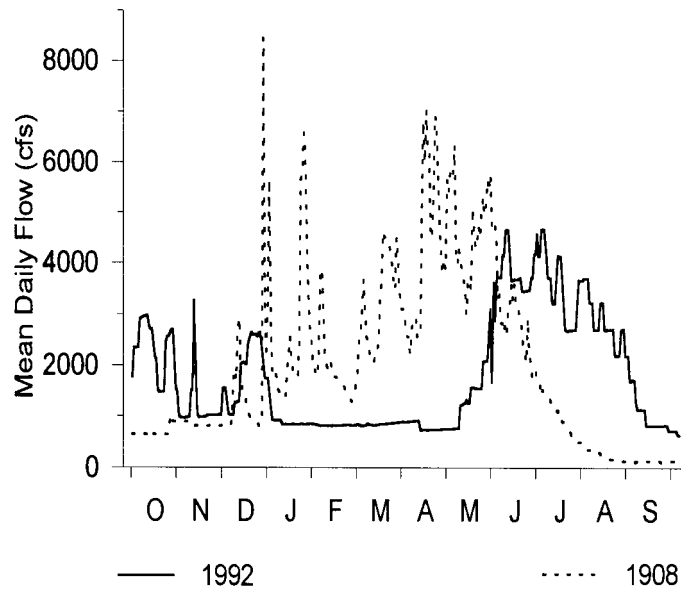


Figure 3 Comparison of flow in the American River in two dry years with approximately equal total discharge, illustrating the effects of regulation on the seasonality and variability of flow

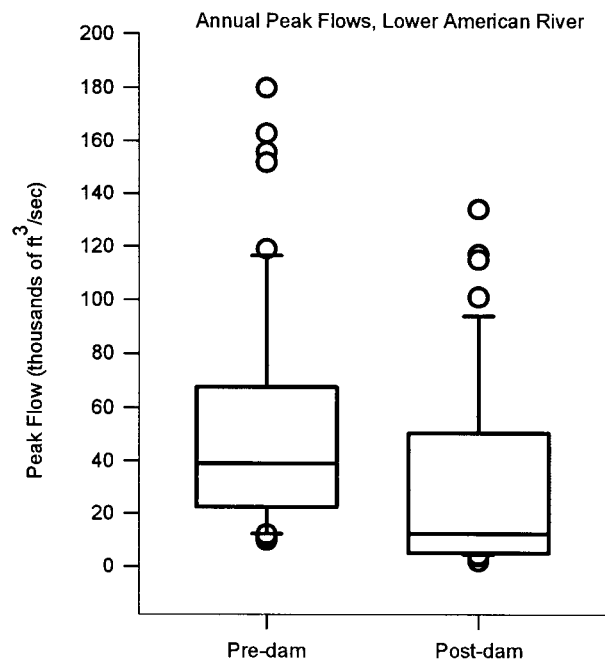


Figure 4 Comparison of the pre- and post-Folsom distributions of peak flows in the lower American River. Box plot conventions are as in Figure 2, except that circles show all values beyond the 5th and 95th percentiles. Data from USGS Fair Oaks gage.

The Hodge Decision

In 1970, the East Bay Municipal Utility District (EBMUD) negotiated a contract with the Bureau of Reclamation to take up to 150,000 acre-feet of water annually from the American River, through the Folsom-South Canal. The Environmental Defense Fund (EDF), Save the American River Association (SARA), and Sacramento County sued to block the contracts in 1972. Over the next 17 years, the California Department of Fish and Game (DFG) and the State Lands Commission (SLC) joined the litigation, the case went to the California Supreme Court twice, to the United States Supreme Court once, and to the State Water Resources Control Board (SWRCB) for a report of referee, before coming to trial in the Alameda County Superior Court of Judge Richard Hodge in 1989.

Simply put, the question was whether EBMUD could divert water through the Folsom-South Canal, or whether it must divert the water at some point farther downstream, so that the water could also serve instream uses. EBMUD wanted to divert through the canal because water quality decreases downstream. In its Report of Referee, the SWRCB recommended that EBMUD could divert through the canal, provided that certain instream flow standards were met. These standards were acceptable to EBMUD, but not to the plaintiffs. When the case went back to the Alameda County Superior Court, the substantive issues concerned the relation between water quality and public health on one hand and instream flow needs on the other.

Judge Hodge ruled that EBMUD could take water through the Folsom-South Canal, provided that enough water remained in the river to protect public trust resources. Based on the evidence in the record, Judge Hodge determined that “enough” meant: October 16 through February, 2,000 cfs; March through June, 3,000 cfs; July through October 15, 1,750 cfs. These flow standards, which apply to the whole 23-mile reach from Nimbus Dam to the Sacramento River confluence, are to remain in effect unless evidence is developed that justifies changes. The conditions apply only to diversions by EBMUD or by other parties to the litigation. Because the Bureau of Reclamation was not a party, the standards do not control the Bureau’s operation of Folsom.

Judge Hodge emphasized that the evidence presented was inadequate to support a final determination of the flows necessary to protect public trust resources, however, so he retained jurisdiction, ordered the parties to cooperate in scientific studies to reduce the uncertainty regarding the necessary flows, and appointed the author as special master to supervise the continuing jurisdiction (Hodge 1990):

Perhaps the most salient aspect of the fishery/hydrology testimony consists of its large area or remaining uncertainty. ...The task for this court is to recognize the fundamental inadequacy of existing studies as they relate to the American River, to extract from the 'consensus' and from the testimony those factors which can provide a guide for protecting fishery values, and significantly, to retain jurisdiction until the scientific community can provide definitive answers. (p 88, 95).

By emphasizing scientific uncertainty and framing a course of action that protects public trust resources while taking uncertainty into account, the Hodge Decision provides a good example of adaptive management (Castleberry and others 1996; Williams 1998).

Instream Flow Standards

In 1958, the SWRCB issued Decision 893, which granted the Bureau of Reclamation a permit for Folsom Dam, and set very low instream standards for the lower American River: 500 cfs from mid-September through October and 250 cfs otherwise. These remain the nominal state standards. The SWRCB set higher standards in Decision 1400, regarding Auburn Dam (for fish, 1,250 cfs from mid-September through June, 800 cfs otherwise), but since Auburn has not been constructed, these have not been binding. Nevertheless, the Bureau typically managed the lower American River to meet an approximation of the D-1400 standards called the "modified" D-1400 standards. [Why the SWRCB has never made the D-1400 standard applicable to Folsom is a fair question, but it has not. And as noted above, the Hodge standards only apply to diversions by the parties.] Since late 1997 the Bureau has operated Folsom with flow objectives set by the Anadromous Fish Restoration Plan (AFRP) (Table 1), developed under the Central Valley Project Improvement Act (CVPIA) which became law in 1992. Besides operating Folsom to meet the AFRP flows, the Bureau now meets regularly with the resource agencies and other interested parties to review details of dam operations.

Table 1 AFRP flow objectives for the lower American River

| <i>Month</i> | <i>Wet</i> | <i>Above and below normal</i> | <i>Dry and critically dry</i> | <i>Critical relaxation</i> |
|----------------------|------------|-------------------------------|-------------------------------|----------------------------|
| October | 2,500 | 2,000 | 1,750 | 800 |
| November to February | 2,500 | 2,000 | 1,750 | 1,200 |
| March to May | 4,500 | 3,000 | 2,000 | 1,500 |
| June | 4,500 | 3,000 | 2,000 | 500 |
| July | 2,500 | 2,000 | 1,500 | 500 |
| August | 2,500 | 2,000 | 1,000 | 500 |
| September | 2,500 | 1,500 | 500 | 500 |

As the AFRP flow objectives suggest, the amount of water available in the American River is limited in many years, and allocation of water to instream flows involves trade-offs among seasons, life-stages, and species, especially chinook and steelhead. Hence there is a need to understand the expected benefits of different seasonal flow regimes, typically in the face of uncertainty about future inflows to Folsom Reservoir and so about the amount of water that will be available to allocate in subsequent seasons. For example, a decision about how much water to allocate for spawning flows requires more than an understanding of the relation between flow and spawning habitat; it also requires an understanding of the importance of flows for juveniles and of the probability that water will be available for rearing flows, which will depend on post-spawning weather. One recent attempt to address this problem depended on the subjective assessment of biologists and did not spell out the rationale for the recommended allocation rules (Bratovich and others 1995), making it impossible to test the assumptions underlying the rules and to revise them in light of new information. A more transparent framework based on explicit assumptions and hypotheses is needed for guiding allocation decisions. Decision analysis (Peterman and Anderson 1999) seems well suited for this purpose.

Salmon in the American River

The EDF vs. EBMUD "Consensus"

With the agreement of the parties, Judge Hodge had the fish experts for both sides in the trial meet in closed session, without attorneys, to see how much agreement they could reach among themselves. The result was a "Report on Agreements and Recommendations," referred to elsewhere in the decision as the "consensus," that provides a useful summary of the understanding of chinook salmon at the time.

Life History Periodicities

1. Adult fall run chinook salmon are known to enter the lower American River from approximately mid-September through January. There is a high year-to-year variability; however, the bulk of the migration occurs from approximately mid-October through December.
2. Adult chinook salmon are known to spawn in the lower American River from approximately mid-October through early February. There is high variability from year to year; however, the bulk of the spawning occurs from approximately mid-October through December.

3. Chinook salmon egg and alevin incubation is known to occur in the lower American River from approximately mid-October through April. There is high variability from year to year; however, most incubation occurs from approximately mid-October through February.
4. Chinook salmon fry emergence is known to occur in the lower American River from January through mid-April.
5. Chinook salmon young-of-the-year juvenile rearing is known to occur in the lower American River from January to approximately mid-July. There is high year-to-year variability; however, the bulk of the rearing occurs from February through May. During March 1989, a few yearling chinook salmon were collected in the lower American River, suggesting that some fish may rear year round.

Water Temperature

1. Based on the scientific literature, the range of water temperatures for highest survival of incubating chinook salmon eggs appears to be between 43 °F to 58 °F. Prolonged (that is, more than a few days) exposure of eggs to temperatures in excess of 58 °F results in high egg mortality. 62 °F should be avoided.
2. Any definition of an “optimum” water temperature or temperature range for juvenile chinook salmon should include a synthesis of information on the effects of temperature on (a) growth rates; (b) effects on and availability of food supply ration; (c) predation; (d) disease; (e) stimulation of emigration; (f) physiological transformation to endure seawater; and (g) acclimation to the waters of the Lower Sacramento River and Delta when warmer than the American River.

Consensus on the optimum temperature range could not be reached.

Flow Needs

1. SWRCB Decisions 893 and 1400 are inadequate to meet the chinook salmon spawning habitat management objective for the lower American River.
2. The group could not reach consensus on the optimum spawning flow (or range of flows) needed to meet the fishery habitat management objective for chinook salmon in the lower American River.

3. Consensus could not be reached on the levels of flow required to provide optimum rearing habitat needed for juvenile chinook salmon in the lower American River.
4. SWRCB Decision 893 does not provide adequate rearing flows to meet the fish habitat management objective of maximizing the in-river production of juvenile chinook in the lower American River.

Recent Escapement Data

Both naturally and hatchery produced chinook salmon now spawn in the lower American River. Escapement has been estimated for several decades (Figure 5) and is highly variable but averages around 30,000. The data need to be regarded with considerable caution (Williams 1995). Returns to the hatchery are counts, but escapement to the river is estimated from mark-recapture methods applied to carcasses. Rich (1985) detailed problems with early estimates, and even recent estimates based on intensive carcass surveys involve great uncertainty, arising both from sampling errors and from the methods used to make estimates from the observations. Since 1976, DFG has used a modification of the Schaefer method, a multi-sample version of the Peterson method, but recently has reported estimates based on the Jolly-Seber method (e.g., Snider and Reavis 1996). For 1995, for example, the Schaefer estimate of escapement to the river was 70,096, while the Jolly-Seber estimate was 42,973, or 61% of the Schaefer estimate. The methods have been evaluated on Bogus Creek, a small tributary of the Klamath River for which weir counts are also available (Sykes and Botsford 1986; Boydston 1994; Law 1994), but conditions are less favorable for mark-recapture studies on larger rivers where a smaller percentage of marked fish are recaptured (Boydston 1994). Mark-recapture methods are also used to estimate escapement on other large rivers in the Central Valley and an evaluation by a competent statistician of their use on such rivers is sorely needed, as is a method for developing confidence intervals for the estimates.

The percentage of hatchery-produced fish among spawners in the American River is unknown, but presumably is large. Dettman and Kelley (1986) tried to evaluate this percentage; but as demonstrated by Hankin (1988) their calculations used so many approximate numbers and assumptions that it is hard to assign meaning to their results. Cramer (1992) applied a more sophisticated approach to the same question but the basic problem arises from the nature of the available data rather than the particular approach taken, so his estimates are also highly uncertain. For example, the results would depend on whether one used Schaefer or Jolly-Seber estimates of escapement. Cramer (1992, p 99) acknowledges this uncertainty:

Escapement Estimates for the American River

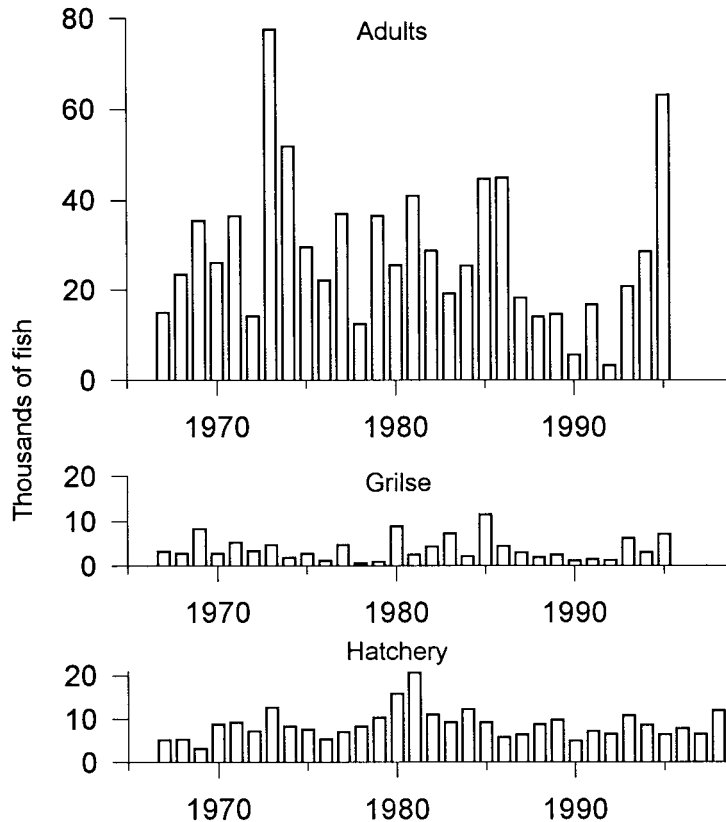


Figure 5 Escapement estimates for the lower American River from carcass surveys for “adults” and grilse, and counts at Nimbus Hatchery. Note that criteria for distinguishing grilse are not consistent and are of uncertain biological meaning (Williams 1995, p 100).

I conclude from these comparisons that Dettman and Kelley’s predications of the escapement of hatchery fish are too high. However, evidence cited in this chapter also indicates escapement of hatchery fish predicted by run reconstruction may be too low. Clearly, hatchery and natural contributions cannot be estimated with confidence until a well designed marking program of hatchery fish and wild fish, extended to all release types, is initiated and systematic sampling is begun for all major spawning areas and river fisheries.

It is remarkable that almost eight years after passage of the CVPIA, which calls for doubling the number of naturally produced anadromous fishes, the proportion of the salmon spawning in Central Valley rivers that are of hatchery origin remains unknown.

Hatchery Production

About half the chinook spawning habitat below Folsom was inundated by Nimbus Dam and Lake Natoma (USFWS and DFG 1953). Nimbus Hatchery was constructed to mitigate only for the spawning and rearing habitat inundated by Nimbus Dam and Lake Natoma, since passage of salmon was largely blocked by the Old Folsom Dam [loss of the opportunity to build a successful ladder over that dam apparently was not considered]. Nimbus now operates with a target of producing 4 million smolts for release in the estuary from May to July, for which it may collect up to 8 million eggs, distributed over the spawning season. The target size at release is 60 per pound (7.6 grams) or larger. Nimbus hatchery production of fingerlings for recent years is given in Table 2².

In the past, Nimbus Hatchery typically hatched more fry than it could rear, and over the period 1955–1967 released an average of almost 14 million fry annually. Emphasis then shifted toward producing larger juveniles, and average production of fry dropped to 3 million annually for 1968–1984 (Dettman and Kelley 1987). After 1990, fry were released into the Sacramento River at Garcia Bend so not to interfere with studies in the American River. But this too has recently ended; beginning with brood year 1998, DFG policy has been to rear to smolts all eggs hatched, and to limit egg take to meet smolt production goals (Bruce Barngrover, DFG, 1999, personal communication).

Table 2 Production of chinook salmon by Nimbus Hatchery ^a

| <i>Brood year</i> | <i>Fingerlings (≤ 7.6 grams, 90 mm)</i> | <i>Advanced fingerlings (> 7.6 grams)</i> |
|-------------------|---|--|
| 1985 | 5,241,020 | 3,139,240 |
| 1986 | 3,167,680 | 3,040,375 |
| 1987 | 1,257,770 | 4,278,750 |
| 1988 | --- | 3,210,570 |
| 1989 | 7,437,911 | 4,092,000 |
| 1990 | 6,069,505 | 1,244,800 |
| 1991 | 9,218,652 | 1,734,200 |
| 1992 | 7,930,390 | 1,988,700 |
| 1993 | 7,940,000 | 1,183,900 |
| 1994 | 8,103,143 | 1,378,100 |

^a Data from California Department of Fish and Game.

2. Data for earlier years are available in Dettman and Kelley (1986) or Cramer (1992), but are given in different size categories.

The biological consequences of hatchery production for chinook salmon in the American River are unclear, but merit more attention. (General concerns about the effects of hatchery production on salmon populations are reviewed in NRC [1996]; see also Hilborn [1999]). Recent studies in New Zealand have shown that hatchery fish can replace naturally produced chinook rather than supplement them (Unwin 1997), probably because of density-dependent mortality in early ocean life, and some biologists believe that the same is true here (Walters 1997; Hilborn 1999). Hatchery production can lead to changes in life history patterns (Unwin and Glova 1977). Unwin (1997) also found that the size-adjusted mortality rates of hatchery fish were much higher than naturally produced fish, even though many of the naturally produced fish were progeny of hatchery fish.

One possible consequence of hatchery production on American River chinook may be decreased fecundity (discussed in the following paragraphs). Another possible indication of detrimental biological effects of hatchery production involves the composition of otoliths. The calcium carbonate in salmonid otoliths normally occurs as aragonite, which is opaque, and all the juvenile salmon sampled from the American River by Castleberry and others (1991, 1993) had opaque otoliths. However, some transparent otoliths were noted in juveniles from Nimbus Hatchery during supplemental work on marking otoliths with oxytetracycline (D. Castleberry, USFWS, 1995, personal communication). In transparent otoliths, the calcium carbonate occurs as vaterite. Such otoliths have been observed in high frequencies in some hatcheries in British Columbia, and there is concern that vaterite otoliths reflect inbreeding. Additionally, in British Columbia some of vaterite otoliths are also misshapen, raising concerns about how well they function (Blair Hotlby, June 1992, personal communication).

Life History Patterns

Chinook salmon remaining in the American River are fall-run, ocean-type fish that migrate to the ocean within a few months of emerging. Fish of this life history pattern simply avoid the period when flows in Central Valley rivers are naturally low and warm. Although late summer flows in the lower American River are now much higher and somewhat cooler than in natural conditions (Williams 1995), conditions are still unsuitable for chinook rearing, and water temperature in the lower Sacramento River often becomes very warm for juvenile chinook in late May or early June. Juveniles that fail to emigrate before the Sacramento River gets too warm probably have little chance of survival.

Spawning

Adult salmon appear in the American River in July, but many local biologists and fishermen believe that these early arrivals are hatchery strays from the Feather River, where spawning begins earlier than in the American. Spawning in the American River begins in October or November, typically when the water cools to about 15.5 °C (60 °F), approximately the temperature at which egg survival is possible. Facilities for controlling the temperature of releases from Folsom Dam were improved in 1996, and salmon responded by starting to spawn about two weeks sooner than had been common in the past. In 1997 water remained above 15.5°C until mid-November, however, and spawning was similarly delayed (Kris Vyverberg, DFG, 1999, personal communication). This variation in timing supports the hypothesis that water temperature rather than some correlated variable such as day length mainly controls the initiation of spawning.

Chinook redds normally show up well in aerial photographs of the American River because the water is usually clear and undisturbed gravel has a darkening surface layer of algae. Aerial photographs have been taken at intervals throughout the spawning season since 1991, producing a good record of where and when salmon spawn, at least for the early part of the season (Figure 6). Later, the popular areas are dug up so thoroughly that it is no longer possible to see individual redds or estimate the numbers of spawning fish from the photographs (Snider and Vyverberg 1996). Nevertheless, the approach should allow development of an empirical relation between flow and spawning habitat. The aerial photography also shows that spawning sites are related to geomorphic features in the channel that promote subsurface flow, as reported for the Columbia River by Geist and Dauble (1998).

Snider and Vyverberg (1996) report data on redd size, which is substantially smaller when measured on the ground (average 62 ft²) than when measured from aerial photographs (average 196 ft²). They discuss possible reasons for the difference, but until the matter is further clarified estimates of superimposition based on aerial photography should be viewed with some caution. Nevertheless, superimposition data (Table 3) indicate that density-dependent mortality can occur during spawning, and tends to vary inversely with flow (Snider and Vyverberg 1996).

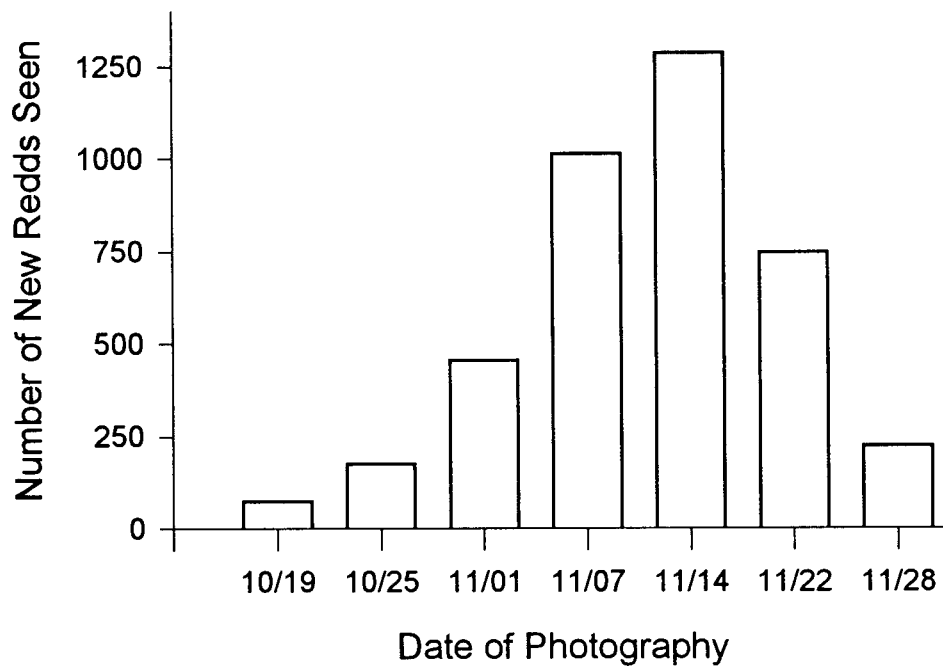
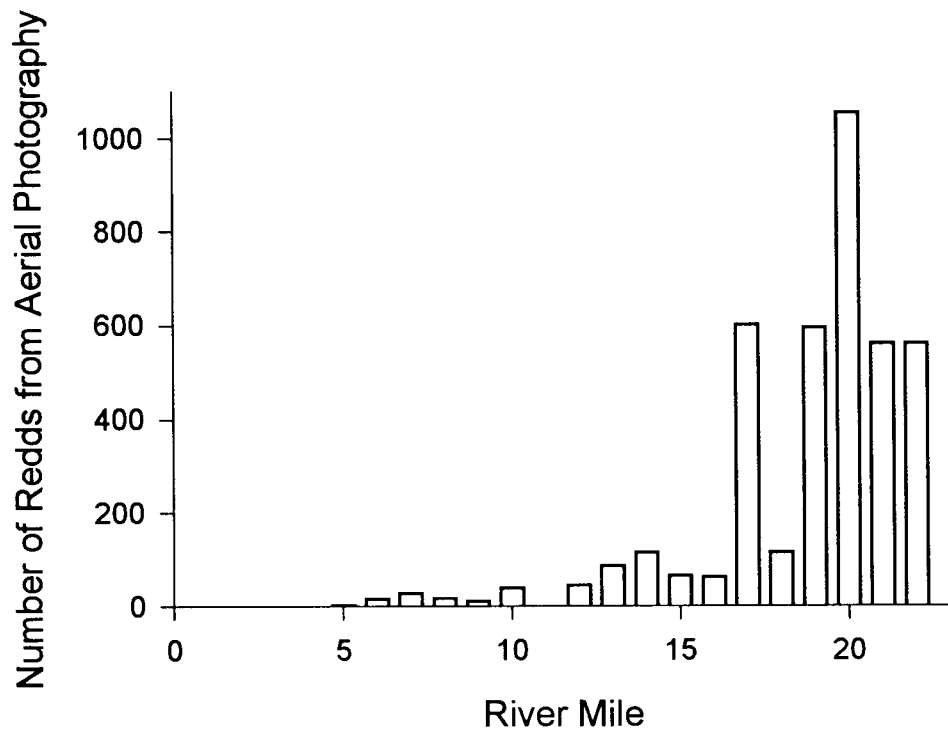


Figure 6 The spatial and temporal distribution of spawning in the lower American River in 1995. Data from Snider and Vyverberg (1996).

Table 3 Observed superimposition of redds, 1991–1995 ^a

| <i>Year</i> | <i>Percent of redds superimposed</i> | <i>Number of redds affected</i> | <i>Escapement estimate</i> | <i>Average flow (cfs)</i> |
|-------------|--------------------------------------|---------------------------------|----------------------------|---------------------------|
| 1991 | 8 | 137 | 18,145 | 1,200 |
| 1992 | 42 | 474 | 4,472 | 500 |
| 1993 | 19 | 1,156 | 20,820 – 26,786 | 1,750 |
| 1994 | 17 | 450 | 26,881 – 31,333 | 1,500 |
| 1995 | 1.3 | 51 | 42,924 – 69,892 | 2,625 |

^a Data from Snider and Vyverberg (1996); where two escapement estimate are given the first is a Jolly-Seber estimate, others are Schaefer estimates. There is a slight discrepancy between population estimates for 1995 given here for 1995 and those in Snider and Reavis (1996).

Spawning gravels in the lower American River are well described by Vyverberg and others (1997), who used both bulk sampling and pebble counts to estimate gravel size distributions and characterized intragravel conditions in terms of dissolved oxygen, water temperature, and hydraulic permeability. Gravel conditions are generally good but there are subsurface layers of coarse gravels that inhibit redd construction in some areas. These coarse gravels probably are deposits of stones too large for salmon to move during spawning in previous years. Vyverberg and others (1997) proposed that substrate conditions in these areas probably could be improved by “ripping” the gravel to break up the subsurface layers and to reduce compaction, which was done in late summer 1999 with an experimental design that includes pre- and post-project data collection in both treatment and control areas. Gravel was also added to the river as part of this project, funded through the CVPIA, despite a finding by Vyverberg and others (1997) that addition of gravel may not be necessary.

Vyverberg and others (1997) also showed that there is a good relation between the areas where salmon spawn and the permeability of the gravel and the estimated rate of subsurface flow, but the traditional microhabitat variables of depth and velocity do not distinguish areas that are used from those that are not (Figures 7 and 8). This should not be a surprise. According to Healey’s review of chinook salmon life history (Healey 1991):

Provided the condition of good subgravel flow is met, chinook apparently will spawn in water that is shallow or deep, slow or fast, and where the gravel is coarse or fine.

Nevertheless, the data provide further evidence that weighted usable area (WUA), the statistic calculated by the Physical Habitat Simulation Model (PHABSIM), is not a good measure of chinook spawning habitat because it ignores subsurface flow, the factor that seems most important to the fish. Gallagher and Gard (1999) reported statistically significant relations between WUA and the number of redds in PHABSIM "cells" in the American and Merced rivers, but the relations are not strong ($r^2 = 0.40$ and 0.38 respectively) and the study was conducted in areas that salmon were known to favor for spawning, and so presumably had good subsurface flow. Whether there is much of a relation between WUA and number of redds in randomly chosen areas of the river is unknown but doubtful in light of the results in Vyverberg and others (1997) on the American River and Geist and Dauble (1998) on the Columbia River.

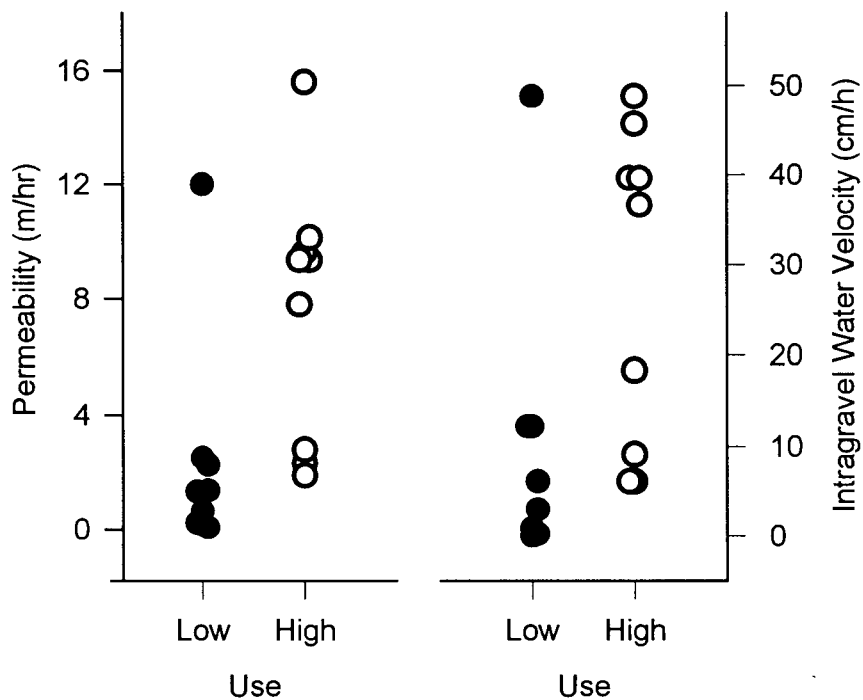


Figure 7 Permeability and estimated intragravel water velocity at ten sites that are selected (open circles) or avoided (closed circles) for spawning by chinook salmon. Data from Vyverberg and others 1997).

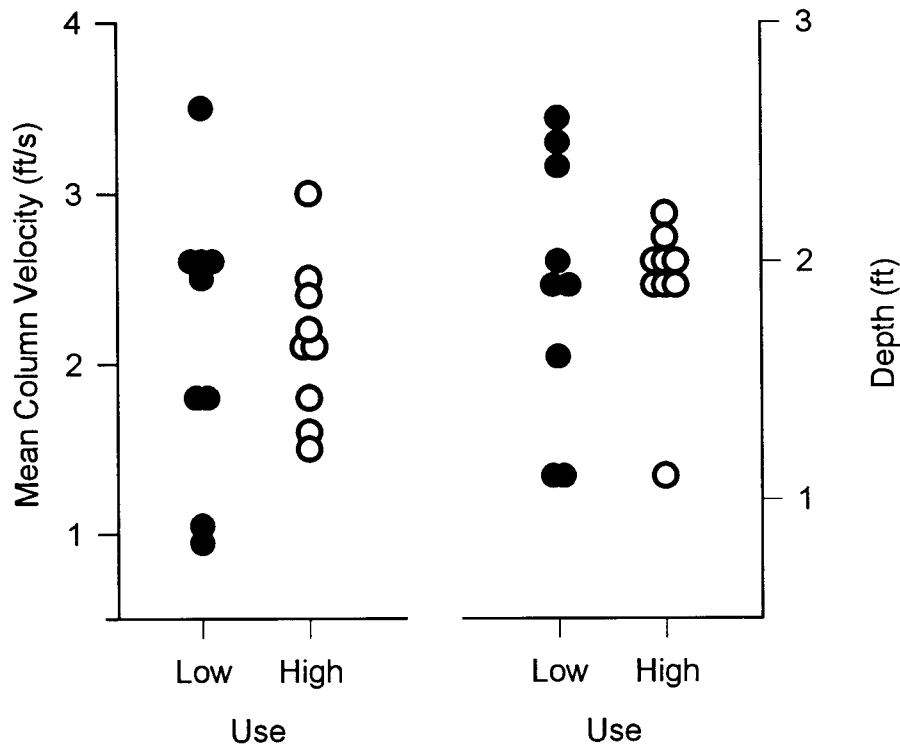


Figure 8 Mean column water velocity and depth at ten sites that are selected (open circles) or avoided (close closed circles) for spawning by chinook salmon. Data from Vyverberg and others (1997).

Pre-Spawning Mortality

The percentage of females that spawn completely before dying varies from year to year, ranging from 94% in 1993 to 68% in 1995 in samples of several hundred fish examined during DFG escapement surveys (Table 4) (Snider and others 1993, 1995; Snider and Bandner 1996; Snider and Reavis 1996). The reasons for the variation are not obvious; high proportions of unspawned carcasses were found in 1995 well into the spawning season, when water temperature should not have been a problem, and effective density as measured by redd superimposition was low. These data also illustrate the danger of drawing quick conclusions from short-term studies.

Table 4 Observed pre-spawning mortality (percent) from 1992 to 1995^a

| | 1992 | 1993 | 1994 | 1995 |
|-------------------|------|------|------|------|
| Fully spawned | 92% | 94% | 74% | 68% |
| Partially spawned | 3% | 3% | 9% | 13% |
| Unspawned | 5% | 3% | 17% | 19% |

^a Data from Snider and Reavis (1996).

Incubation

Incubation is relatively rapid for fall-run chinook salmon in Central Valley streams because the water is warm compared to more northerly streams; in the lower American River water temperature usually averages between 6 and 9 °C in January, the coldest month. There are no available data on mortality during incubation on the American River. Emergence traps deployed in 1996 and 1997 were destroyed by high flows. However, Vyverberg and others (1997) estimated mortality using published relations between survival and gravel size (Tappel and Bjornn 1983) and between survival and intragravel water velocity (Gangmark and Bakkala 1960). There was no clear relation between the two estimates, which varied from 66% to 100% at 18 sites based on gravel size, and from 54% to 79% based on intragravel water velocity, except that estimates based on gravel size were always higher. Intragravel water velocity is directly related to the supply of oxygen to the eggs and alevins and the removal of metabolic wastes and seems a sounder basis for estimating survival.

Emergence

The timing of emergence depends on the timing of spawning and on water temperature, which strongly affects the rate of development of eggs and alevins. Chinook fry have been captured as early as late November in recent DFG studies (Snider and others 1998), earlier than suggested by the EDF vs. EBMUD "consensus." This change may reflect new sampling methods (rotary screw traps), and perhaps the relatively warm water temperature in the fall and winter of 1995-1996. Fry usually begin to emerge in large numbers in January and continue to emerge until April, or even later in some years (Snider and Keenan 1994).

Juvenile Rearing

Although most juvenile chinook leave the American River shortly after emerging, some rear in the river for a few months before emigrating. Even of this group, however, most are gone by mid-May and relatively few remain in June based on both trap (Snider and Titus 1995; Snider and others 1997, 1998) and seine data (Brown and others 1992; Snider and McEwan 1993; Snider and Keenan 1994; Snider and Titus 1996). Snider and others (1998) note that juvenile chinook now emigrate earlier in the year than when the USFWS operated fyke traps on the river in 1945–1947 (USFWS and DFG 1953). Warmer water during the incubation period resulting from the thermal effects of Folsom Reservoir seems the most likely explanation for this change (Rob Titus, DFG, 1999, personal communication).

Jackson (1992) observed habitat use by juvenile chinook in late April or early May at two flows, 350 cfs in 1991 and 3,700 cfs in 1989. Although his efforts were hampered by poor visibility, he summarized his observations as follows (p 104–105):

Juvenile chinook salmon in the lower American River exhibited trends in habitat selection and behavior similar to what has been observed by other researchers in other rivers. Juvenile chinook salmon occurred in groups of two fish to schools of thousands and ranged from 50 to 120 mm (FL), but predominantly were 50 to 80 mm in length. Schools were always associated with cover which provided visual and/or velocity shelter, the latter was utilized most often. As the juvenile chinook salmon became larger (80 to 120 mm), a progression toward deeper and faster water was observed. The larger fish were either paired or more often alone utilizing large cobble/boulder substrate as velocity cover and would move quickly from their shelter to feed on drift organisms. Individual chinook salmon were aggressive and territorial.

During the high flow period a considerable amount of terrestrial vegetation was submerged and utilized extensively by juvenile chinook salmon. Root wad/debris jams were limited in quantity in the upper two reaches of the lower American River. These were utilized extensively and provided a significant juvenile chinook salmon microhabitat niche. On all occasions where root wad/woody debris jams were available as a cover type, except [for one], large schools of juvenile chinook salmon were observed. No juvenile chinook salmon were observed at either flow utilizing the one area surveyed ... with riprap. During high flow juvenile chinook salmon were observed utilizing eddies and small microniches within undulating sandy substrate.

While in the river the juveniles feed mainly on drifting invertebrates. Chironomids (midges) are most frequently eaten, but the larger caddisflies and mayflies make up most of the diet by weight (Brown and others 1991; Merz 1993).

Castleberry and others (1991; 1993) evaluated the physiological condition of juvenile chinook in the lower American River in 1991 and 1992, years with moderately low flows and warm water in late winter and early spring³. They found that non-polar lipid percentages for juveniles increased with length and tended to decrease with distance downstream, averaging about 6% to 8% dry weight for 40 to 49 mm fish, and 10% to 14% dry weight for fish 60 to 69 mm. This is in the low range for hatchery fish, but there are few comparable data for wild fish. They found that activity levels for Na⁺-K⁺ ATPase, an enzyme found in special cells in the gills that remove excess sodium and chloride ions from the blood, were high compared to published values. These data indicate that conditions in the river in 1991 and 1992 did not hinder the development of sea-water tolerance by juvenile chinook.

Approximate ages were determined from otoliths (Castleberry and others 1991, 1993, 1994), and showed that juveniles were growing well, averaging about 0.38 mm per day at 50 mm fork length (Williams 1995; estimates given in Castleberry and others 1991, 1993 are incorrect). Data on length by month suggest that juvenile chinook grew more slowly in 1993, when flow was higher and temperature lower, but this remains to be confirmed by analysis of the otoliths of fish collected and archived in 1993. DFG has this work underway (Rob Titus, DFG, 1999, personal communication).

Emigration

It has long been known that some ocean-type juvenile chinook emigrate as fry, shortly after emerging from the gravel, while others rear in the river for a few months and emigrate as smolts or large parr (Healey 1991). Based on the poor survival of coded-wire tagged fry released in the Delta (USFWS 1983), many biologists have assumed that the parr or smolt emigrants account for most returning adults. For example, the following assertion in Kelley and others (1985) was unchallenged in the trial of EDF vs. EBMUD:

Many of the small salmon are either washed, or voluntarily move, down into the estuary soon after they emerge from the gravel of the river bottom. The survival of these fish is very small, and fish that remain in the river and grow to a larger size have a much better chance of becoming adults.

Some biologists argued that fry emigrants have continued to produce good returns in wet years; however, and a different view was expressed in the past. In the SWRCB hearings on Folsom in 1957, George Warner, a DFG biologist, argued the importance of fry emigrants:

3. See Williams (1995) for detailed temperature and flow data for 1991-1993.

Small fingerlings which are flushed rapidly out of the river to the rich feeding grounds in the Delta and in the ocean have a good chance of survival. A speedy downstream migration at high flows cuts down the losses from predation and losses in irrigation diversions. In addition these fish grow faster than fish which spend considerable time in the river. This has been amply proved in fingerling marking experiments and scale studies⁴.

Recent investigations by DFG using screw traps near Watt Avenue (Snider and Titus 1995; Snider and others 1997, 1998) show that the overwhelming majority of fry leave the spawning areas in the lower American River shortly after emerging, with emigration usually peaking in February. Comparison of the size distribution of fish collected in the screw traps with that of fish collected with seines near the upstream limit of spawning suggests that this behavior has a temporal component, such that early emerging fry tend to emigrate directly (almost all fish are <50 mm before April), but later emerging fry are more likely to rear for some period before emigrating (Figure 9).

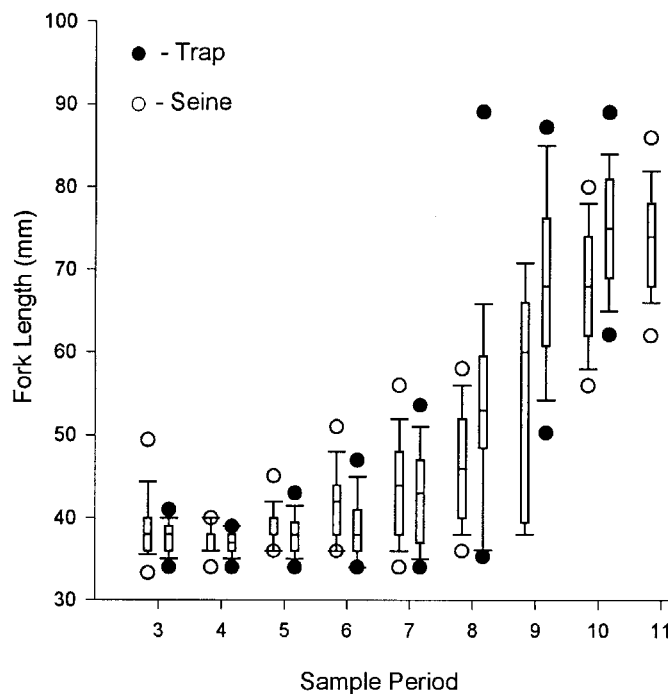


Figure 9 Size distributions of juvenile chinook salmon captured in the lower American River in screw traps (box plots with closed circles) and seines (plots with open circles) in 1995. Sample periods are two weeks: period 3 is 2/6–2/19, period 7 is 4/3–4/16, period 11 is 5/29–6/11. Box plot conventions are as in Figure 2. Data from DFG.

4. Unfortunately, he did not cite the studies; except for Clark's (1929) discussion of scale patters, I have not found any that fit his description.

There is controversy in the literature whether fry emigration is a forced, density-dependent behavior, or a volitional behavior (see Healey 1991 for a review). In the American River, the lack of larger juveniles in the seine samples early in the year when fish density is still low suggests early emigration is volitional, rather than a response to fish density or territorial behavior. Unpublished work relating length to otolith microstructure has developed no evidence that the fry captured in the traps are growing more slowly than others (Rob Titus, DFG, 1999, personal communication). More light could be shed on this issue by comparing the physiological condition of fry captured in the rotary screw trap with fry captured near the upper limit of spawning. Unfortunately, the traps were not effectively in service during the period that Castleberry and others (1991, 1993) were doing their work. Nevertheless, Castleberry and others (1993) found that ATPase activity increased downstream in fry <40 mm that were captured in seines, which is consistent with volitional emigration.

The large percentage of fry emigrants makes it seem likely that this is a viable life history pattern (Healey 1991). As noted by Snider and others (1998), the large proportion of fry emigrants emphasizes the importance of downstream rearing conditions for American River chinook salmon. Recent work by Sommer and others (2001) indicates that juvenile chinook in the Yolo Bypass grew more rapidly and had better survival to Chipps Island than fish in the Sacramento River, which supports the idea that natural floodplains along the lower Sacramento provided important habitat for juvenile chinook from the American River before the river was leveed.

Almost all juveniles leave the river before developing the full classic suite of smolt characteristics. DFG recently has classified juveniles collected in the screw traps as sac-fry, fry, parr, silvery parr, and smolts, (Snider and Titus 1995; Snider and others 1997, 1998) and reports less than 1% smolts and 74% or more fry or sac-fry (Table 5). Generally, however, the size distribution of fish collected in the screw trap is bimodal, with the great majority of the fish less than 45 or 50 mm, relatively few between 50 and 60 mm, and a second, much smaller group larger than 60 mm. The life stages are not well correlated with length, however, in part because the length of parr and silvery parr tends to increase over the season (Snider and others 1998).

Table 5 Life stage statistics for emigrating chinook, 1994–1996 ^a

| <i>Life stage</i> | <i>1994</i> | <i>1995</i> | <i>1996</i> |
|-------------------|-------------------|-------------|-------------|
| Yolk-sac fry | not distinguished | 3.5% | 22.6% |
| Fry | 96.7% | 70.5% | 59.6% |
| Parr | 1.6% | 22.5% | 17.4% |
| Silvery parr | 1.4% | 0.1% | 4% |
| Smolt | 0.3% | 0.4% | 0% |

^a Source: Data from Snider and others 1998.

Although the rotary screw trap data appear to provide good information on the timing of emigration and the nature of the emigrants, they do not provide good estimates of numbers of emigrants. Mark-recapture work by DFG shows that the capture efficiency of the rotary screw trap used by DFG is less than 1% (Snider and others 1998), and Roper (1995) argues that a capture efficiency of 10% or more is necessary for usefully accurate population estimates.

Age at Return

There are no data on the age or length at age of naturally produced chinook salmon returning to the American River, and very few data on hatchery fish, since fish from Nimbus are not normally coded-wire tagged. Recent information on length at age for Central Valley chinook generally is remarkably scarce, although it is commonly assumed that most spawners are three years old. Clark (1928) reported age data for salmon taken in the Delta gill net fishery in 1919 and 1921 (Figure 10), with ages determined by reading scales, showing more four- and five-year-old fish than three-year-old fish. However, chinook scales are hard to read (Godfrey and others 1968), and Clark may have overestimated ages (Frank Fisher, DFG, 1993, personal communication), but there is little doubt that the ocean troll fishery reduces that average age at return (Hankin and others 1994 and references therein). There is also good evidence that the size of returning adults has decreased from a comparison of the sizes reported by Clark and by a DFG survey in the American River (Figure 11). Hankin and others (1994) posit a genetically-influenced threshold size for maturation (see also Mangel 1994) that could be affected by inadvertent selection by the fishery and perhaps by hatchery practices.

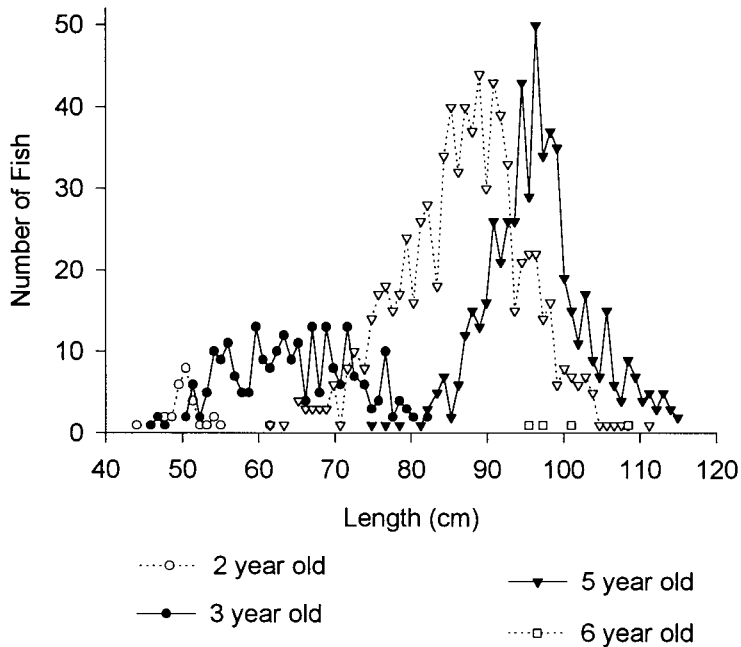


Figure 10 Ages of chinook salmon captured in the Sacramento gill net fishery in 1919 and 1921, estimated from scales. Data from Clark (1929).

Fecundity

There is substantial variation and a significantly declining trend in the average fecundity of females spawned at Nimbus Hatchery (Figure 12) from about 5,800 in the period 1955–1964 to about 5,100 for 1988–1997. Values for 1983 and 1984 stand out as low outliers, presumably reflecting poor ocean conditions associated with El Niño conditions. Unfortunately, the data were taken as the total number of eggs divided by the number of females, and there is information on the variance in fecundity among females and on the relation between fecundity and length for only one year, 1997. Fecundity of 135 individuals in 1997 varied from about 3,100 to 7,800 eggs, with length accounting for just over half the variation when fitted by fecundity = 6.385 (fork length)^{1.564} (DFG 1998)⁵. Accordingly, the decline in average fecundity could reflect either a decline in fecundity at length, a decline in average length, or both. Fecundity is a basic biological parameter that deserves more attention.

5. A decline in average length probably accounts for the difference between the fecundity reported for Sacramento River chinook by McGregor (1923), which is cited by Healey and Heard (1984) and Healey (1991), and the fecundity at Nimbus in the late 1950s; in any event the fish measured by McGregor were large.

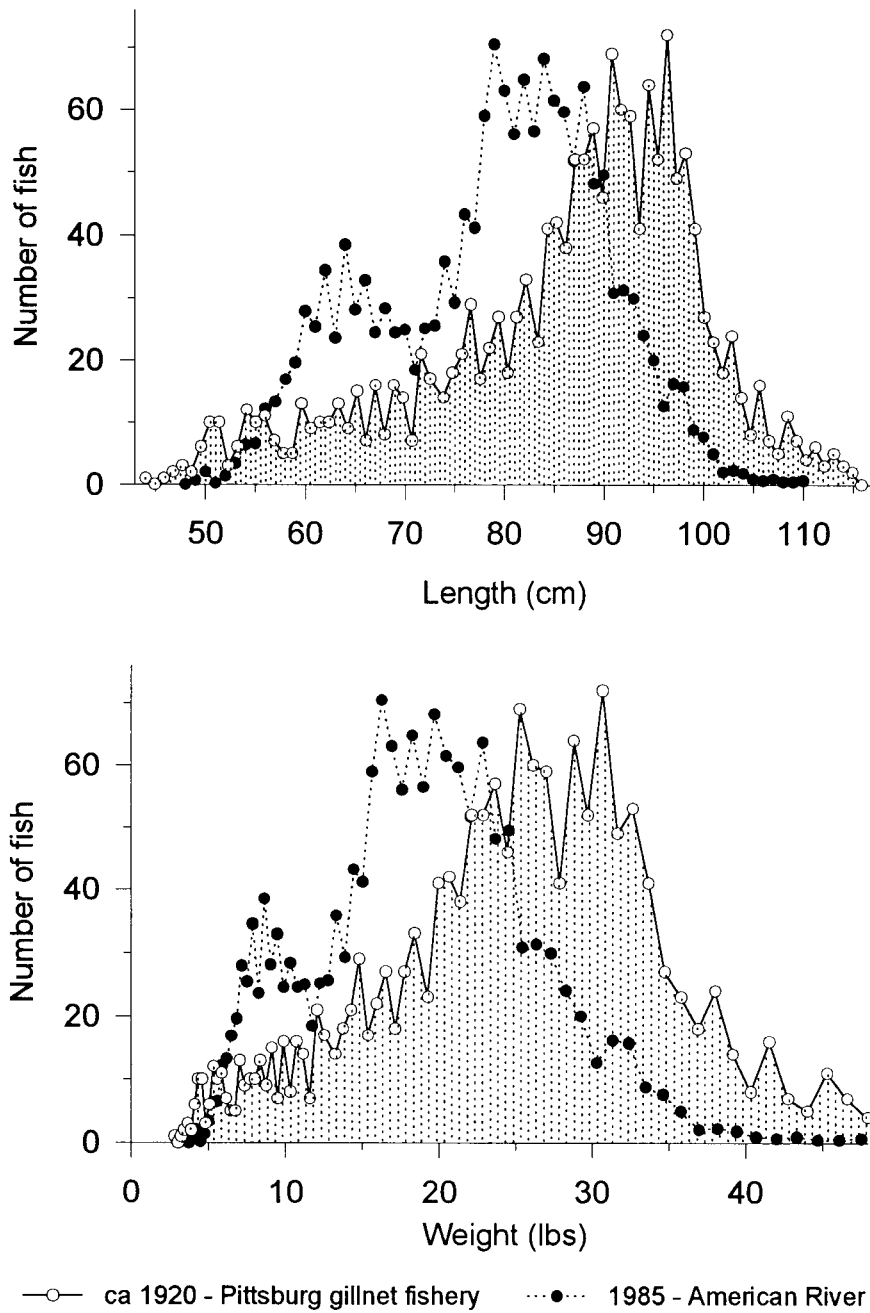


Figure 11 Length and weight distributions of chinook salmon captured in the Sacramento gill net fishery in 1919 and 1921, and from carcass surveys by DFG in 1985. Weights estimated with a length-weight relationship provided by Frank Fisher of DFG. Data from Clark (1929) and Fred Meyer of DFG.

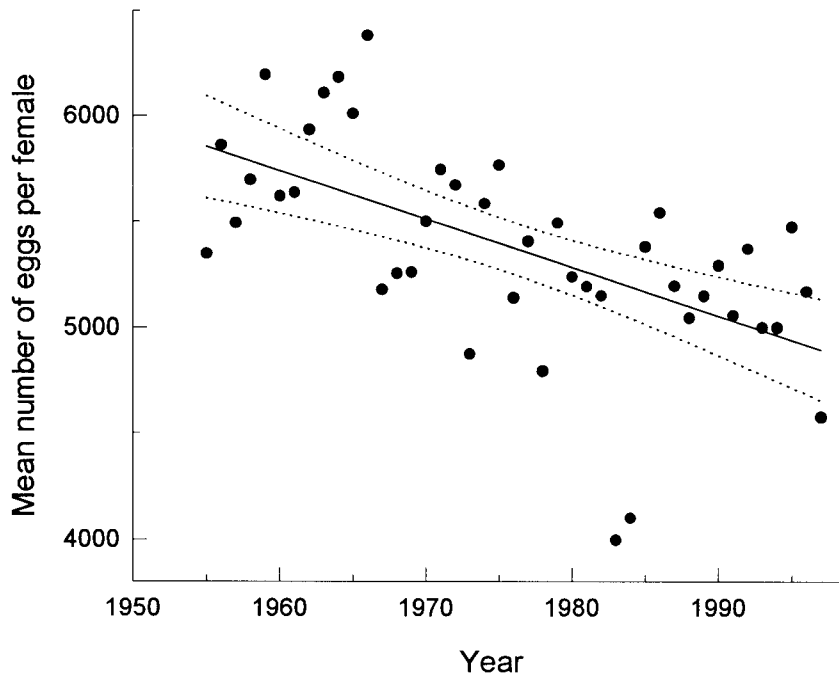


Figure 12 Declining trend in the average fecundity of chinook salmon at Nimbus Hatchery. Data from Fred Meyer and Terry West of DFG.

Salient Uncertainties and Research Needs

Several topics that deserve better understanding, such as fecundity and pre-spawning mortality, have been described above. Some additional topics follow.

Relation Between Flow and Rearing Habitat

The relation between flow and rearing habitat remains unclear. According to the consensus statement from a small workshop that discussed the American River at some length, "... currently no scientifically defensible method exists for defining the instream inflows needed to protect particular species of fish or ecosystems" (Castleberry and others 1996; Williams 1997). Methods such as PHABSIM suffer from measurement, statistical, and conceptual problems (Shirvell 1986, Shirvell 1994; Williams 1995, 1996; Campbell 1998; Bult and others 1999; Kondolf and others forthcoming). Simple empirical approaches that depend on measures such as smolts per spawner are confounded by measurement problems and density-dependent mortality (Williams 1999) and by the unknown percentage of hatchery fish. An adaptive approach that emphasizes measures of condition of juvenile fish, exemplified by the work of Castleberry and others (1991, 1993) on the American River, appears to be most

promising, especially when linked to population-level responses by individual-based modeling (Osenberg and others 1994; Maltby 1999). More observations of habitat use like those of Jackson (1992) would be helpful, especially if they are directed toward developing a better understanding of the way juvenile chinook use habitat rather than "habitat suitability criteria" for PHABSIM studies. In any event, understanding the cause-and-effect relationships that underlie the responses of populations to habitat change seems crucial for effective management of habitats in regulated rivers (Jones and others 1996; Williams 1999).

The Importance of Fry Emigrants

The relative viability of fry that emigrate soon after emerging and fry that rear in the river for some time remains poorly known, as described above, but has important implications for management of the American River and investment in habitat restoration in the Delta. For example, there appears to be a trade-off between providing high flows for spawning in the fall and the risk of low carryover storage for flows the following spring, should the winter be dry. The optimal allocation of water to spawning probably depends on viability of fry emigrants, which in turn may depend upon habitat conditions in the lower Sacramento River and the Delta. DFG has work on otolith microstructure in progress that among other things aims to distinguish patterns associated with different juvenile life history patterns. If this can be done with even modest accuracy, then analysis of otoliths from adults should clarify the viability of fry emigrants. Monitoring the physiological condition of emigrating fry in the lower Sacramento River as well as in the American, and comparing these with fish remaining near upstream spawning areas in the American River, would be an alternative and complementary approach.

Density-dependent Mortality

Understanding the mechanisms of density-dependent mortality for chinook salmon in the American River should allow better management, even if measurement problems preclude quantifying the relationship accurately. As noted above, aerial surveys have provided some information on density-dependent mortality at spawning. Assuming that density-dependent mortality for juveniles works through mechanisms that also produce sub-lethal stress in juveniles, measures of condition such as lipids, otolith increment widths, or inter-renal distance (Castleberry and others 1991, 1993; Norris and others 1996) may be most useful. Otolith data on growth during early ocean life may provide evidence for density-dependence in that life stage, especially if combined with population data from streams where populations can be estimated more accurately than seems possible on the American River. Bold adaptive variation in hatchery production at a regional scale may be required to clarify this issue, however.

Temperature Tolerance of Juveniles

The temperature tolerance of juvenile chinook was much debated in the trial of EDF vs. EBMUD and despite recent progress remains unclear. Analyses of juvenile chinook and steelhead in the lower American River in 1991 and 1992 showed that they appeared to be growing well and be in good physiological condition, despite moderately low flows and warm water in late winter and early spring (Castleberry and others 1991, 1993; Williams 1995). Coded-wire-tagged fish in the Yolo Bypass grew more rapidly and showed better survival to Chipps Island than did paired releases of fish in the Sacramento River, where water temperature was lower (Sommer and others 2001). Juvenile chinook that move up relatively warm intermittent tributaries of the Sacramento River to rear grow rapidly (Moore 1997; Maslin and others 1997). Recent laboratory studies at the University of California at Davis (Marine 1999) showed that juvenile chinook from Coleman Hatchery grew as rapidly at 17 to 20 °C on full ration as they did at 13 to 16 °C. On the other hand, Clarke and Shelbourn (1985) described delayed mortality associated with scale loss in fish that were raised in freshwater at 16 or 17 °C, so freshwater growth and survival may not be the whole story. Paired coded-wire-tag releases like those of Sommer and others (2001), which will allow estimates of survival to catchable size from tag returns from the ocean fishery, could be especially useful in this regard. In any event, water temperature is an important predictor of the survival of coded-wire-tagged smolts, regardless of the statistical method used on the data (Ken Newman, University of Idaho, 1999, personal communication), while other variables such as flow seem important in some analyses but not in others. Assays for stress proteins (Iwama and others 1998) in fish collected at Chipps Island for the coded-wire tag studies could provide independent evidence of temperature stress. A literature review of the temperature tolerance of juvenile chinook that should clarify this issue is currently underway by Chris Myrick at the University of California at Davis.

The Importance of Hatchery Production

Intelligent management of chinook salmon in the American River depends on distinguishing fish of natural and hatchery origin. Hatchery fish can be marked easily and economically by manipulating water temperature in the trays in which larval fish (alevins) are reared. This creates visible bands of narrow and wide growth increments in otoliths (ear-stones) that mark fish as hatchery produced; the bands can even form bar-codes by which fish from different hatcheries or batches can be distinguished (Volk and others 1990, 1994). If all hatchery fish are marked, the proportion of naturally produced spawners could be estimated accurately from a relatively small sample, and the associated analysis of otoliths could also provide information on length at age of adults and perhaps information on year-to-year variation in ocean condition and on the life history patterns of fish that survive to spawn. A pro-

gram for thermally marking the otoliths of hatchery fish is now being developed by DFG.

Quantitative Methods

Methods for analyzing biological data have developed rapidly in recent years (for example, Jongman and others 1987; Efron and Tibshirani 1991, 1993; Hilborn and Mangel 1997; Peterman and Anderson 1999). Unfortunately, these methods are unfamiliar to most Central Valley salmon biologists and even methods such as the bootstrap that are easy to implement are seldom used. Data analysis routinely should include the development and testing of models of the biological and sampling processes that generate the data (Elliott 1994; Hilborn and Mangel 1997). Besides guiding field studies to address the most relevant issues, this approach helps avoid the waste of resources on field studies that cannot generate useful information. The recent analyses of coded-wire tag data by Ken Newman and John Rice reveal a large gap between the quality of analysis that is possible and the quality that is typical in studies of salmon in the Central Valley, bearing out the observation of Efron and Tibshirani (1993) that "Statistics is a subject of amazingly many uses and surprisingly few effective practitioners."

Concluding Remarks

Much is known about chinook salmon in the American River and elsewhere, but much remains to be learned. Because of EDF vs. EMBUD, there have been many recent studies of chinook in the American River. In many respects, however, the American River is not a good study stream. Developing good population estimates for chinook salmon in the river does not seem to be practicable, especially for juveniles, mainly because the river is so big. The urban setting and heavy recreational use of the river create other problems, as does the heavy presence of hatchery fish. Efforts to understand density-dependent mortality or other aspects of chinook biology that require good population estimates probably should be focused on smaller streams such as Butte Creek or Clear Creek, or the Feather River side-channel where Castleberry and others (1994) confirmed that juvenile chinook form otolith increments daily. The low flow channel of the Feather River (see Sommer and others, Volume 1) probably is a better system than the American River for intensive studies on a larger scale because better experimental control of flows is possible.

Much could be gained by a regional perspective among salmon researchers that would allow a coordinated approach to addressing some questions and allow others to be addressed primarily in the parts of the system with the most favorable study conditions. Unfortunately, there is a tendency toward

Balkanization of salmon research in the Central Valley, with divisions among regions and agencies that discourages communication, let alone cooperation. Workshops such as the one giving rise to this publication are a step in the right direction, but much remains to be done to create an effective community of scientists in which the efforts and intelligence of those studying salmon in the Central Valley can realize their potential. (See also Kimmerer and others, this volume.)

References

- Beak Consultants, Inc., Hyromet, Inc., Norman S. Brainthwaite, Inc. 1992. American River temperature model: pond survey and river hydraulics. Unpublished report to Sacramento County.
- Boydston LB. 1994. Analysis of two mark-recapture methods to estimate the fall chinook salmon, *Oncorhynchus tshawytscha*, run into Bogus Creek, upper Klamath River, California. California Fish and Game 80:1-3.
- Bratovich PM, Taylor SL, Christophel DB. 1995. Final fish biologists' working session summary. Unpublished report by Beak Consultants to the City-County Office of Metropolitan Water Planning. Sacramento, California.
- Brown LR, Moyle PB, Vanicek CD. 1992. American River studies: intensive fish surveys, March-June 1991. Unpublished report to California Department of Fish and Game, Environmental Services Division. Sacramento, California.
- Bult TP, Riley SC, Haedrich RL, Gibson RJ, Heggenes J. 1999. Density-dependent habitat selection by juvenile Atlantic salmon (*Salmo salar*) in experimental riverine habitats. Can J Fish Aquat Sci 56:1298-1306.
- Campbell EA. 1998. Influence of streamflow and predators on habitat choice by trout [PhD thesis]. University of California, Davis.
- Castleberry DT, Cech JJ Jr., Erman DC, Hankin D, Healey M, Kondolf GM, Mangel M, Mohr M, Moyle PB, Nielsen J, Speed TP, Williams JG. 1996. Uncertainty and instream flow standards. Fisheries 21(8):20-1.
- Castleberry DT, Cech JJ Jr., Saiki MK, Martin BA. 1991. Growth, condition, and physiological performance of juvenile salmonids from the lower American River: February through July, 1991. Unpublished report to EBMUD. Oakland, California.
- Castleberry DT, Cech JJ Jr., Saiki MK, Martin BA. 1993. Growth, condition, and physiological performance of juvenile salmonids from the lower American River: February through July, 1992. Unpublished report to EBMUD. Oakland, California.

- Castleberry DT, Saiki MK, Marin BA. 1994. Field validation of daily increment formation on the sagittal otoliths of juvenile chinook salmon. Unpublished report to EBMUD. Oakland, California.
- Clark GH. 1929. Sacramento-San Joaquin salmon (*Oncorhynchus tshawytscha*) fishery of California. Division of Fish and Game of California, Fish Bulletin nr. 17.
- Clarke WC, Shelbourn JE. 1985. Growth and development of seawater adaptability by juvenile fall chinook salmon (*Oncorhynchus tshawytscha*) in relation to temperature. *Aquaculture* 45:21-31.
- Cramer SP. 1992. Contribution of Sacramento Basin hatcheries to ocean catch and river escapement of fall chinook salmon. Unpublished report to the California Department of Water Resources, Sacramento, California.
- Dettman DH, Kelley DW. 1986. The roles of Nimbus hatchery and natural production in maintaining the lower American River salmon run. Unpublished report to East Bay Municipal Utilities District, Oakland, California.
- [DFG] California Department of Fish and Game. 1998. Lower American River ramping study, status report for July-December 1997. Environmental Services Division. Sacramento, California.
- [DWR] California Department of Water Resources. 1999. Results and recommendations from 1997-1998 Yolo Bypass studies, draft report. Unpublished report to CALFED Bay-Delta Program. Sacramento, California.
- Gallagher SP, Gard MF. 1999. Relationships between chinook salmon (*Oncorhynchus tshawytscha*) redd densities and PHABSIM-predicted habitat in the Merced and lower American rivers, California. *Canadian Journal of Fisheries and Aquatic Habitat* 56:570-7.
- Gangmark HA, Bakkala RG. 1960. A comparative study of stable and unstable (artificial channel) spawning streams for incubating king salmon at Mill Creek. *California Fish and Game* 151-64.
- Geist DR, Dauble DD. 1998. Redd site selection and spawning habitat use by fall chinook salmon: the importance of geomorphic features in large rivers. *Environmental Management* 22:655-669.
- Godfrey HD, Worlund D, Bilton HT. 1968. Tests on the accuracy of aging chinook salmon (*Oncorhynchus tshawytscha*) from their scales. *Can J Fish Res Board* 25:1971-82.
- Hankin DG. 1988. Examination of methods and statistical analysis in EBMUD exhibits concerning the relative contributions of hatcheries and natural production to the populations of chinook salmon in the lower American River. Unpublished Report to McDonough, Holland & Allen. Sacramento, California.

- Hankin DG, Nicholas JW, Downey TW. 1994. Evidence for inheritance of age at maturity in chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 50:347-358.
- Healey MC. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). In: Groot C, Margolis L, editors. Pacific salmon life histories. Vancouver, BC: University of British Columbia Press.
- Healey MC, Heard WR. 1984. Inter- and intra-population variation in the fecundity of chinook salmon *Oncorhynchus tshawytscha* and its relevance to life history theory. Can J Fish Aquat Sci 41:476-483.
- Hilborn R. 1999. Confessions of a reformed hatchery basher. Fisheries 24(5):30-31.
- Hilborn R, Mangel M. 1997. The ecological detective: confronting models with data. Monographs in Population Biology #28. Princeton University Press.
- Hodge R. 1990. Statement of Decision, Environmental Defense Fund et al. v. East Bay Municipal Utility District, Alameda County (California) Superior Court Action Nr. 425955.
- Iwama GK, Thomas PT, Forsyth RB, Vijayan MM. 1998. Heat shock protein expression in fish. Reviews in Fish Biology and Fisheries 8:35-56.
- Jackson TA. 1992. Microhabitat utilization by juvenile chinook salmon (*Oncorhynchus tshawytscha*) in relation to stream discharge in the lower American River, California [MS thesis]. Oregon State University.
- Jones ML, Randall RG, Hayes D, Dunlop W, Imhof J, Lacroix G, Ward NJR. 1996. Assessing the ecological effects of habitat change: moving beyond productive capacity. Can J Fish Aquat Sci 54(Suppl):446-457.
- Kelley DW, Bratovich PM, Dettman DH, Rooks H. 1985. The effects of streamflow on fish in the lower American River. Unpublished report to Best, Best & Krieger. Riverside, California.
- Kimmerer W, Mitchell B, Hamilton A. 2001. Building models and gathering data: can we do this better? In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 2. Sacramento (CA): California Department of Fish and Game.
- Kondolf GM, Larsen EW, Williams JG. Measuring and modeling the hydraulic environment for determining instream flows. Manuscript accepted with modifications by North American Journal of Fisheries Management.
- Law PW. 1994. A simulation study of salmon carcass survey by capture-recapture method. California Fish and Game 80:14-28.

- Maltby L. 1999. Studying stress: the importance of organism-level responses. *Ecological Applications* 9:431-40.
- Mangel M. 1994. Climate change and salmonid life history variation. *Deep Sea Research II* 41:75-106.
- Marine KR. 1999. Effects of elevated water temperature on some aspects of the physiological condition and ecological performance of juvenile chinook salmon (*Oncorhynchus tshawytscha*): implications for management of California's Central Valley salmon stocks [MS thesis]. University of California, Davis.
- Maslin P, Lennox M, Kindopp J, McKinney W. 1997. Intermittent streams as rearing habitat for Sacramento River chinook salmon (*Oncorhynchus tshawytscha*). Unpublished report to the US Fish and Wildlife Service.
- McGregor EA. 1923. A possible separation of the river races of king salmon in ocean-caught fish by means of anatomical characters. *California Fish and Game* 9:138-150.
- Merz J. 1993. A survey of drift and epibenthic communities and their utilization as forage by target fish in the lower American River, California, February-July, 1992. Unpublished report to California Department of Fish and Game. Department of Biology, California State University, Sacramento.
- Moore TL. 1997. Condition and feeding of juvenile chinook salmon in selected intermittent tributaries of the upper Sacramento River [MS thesis]. California State University, Chico.
- [NRC] National Research Council. 1996. *Upstream: salmon and society in the Pacific Northwest*. National Academy Press.
- Norris D, Woodling J, Felt S, Donahue S, Clark N, Larson E, Maldonado T, Dores R. 1996. Metal pollution and stress response in Colorado brown trout: correlations with measurements of acute and chronic stress. In: Barton B, MacKinlay D, editors. *Contaminant effects on fish symposium, International Congress on the Biology of Fishes, San Francisco State University*. American Fisheries Society, Physiology Section. p 107-113.
- Osenberg CW, Schmitt RJ, Holbrook SJ, Abu-Saba KE, and AR Flegal. 1994. Detection of environmental impacts: natural variability, effect size, and power analysis. *Ecological Applications* 4:16-30.
- Peterman RM and JL Anderson. 1999. Decision analysis: a method for taking uncertainties into account in risk-based decision making. *Human Ecological Risk Assessment* 5(2).
- Rich AA. 1985. Re-evaluation of fall chinook salmon (*Oncorhynchus tshawytscha*) spawning escapement estimates in the lower American River, California. Unpublished report to Sacramento County.

- Roper BB. 1995. Ecology of anadromous salmonids within the Upper South Umpqua River Basin, Oregon [PhD thesis]. University of Idaho.
- Shirvell CS. 1986. Pitfalls of physical habitat simulation in the instream flow incremental methodology. Canadian Technical Report of Fisheries and Aquatic Sciences Nr. 1460.
- Shirvell CS. 1994. Effect of change in streamflow on the microhabitat use and movements of sympatric juvenile coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*) in a natural stream. Can J Fish Aquat Sci 51:1644-52.
- Sommer T, McEwan D, Brown R. 2001. Factors affecting chinook salmon spawning in the lower Feather River. In Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Christophel DB, Jackson BL, Bratovich PM. 1992. Habitat characterization of the lower American River. Unpublished report by Beak Consultants to the California Department of Fish and Game, Environmental Services Division.
- Snider WM, Keenan N, Munos M. 1993. Lower American River chinook salmon escapement survey, September 1992 – January 1993. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Bandner K. 1996. Lower American River chinook salmon escapement survey, October 1994 - January 1995. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Chappelle AJ, Villa N. 1995. Lower American River chinook salmon escapement survey, October 1993 - January 1994. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Christophel DB, Jackson BL, Bratovich PM. 1992. Habitat characterization of the lower American River. Unpublished report to California Department of Fish and Game, Environmental Services Division. Sacramento, CA.
- Snider B, Keenan N. 1994. Lower American River fish community survey, January through June 1993. May 1994. Sacramento (CA): California Department of Fish and Game.
- Snider B, McEwan D. 1993. Fish community survey, lower American River, February - July 1992. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Reavis B. 1996. Lower American River chinook salmon escapement survey, October 1995 - January 1996. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Titus RG. 1995. Lower American River emigration survey, November 1993 - July 1994. Sacramento (CA): California Department of Fish and Game.

- Snider WM, Titus RG. 1996. Fish community survey, lower American River, January through June 1995. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Titus RG, Payne BA. 1997. Lower American River emigration survey, October 1994 - September 1995. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Titus RG, Payne BA. 1998. Lower American River emigration survey, October 1995 - September 1996. Sacramento (CA): California Department of Fish and Game.
- Snider WM, Vyverberg K. 1996. Chinook salmon redd survey, lower American River, Fall 1995. Sacramento (CA): California Department of Fish and Game.
- Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. *Can J Fish Aquat Sci* 58(2):325-33.
- Sykes SD, Botsford LW. 1986. Chinook salmon, *Oncorhynchus tshawytscha*, spawning escapement based on multiple mark-recapture of carcasses. *Fishery Bulletin* 84:261-270.
- Tappel PD, Bjornn TC. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. *N Am J Fish Manage* 3:123-135.
- [USACE] US Army Corps of Engineers. 1991. American River watershed investigation, California. US Army Corps of Engineers, Sacramento District.
- [USFWS] US Fish and Wildlife Service. 1983. Determine survival and productivity of juvenile chinook salmon in the Sacramento-San Joaquin Estuary. Annual Progress Report. AWPA 750-29. Stockton (CA): USFWS Fisheries Assistance Office.
- [USFWS and DFG] US Fish and Wildlife Service, California Department of Fish and Game. 1953. A plan for protection and maintenance of salmon and steelhead in the American River, California, together with recommendations for action.
- Unwin MJ. 1997. Fry-to-adult survival of natural and hatchery-produced chinook salmon (*Oncorhynchus tshawytscha*) from a common origin. *Can J Fish Aquat Sci* 54:1246-54.
- Unwin MJ, Glova GL. 1997. Changes in life history parameters in a naturally spawning population of chinook salmon (*Oncorhynchus tshawytscha*) associated with releases of hatchery fish. *Can J Fish Aquat Sci* 54:1235-45.
- Volk EC, Schroder SL, Fresh KL. 1990. Inducement of unique otolith banding patterns as a practical means to mass-mark juvenile Pacific salmon. *American Fisheries Society Symposium* 7:203-15.

- Volk EC, Schroder SL, Grimm JJ. 1994. Use of a bar code symbology to produce multiple thermally induced otolith marks. *Trans Am Fish Soc* 123:811-6.
- Vyverberg K, Snider B, Titus RG. 1997. Lower American River chinook spawning habitat evaluation, October 1994. Sacramento (CA): California Department of Fish and Game.
- Walters C. 1997. Information requirements for salmon management. In: Strouder DJ, Bisson PA, Naiman RJ, editors. *Pacific salmon and their ecosystems*. New York (NY): Chapman & Hall. p 61-68.
- Williams JG. 1995. Report of the Special Master. Environmental Defense Fund et al. v. East Bay Municipal District, Alameda County (California) Superior Court, Action Nr. 425955.
- Williams JG. 1997. Transcript of workshop on instream flow standards, University of California, Davis, April 7, 1995. Water Resources Center Report Nr. 89, 1997, Centers for Water and Wildlands Resources. Davis (CA): University of California, Davis.
- Williams JG. 1998. Thoughts on adaptive management. Interagency Ecological Program for the Sacramento-San Joaquin Estuary Newsletter 11(3):5-11. Sacramento (CA): California Department of Water Resources.
- Yoshiyama RM, Gerstung ER, Fisher FW, Moyle PB. 2001. Historical and present distribution of chinook salmon in the Central Valley drainage of California. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids*. Volume 1. Sacramento (CA): California Department of Fish and Game. This volume.

Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary

Patricia L. Brandes and Jeffrey S. McLain

Abstract

All four races of juvenile Central Valley chinook salmon migrate through and many rear in the Sacramento-San Joaquin Delta and Estuary. Delta residence and migration is considered important in determining adult production, as it is generally believed that density dependent effects are minimal after this life stage. Populations of winter run and spring run are presently listed as endangered and threatened species, while the remaining populations in the Central Valley are candidate species. Actions in the Delta to improve survival are likely important in the recovery of these depressed populations. The tidally influenced freshwater Delta also is an important area for water management in California, as it is where the Central Valley and State Water Project pump large volumes of water to southern California, the San Joaquin Valley and the Bay area. To document the effect of these various water management activities in the Delta on juvenile salmon, monitoring and special studies have been conducted since the early 1970s to the present. Changes in abundance in the Delta and estuary appear related to flow; high flows increase the use of the Delta and San Francisco Bay by fry. Relative survival of fry appears greater in the upper Sacramento River than in the Delta or bay, especially in the wetter years. Survival appears lower in the Central Delta relative to that in the North Delta in drier years for both fry and smolts. Fall-run smolt and late-fall-run yearling survival studies have found that diversion into the Central Delta via the Delta Cross Channel or Georgiana Slough reduces survival through the Delta. Experiments in the San Joaquin Delta have shown that survival appears greater for smolts that migrate down the mainstem San Joaquin River rather than through upper Old River. A temporary barrier in upper Old River was tested and found to improve survival for smolts originating in the San Joaquin basin. These specific experiments have identified management actions that could improve juvenile salmon survival through the Delta. In addition, indices of annual survival provide a way to compare survival through the Delta and could be used to assess restoration and management actions. This work demonstrates how long-term scientific studies can be applied to address management and restoration issues.

Introduction

The Sacramento-San Joaquin Estuary is one of the largest estuaries on the West Coast draining the majority of the Central Valley watershed of California. The Sacramento River from the north and San Joaquin River from the south converge in the freshwater, tidally influenced Delta (Figure 1). The Delta consists of nearly 1,200 km of freshwater channels, with most channels edged with riprap (Kjelson and others 1982). The bays downstream of the Delta are generally shallow, with salinities varying seasonally and affected by a combination of tidal flows and freshwater.

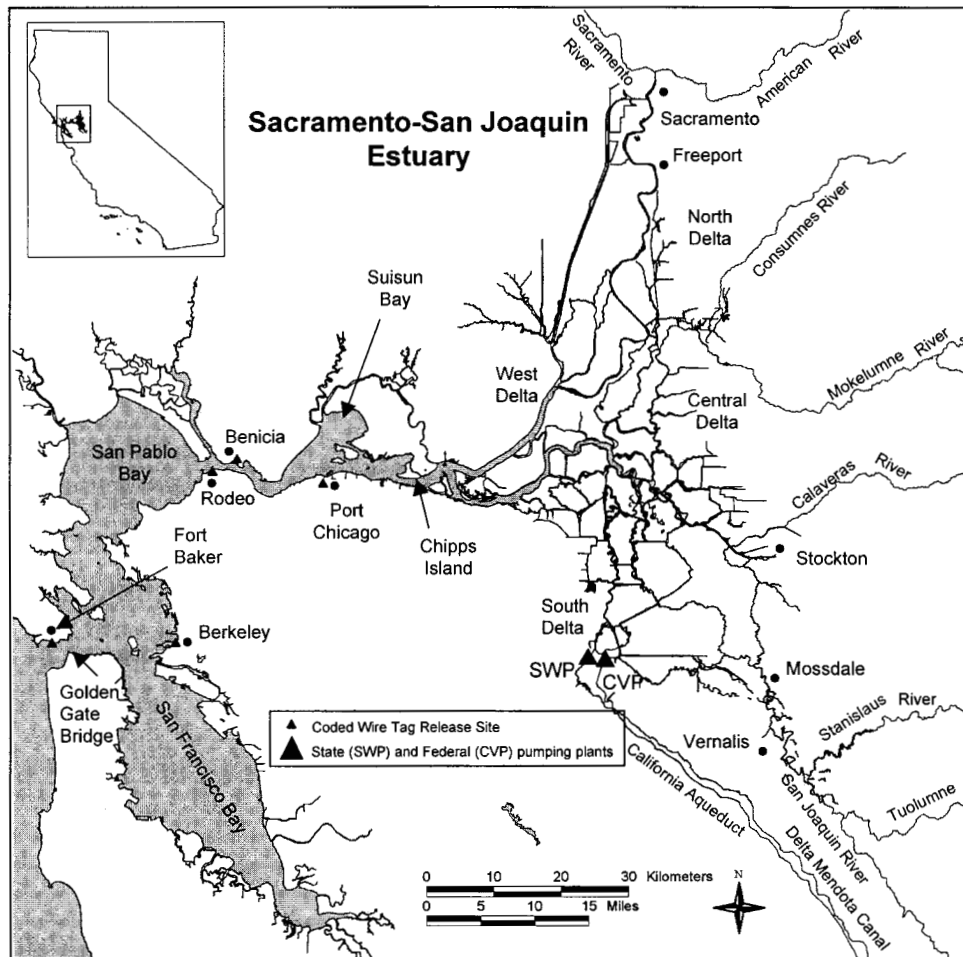


Figure 1 The Sacramento-San Joaquin Estuary, California

There are four races of chinook salmon in the Central Valley: fall, late-fall, spring, and winter. Races are based on their timing of return to freshwater for spawning (Fisher 1994). Historical documents indicate the start of the salmon fishery in California at about 1850 (USFWS 1995). Central Valley salmon continue to support valuable, economically important commercial and recreational fisheries.

During the past 30 years, overall escapement of Central Valley salmon has declined (Fisher 1994). Only the fall run continues to maintain stable spawning runs, likely because they are heavily supported by hatchery production (Fisher 1994). Winter-run chinook salmon were federally listed as threatened in 1990 and endangered in 1994 by the National Marine Fisheries Service. Spring run were recently listed as threatened in 1998 by the State of California. The remaining races and natural populations of chinook salmon in the Central Valley are presently considered candidate species under the Federal Endangered Species Act (NMFS 1999).

All of the various races of chinook salmon in the Central Valley use the Delta as a migration corridor to the ocean and many rear there before emigration. The survival of juvenile salmon through the Delta is considered critical to year class success, as density-dependent mortality after Delta residence is believed to be minimal (Junge 1970). Thus for any given set of ocean conditions, increasing the number of juveniles emigrating from the Delta will increase the production of adults. Actions in the Delta to improve survival are considered important in increasing the production of these Central Valley salmon populations.

In addition to the Delta being important to juvenile salmon, it is also critical to water management in California. Water resource project operations have altered the natural distribution, timing, and magnitude of flows in the Delta (Kjelson and others 1982). The State Water Project (SWP) and the Central Valley Project (CVP) use the Delta to move water from reservoirs in the North to the pumping plants located in the South Delta (Figure 1). The water is pumped (exported) into the State (California Aqueduct) and federal (Delta-Mendota Canal) aqueduct system for agriculture, municipal, and industrial use in the San Joaquin Valley, the Bay area, and southern California. Mean daily exports from the Delta have increased dramatically since the late 1950s and 1960s to peaks in the late 1980s (Figure 2). Due to population growth in California and other factors, there is a continued desire to increase exports further to meet the increased demands.

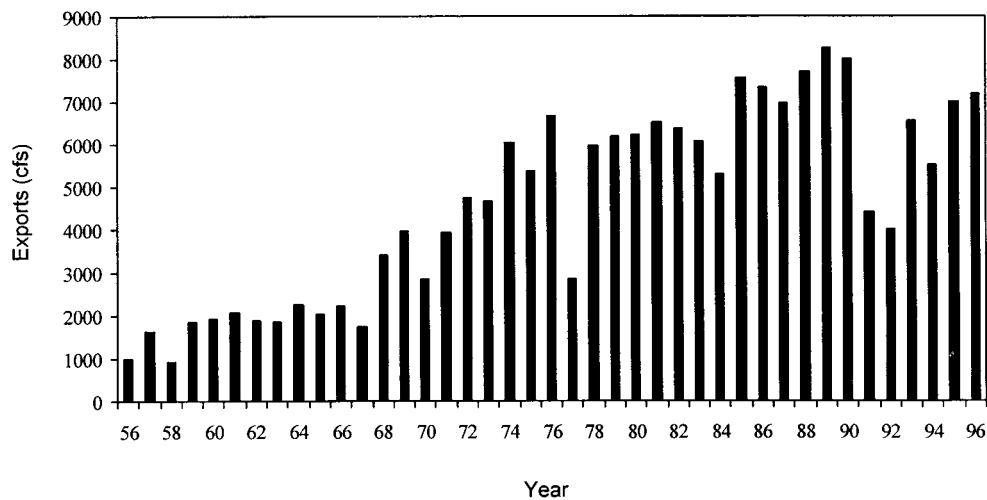


Figure 2 Mean daily combined (SWP + CVP) exports (cfs) between 1956 and 1996. Source: Department of Water Resources, DAYFLOW.

Although tidal fluctuations in the Delta are large relative to net downstream flows, an effect of the present export levels is that net flows in the South Delta often move upstream instead of downstream during periods of low Delta inflows. These net “reverse flows” occur when combined CVP and SWP export rates are higher than the net downstream flow in the San Joaquin River. The remaining water to meet the export needs originates from the Sacramento River. This process creates net flows in the South Delta that move upstream towards the pumping plants instead of downstream toward the ocean (Figure 3). For anadromous fish, such as chinook salmon, these reverse flows may cause confusion or divert them from their main migration routes to the sea. Delays in migration would expose juveniles to various mortality factors for a longer period of time and decrease their survival through the Delta.

Other habitat alterations by the two water projects are the construction of the Delta Cross Channel and the amount of water diverted from the mainstem San Joaquin River into upper Old River (Figure 3). The Delta Cross Channel, located in the North Delta, was built to increase the amount of water originating from the Sacramento River that flows into the Central Delta. The water in the Central Delta is then available by means of gravity to be pumped by the State Water and Central Valley projects located in the South Delta. In addition, the amount of water diverted into upper Old River from the San Joaquin River increases as project exports increase (Oltmann 1995). The CVP diverts water directly from Old River and the SWP diverts water from Clifton Court Forebay, and its intake is on Old River.

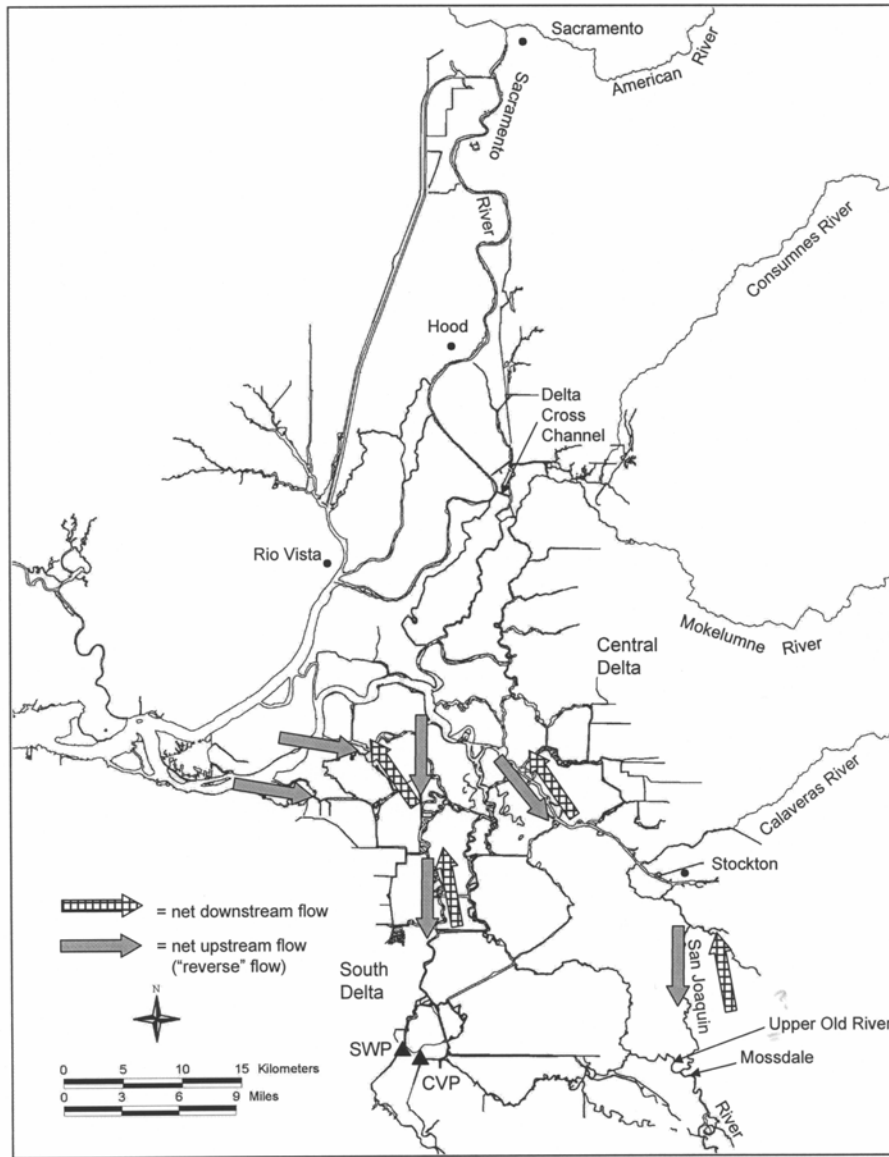


Figure 3 The Sacramento-San Joaquin Estuary, California. Arrows depict net downstream flow and “reverse flows.”

The work presented in this report is derived from juvenile salmon monitoring and special studies conducted by the US Fish and Wildlife Service’s (USFWS) Sacramento-San Joaquin Fishery Resource Office on behalf of the Interagency Ecological Program for the Sacramento-San Joaquin Delta (IEP). The IEP is a consortium of six federal and three State agencies charged with providing information on the factors that affect the ecological resources in the Sacramento-San Joaquin Estuary to allow more efficient management of the estu-

ary. Agencies in the IEP, in addition to the USFWS, include the US Bureau of Reclamation, US Geological Survey, National Marine Fisheries Service (NMFS), US Army Corps of Engineers, US Environmental Protection Agency, California Department of Water Resources, California Department of Fish and Game, and California State Water Resources Control Board.

The IEP has been conducting juvenile salmon studies in the Delta since the early 1970s. The initial goals of the salmon studies were to define the impacts of water development on the estuarine salmon population and to document the water quality requirements (including flow standards) needed to both sustain and enhance salmon production (Kjelson and others 1981). The goals have been broadened since the program's inception and reflect an overall desire to gain information on what management actions can be taken to improve the survival of juvenile salmon rearing or migrating through the Delta.

The results of these studies have been shared in the past in various ways: workshops, *IEP Newsletter* articles, gray literature in the form of annual reports, testimony to the State Water Resources Control Board (USFWS 1987, 1992a) and peer-reviewed journal and symposium articles (Kjelson and others 1981, 1982; Kjelson and Brandes 1989). The purpose of this paper is to consolidate, update, and summarize the juvenile salmon information gained from the IEP salmon studies. Data from some of the studies are limited and do not provide statistically significant results. They are included to provide a more complete record of the results of the various studies. Many times inferences have been made based on limited data, but we acknowledge in that case there is a risk in drawing wrong conclusions. To lessen that risk, we have tried to draw on a variety of independent pieces of information to reach conclusions.

Specific studies were conducted on juvenile salmon abundance, distribution, and survival using beach seines, Kodiak and midwater trawls, and mark and recapture techniques. The beach seine and the trawls are size and habitat selective, with the beach seine targeting smaller fish (fry) near the shore and the midwater and Kodiak trawls generally capturing larger juveniles (smolts and yearlings) that migrate in the center of the channel. Mark and recapture experiments have been conducted with hatchery fry, smolts, and yearlings released in the upper Sacramento River, Delta, San Francisco Bay, and San Joaquin tributaries (Figures 1, 4 and 5) to estimate survival and examine the importance to survival of different environmental conditions (Kjelson and Brandes 1989).

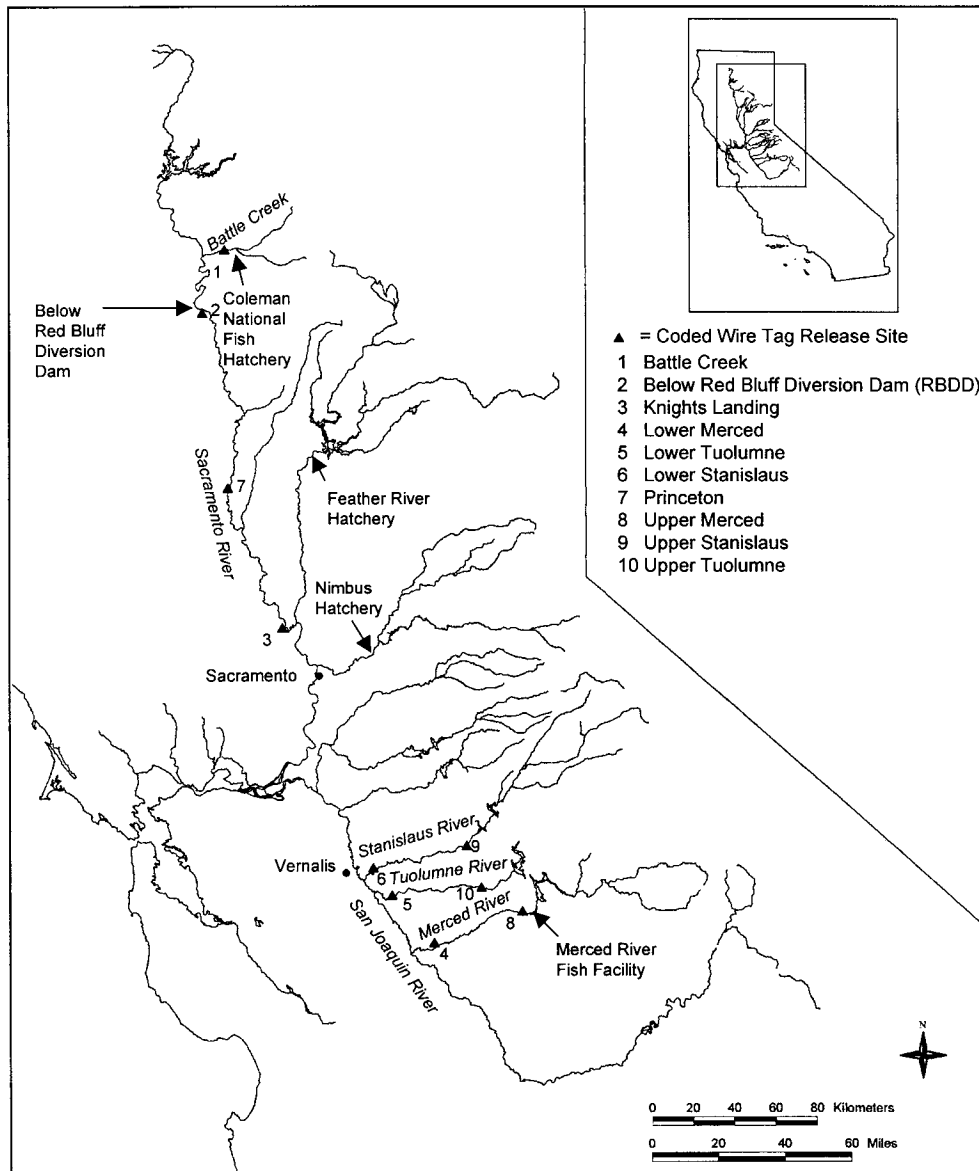


Figure 4 Map of coded wire tag release locations in the upper Sacramento River and San Joaquin River tributaries

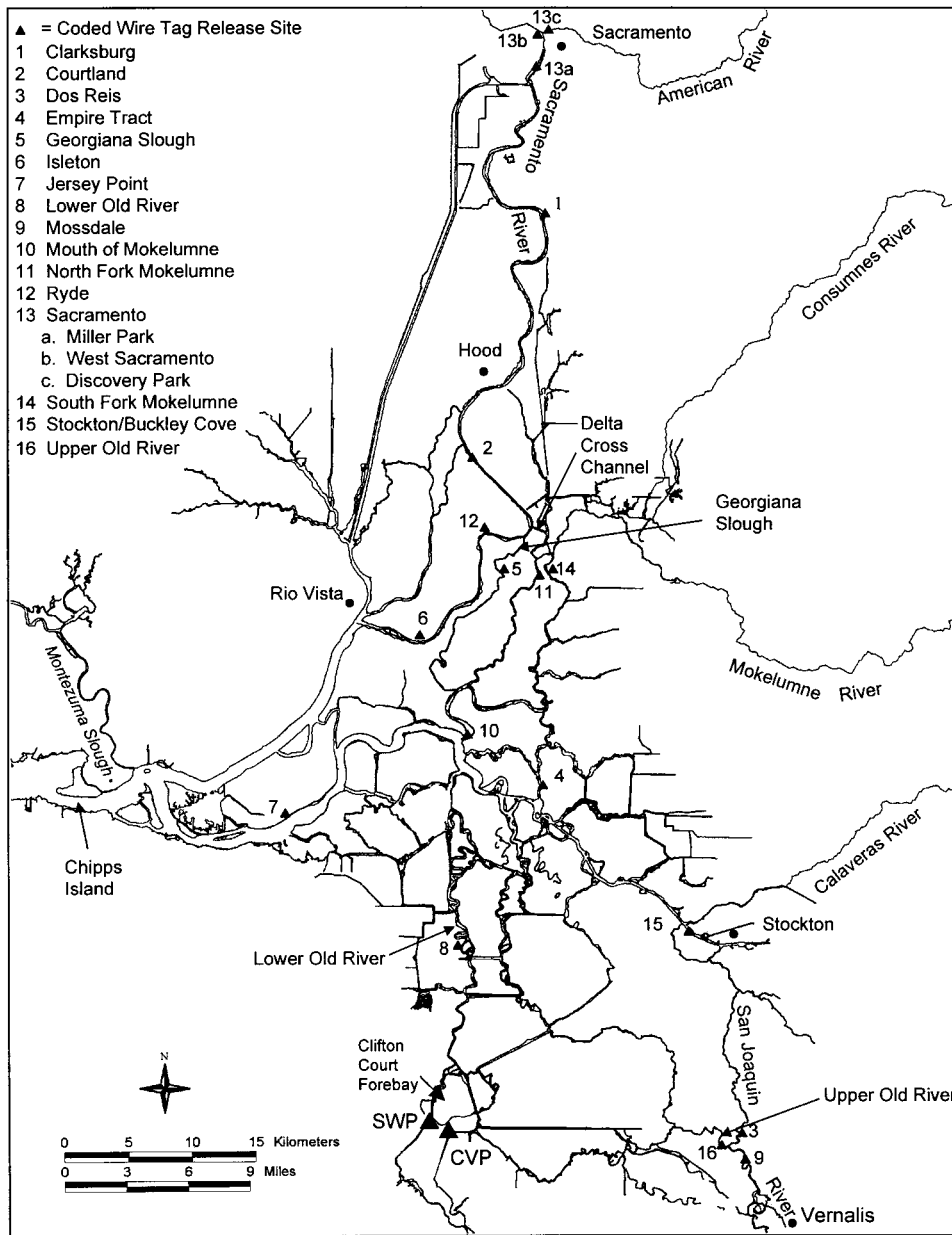


Figure 5 Detailed map of the Sacramento-San Joaquin Delta indicating coded wire tag release locations used between 1978 and 1997

There are many assumptions made in using hatchery fish to estimate the survival of wild fish. It is likely that wild fish survive at a greater rate than those released and reared at a hatchery (Reisenbichler and others 1992), but relative differences in survival of hatchery fish between different locations, times, sizes or other parameters can be informative. Using hatchery smolts to investi-

gate factors affecting wild fish also seems appropriate (Kjelson and Brandes 1989) and we have found it useful in gaining information for managing and protecting wild juvenile salmon.

Chinook "fry," as defined in this report, is the life stage between emergence from the spawning gravel to the completion of upstream or estuarine rearing (<70 mm fork length). Juveniles that are starting to undergo behavioral and physiological changes to prepare for the transition to salt water are termed "smolts." In this report they are identified as juveniles equal to and greater than 70 mm fork length. Yearlings are defined as juveniles greater than 100 mm that have over-summered in freshwater.

Information contained in this paper is presented by topic: "Fry Abundance," "Smolt Abundance," "Fry Survival," and "Smolt Survival." Each topic includes methods, and results and discussion sections. The results and discussion sections under smolt survival are further sub-divided by basin (Sacramento and San Joaquin) and specific management issues.

The California Department of Water Resources provided flow and project export information via their DAYFLOW program. River flows were measured on the Sacramento River at "I" Street (in downtown Sacramento) and at Freeport, and on the San Joaquin River at Vernalis (Figure 1). River flows were estimated using calculations at Rio Vista and Stockton. Exports are the combined mean daily rate at the SWP and CVP in cubic feet per second (cfs).

A variety of statistical methods was used to evaluate relationships between abundance and survival and environmental conditions. Data used in the regression analyses were assessed for normality and heterogeneity of variance using the descriptive statistics function in SYSTAT 7.0 for Windows. Variables were transformed when necessary to meet the assumptions of parametric statistics.

Fry Abundance

Methods

Seasonal abundance and spatial distribution of juvenile salmon in the Sacramento-San Joaquin Estuary were estimated using beach seine surveys at sites in the Delta, lower Sacramento River and San Francisco Bay. Sites within the Delta and on the lower San Joaquin River were added in recent years to provide additional information on juvenile salmon distribution. Abundance and distribution data were collected to document the use of the Delta as a rearing area and evaluate its use relative to flow.

Beach seine sampling was made with a 15.2 by 1.2 m (50 ft by 4 ft) seine, with 3.2-mm (1/8-inch) mesh, during daylight hours. One seine haul was made at each sampling station. Thirty stations have been sampled weekly in the Delta and lower Sacramento River during the spring since 1979 and constitute core "historical" sites. Seven of the stations are located on the lower Sacramento River between Colusa and Elkhorn (10 miles north of Sacramento) and twenty-three sites are located in the Delta (Figure 6). The sites in the Delta were divided into three areas: the North Delta, Central Delta, and South Delta.

In addition, between 1981 and 1986, 16 stations were sampled twice a month in Suisun, San Pablo, and San Francisco bays (Figure 6) of which ten were re-sampled during the spring in 1997. Sites include boat ramps, mud banks, and sandy beaches. There were times when sampling was not possible due to changes in flow or other conditions that prevented site access. The beach seining sites added in recent years are located primarily in the South Delta and lower San Joaquin River (Figure 6). Additional sites on the Sacramento River have also been sampled in recent years, but discussion of these sites is not included in this report.

Water temperature was measured, and all fish species captured were identified and enumerated at each sample site. In each sample, up to 50 juvenile salmon were measured to the nearest millimeter fork length. All tagged salmon were kept for subsequent tag decoding.

Relative juvenile salmon abundance was compared within and between years using catch per haul or catch per cubic meter at the core "historical" sites sampled during similar periods between years. Average catch per haul is defined as the number of juvenile salmon caught divided by the number of seine hauls performed.

It became possible to calculate catch per cubic meter starting in 1985, when the depth, length, and width of the area swept by the beach seine were measured as part of the normal sampling protocol. Depth is the maximum depth swept by the seine haul. Length of the seine haul is the distance the haul was taken from shore and width is the measured scope of the seine haul, which is parallel to shore. The area of the seine haul was used to estimate the volume of water sampled, which was calculated by multiplying the depth of the sample by 0.5, then multiplying the product by the length and width of the seine haul. Catch per cubic meter (C/m^3) is estimated by dividing the catch by the volume of water sampled and yields a more robust density measurement than catch per haul.

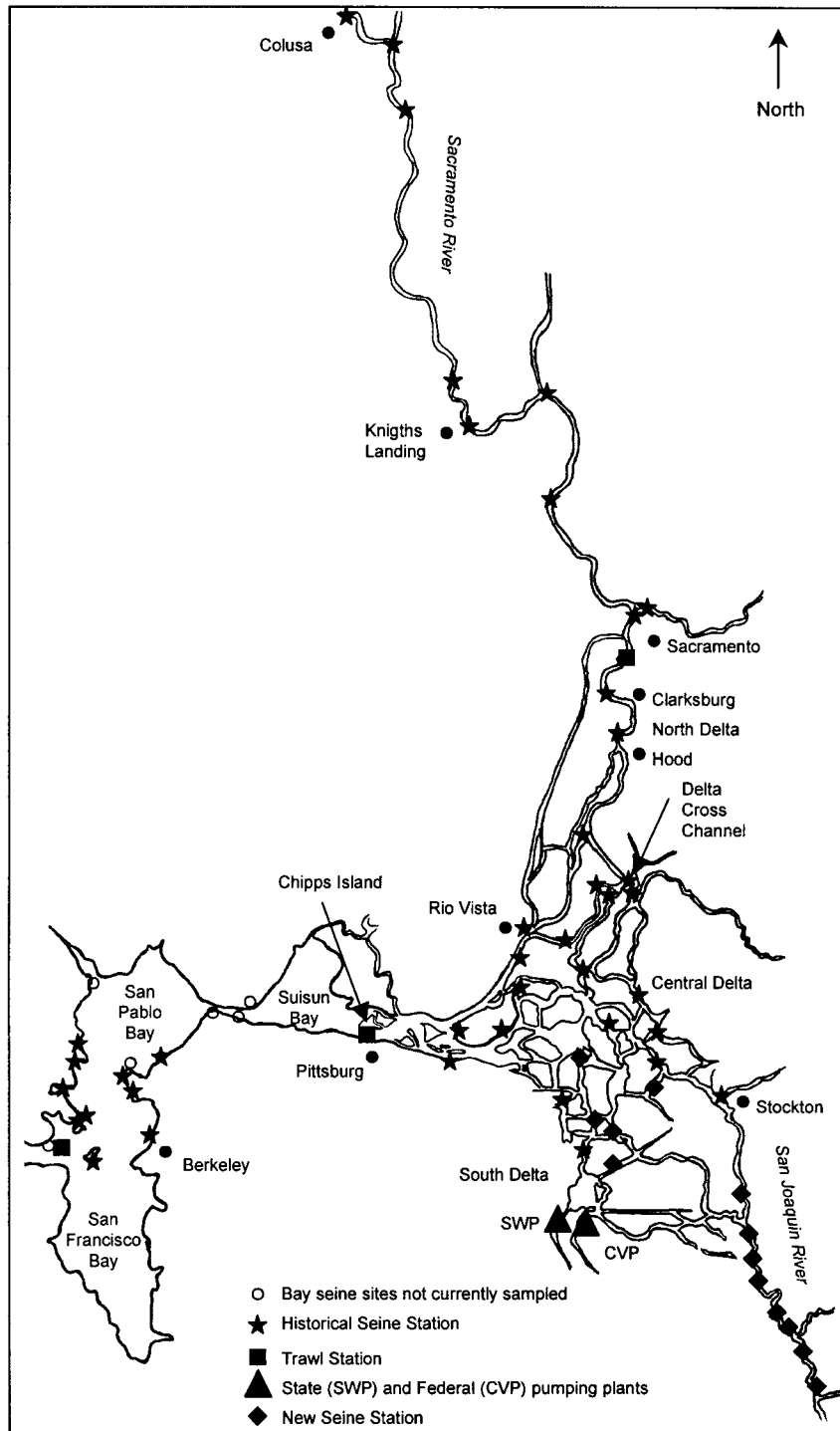


Figure 6 Sampling sites located in the Sacramento-San Joaquin Estuary, California

The average monthly C/m^3 and catch per haul, by area, was calculated by summing the average monthly C/m^3 or catch per haul for all sites within an area, and dividing by the number of sites sampled. The average monthly C/m^3 or catch per haul by site was estimated by summing the monthly C/m^3 or catch per haul for each site and dividing by the number of months sampled. Each monthly C/m^3 or catch per haul by site was estimated by summing the daily C/m^3 or catch per haul and dividing by the number of times the site was sampled within the month. The daily C/m^3 by site was estimated by dividing the catch by the volume of water sampled. Only one sample was taken at each site per day and generally each site was sampled once per week.

Simple linear regression analyses were used to determine if fry abundance in the North Delta and bay varied with flow. A constant 0.0001 was added to the catch per cubic meter in the bay before being log transformed. Sacramento River flow at Freeport was also log transformed for the regression analyses between catch per cubic meter in the bay and flow.

Results and Discussion

The number of fry in the estuary is influenced by the number of eggs deposited and environmental conditions during spawning, incubation, and rearing. Kjelson and others (1982) found that peak catches of fry in the Delta in the spring followed major runoff periods. We found that the annual spring abundance of fry in the Delta was also related to flow, with the highest abundance observed in wet years. Fry abundance in the North Delta between January and March, using catch per cubic meter in the beach seine, was significantly correlated ($r^2 = 0.69$, $P < 0.01$) to the mean flow in the Sacramento River at Freeport in February (Figure 7). Catch per cubic meter reduced the variability in the relationship even though some of the data from earlier years could not be included (Figure 8).

Based on sampling upstream of the Delta, it appears many fall run juveniles from the American and Feather rivers migrate to the Delta as fry in both wet and dry years (Snider and others 1998; Sommer and others 2001, this volume). Fry, originating from the San Joaquin tributaries, also were apparent in the Delta during the spring in the wet years (Figure 9). Sampling has not been conducted early enough in the season in dry years to determine if many fry move downstream into the Delta from the San Joaquin basin to rear in the drier years.

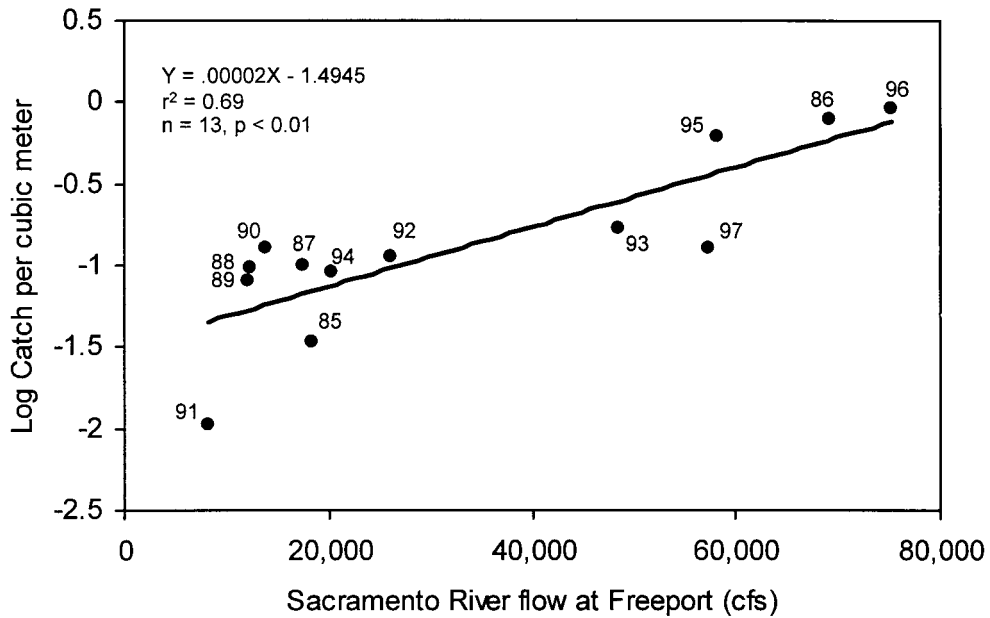


Figure 7 Catch per cubic meter of juvenile chinook salmon in the North Delta beach seine between January and March versus mean February flow on the Sacramento River at Freeport from 1985 to 1997

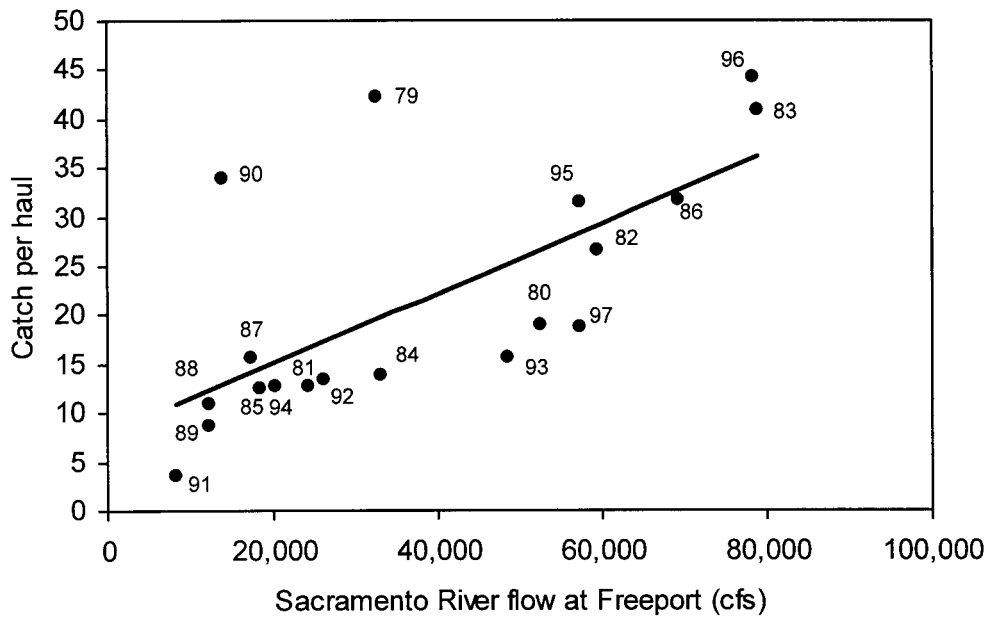


Figure 8 Catch per haul of juvenile chinook salmon in the North Delta beach seine between January and March versus mean February flow on the Sacramento River at Freeport from 1979 to 1997

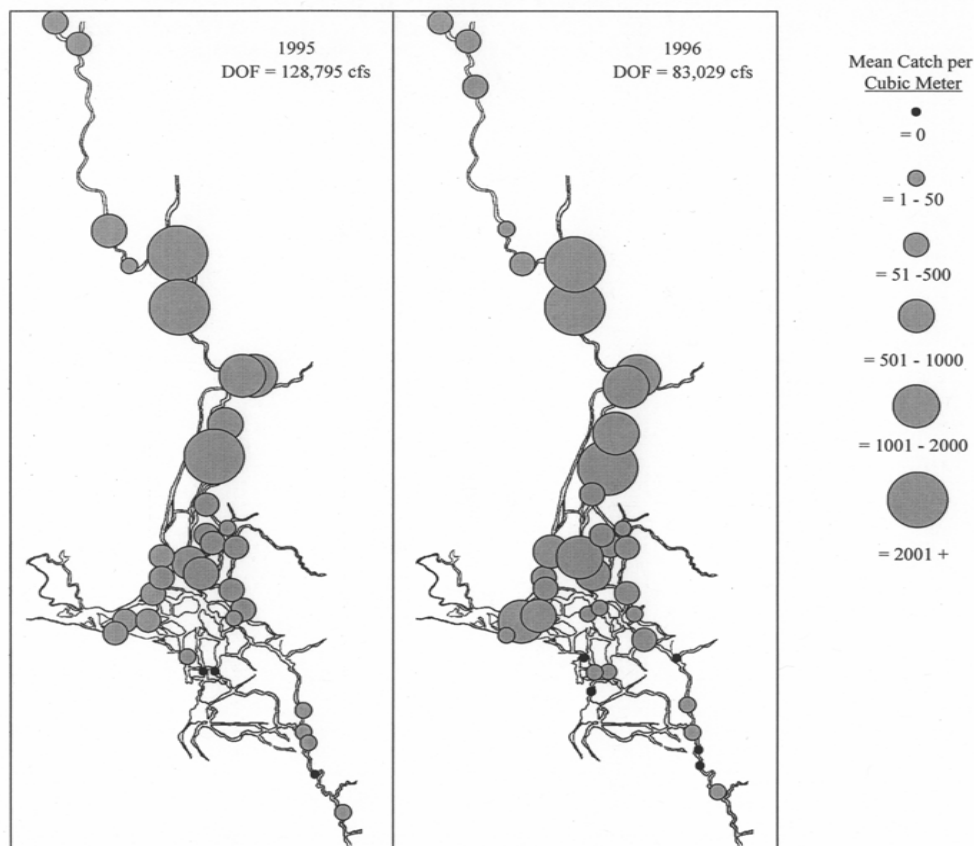


Figure 9 Mean monthly catch per cubic meter (x 1,000) of chinook salmon fry from beach seine sites and mean Delta outflow (DOF) between January and March in 1995 and 1996

Fry abundance during the spring in San Francisco Bay shows a similar effect of flow. We found that the average catch per cubic meter (plus 0.0001 and logged) in ten beach seine sites sampled in San Pablo and San Francisco bays (January through March) was positively correlated to the log of the mean daily Sacramento River flow at Freeport in February ($r^2 = 0.98$, $P < 0.01$) (Figure 10). Flow at Freeport was used, as most of the net flow moving from the Delta into the bay (Delta outflow) originates from the Sacramento River.

These results are consistent with Healy (1980) who observed increased chinook salmon fry catch during increased discharge in the Nanaimo River Estuary in British Columbia. Other studies have speculated that behavioral interactions and density dependent mechanisms were responsible for downstream migration (Healy 1991).

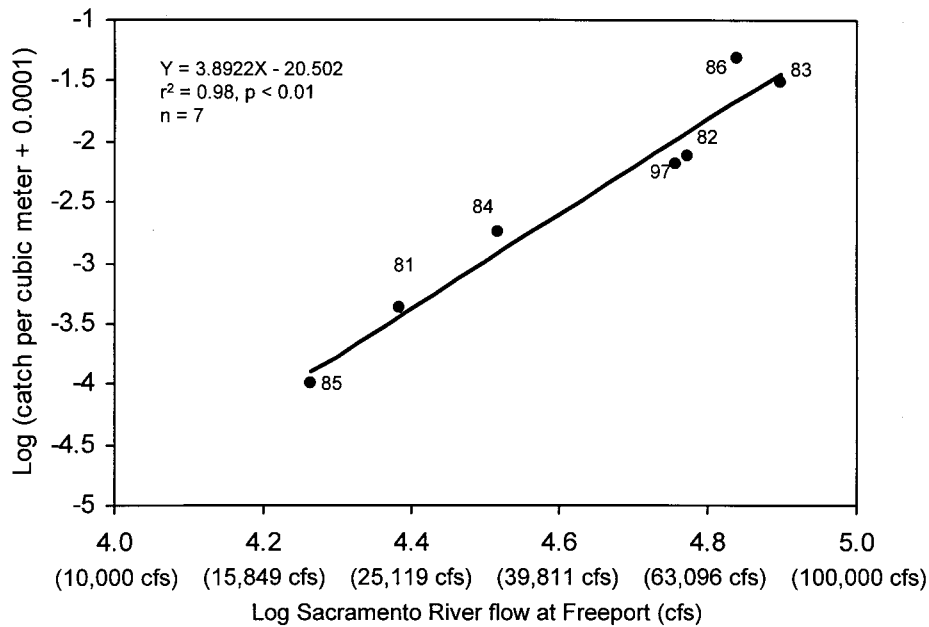


Figure 10 Log of catch of chinook fry per cubic meter (+ 0.0001) between January and March at beach seine sites in the San Francisco Bay versus log of mean flow at Freeport during February between 1981 and 1986 and in 1997. The equation without the 1986 outlier is $y = 3.6218x - 19.316$.

There were relatively few fry in the Delta during the other months of the year and likely reflected the lower abundance of the other races, lower Delta inflow, higher summer water temperatures and different life history strategies. Fry have been observed in the beach seining between April and July in some years; many were assumed to be late-fall run. They ranged in size between 30 and 53 mm. In addition, a nominal number of fry has been recovered in the Delta between November and January that ranged in size between 48 and 67 mm and were likely winter run. Overall, less than 300 fry have been observed in beach seining during the late spring and summer and late fall and winter between 1977 and 1997. In the earlier years, sampling was limited during the fall and winter months, but in recent years sampling frequency has generally been similar to that conducted in the spring.

Smolt Abundance

Methods

Since 1976, Kodiak or midwater trawls have been used near Sacramento and at Chippis Island (located near the city of Pittsburg) for a variety of purposes.

Initially, midwater trawling was conducted for approximately six weeks during the spring on the Sacramento River near Hood (1976–1981) and at Chipps Island (1976 and 1977) to recover marked fish released in those years (Kjelson and others 1982). Since 1978 at Chipps Island and 1988 at Sacramento, midwater trawling has been conducted between April and June to index the number of primarily fall-run smolts entering (Sacramento) and leaving (Chipps Island) the Delta (Figure 6).

Since 1992 at Sacramento and 1994 at Chipps Island, trawling has been conducted consistently between October and June and provides information on all races of juvenile salmon entering and leaving the Delta. Year-round trawling was conducted at Chipps Island in 1980 and at both locations in recent years (1996 and 1997). Starting in the fall of 1994, a Kodiak trawl replaced the midwater trawl at Sacramento during the fall and winter months to allow more intensive sampling of larger individuals from the less abundant races due to the larger net width and herding fashion of the Kodiak trawl (McLain 1998). The midwater trawling has continued at Sacramento between April and June to allow historical comparisons using the same gear.

Midwater trawling also was conducted in San Francisco Bay, near the Golden Gate Bridge (Figure 6) between 1983 and 1987. Sampling was conducted, primarily between April and July, to index the abundance of juvenile salmon migrating out of the bay during those months and to recover marked salmon released at Port Chicago in 1984, 1985, and 1986 (USFWS 1987). Only the survival information is presented in this report.

In general, 10 twenty-minute tows were done per sample day at each location, between three and seven days per week during the months sampling was conducted. Both the midwater trawl and Kodiak trawl fished the net at the surface. Occasionally, inclement weather, mechanical problems, or excessive fish catches required reducing tow times or the number of tows. All trawling at Sacramento was done in the middle of the channel facing upstream against the current within 1.5 km of the sample site. Trawling at Chipps Island also was done within 1.5 km from the sample site in both directions regardless of tide, and in three locations of the channel: north, south, and middle.

The midwater and Kodiak trawl nets at Sacramento, Chipps Island, and in San Francisco Bay varied in size and design. The midwater trawl net used at Sacramento had a mouth opening of 1.8 by 4.6 m (6 ft by 15 ft) (Figure 11a). The net tapered from the mouth to the cod end totaling 23.6 m (77.5 ft) to the beginning of the cod end. Net mesh varied from 102 mm (4 inches) to 6 mm (1/4 inch) at the cod end. Wings were constructed of 203-mm (8-inch) stretch mesh and attached to each of four corners of the net. Lead weights were attached to the bottom rib line of the net and floats attached to the top rib line. A metal depressor door was fastened to each bottom bridle line and an alumi-

num hydrofoil was fastened to each top bridle line. The midwater trawl at Chipps Island and in San Francisco Bay used a net with a mouth opening of 3.0 by 9.1 m (10 ft by 30 ft), was tapered from the mouth to the cod end, and totaled 25 m (82 ft) (Figure 11b). Net mesh and wings were similar to that used for the Sacramento midwater trawl. The Kodiak trawl net also was variable mesh with a fully expanded mouth opening of 1.8 by 7.6 m (6 ft by 25 ft) (Figure 11c). Net mesh varied from 51-mm (2-inch) stretch mesh to 6 mm (1/4 inch). A 1.8 m bar was attached to the front of each wing with lead and float lines on the bottom and top of the net respectively. The Kodiak trawl also incorporated a live box attached to the cod end of the net to avoid fish mortality. The live box consisted of perforated steel plating 6 mm (1/4 inch) in diameter.

Actual fishing dimensions of the nets varied and have been described in past reports (USFWS 1994). Based on these studies, the mean effective-fishing mouth size of the net at Sacramento was found to be 5.1 m² and 18.5 m² at Chipps Island. The estimated fishing net mouth size of the Kodiak trawl, based on these midwater trawl studies, was 12.5 m². The catch per cubic meter and mean amount of water sampled reported in this paper were based on these fishing mouth dimensions.

Cubic meters of water sampled with the trawls were estimated with a General Oceanics mechanical flowmeter (model 2030). Linear meters were calculated by multiplying meter rotations with the Standard Speed Rotor Constant (26,874) and dividing the result by a conversion factor (999999). The volume of water sampled was calculated by multiplying the number of linear meters traveled per tow by the mouth opening of the net.

Relative abundance was compared using average catch per cubic meter (C/m^3), where C/m^3 per tow equaled: catch per tow/net mouth area (m²) × linear meters traveled through the water (m). Averages were calculated for each day, week and month. Each daily C/m^3 was calculated by averaging each C/m^3 per tow and dividing by the number of tows that day. Each weekly C/m^3 was calculated by summing the daily C/m^3 and dividing by the number of days sampled within the week. The monthly C/m^3 was the sum of weekly averages divided by the number of weeks sampled per month. Weeks were designated as Monday through Sunday and weeks which overlap months were split and included in their respective months.

Simple linear regression techniques were used to evaluate the relationships between C/m^3 and river flow. Mean C/m^3 between April and June at Sacramento was squared before regression analysis.

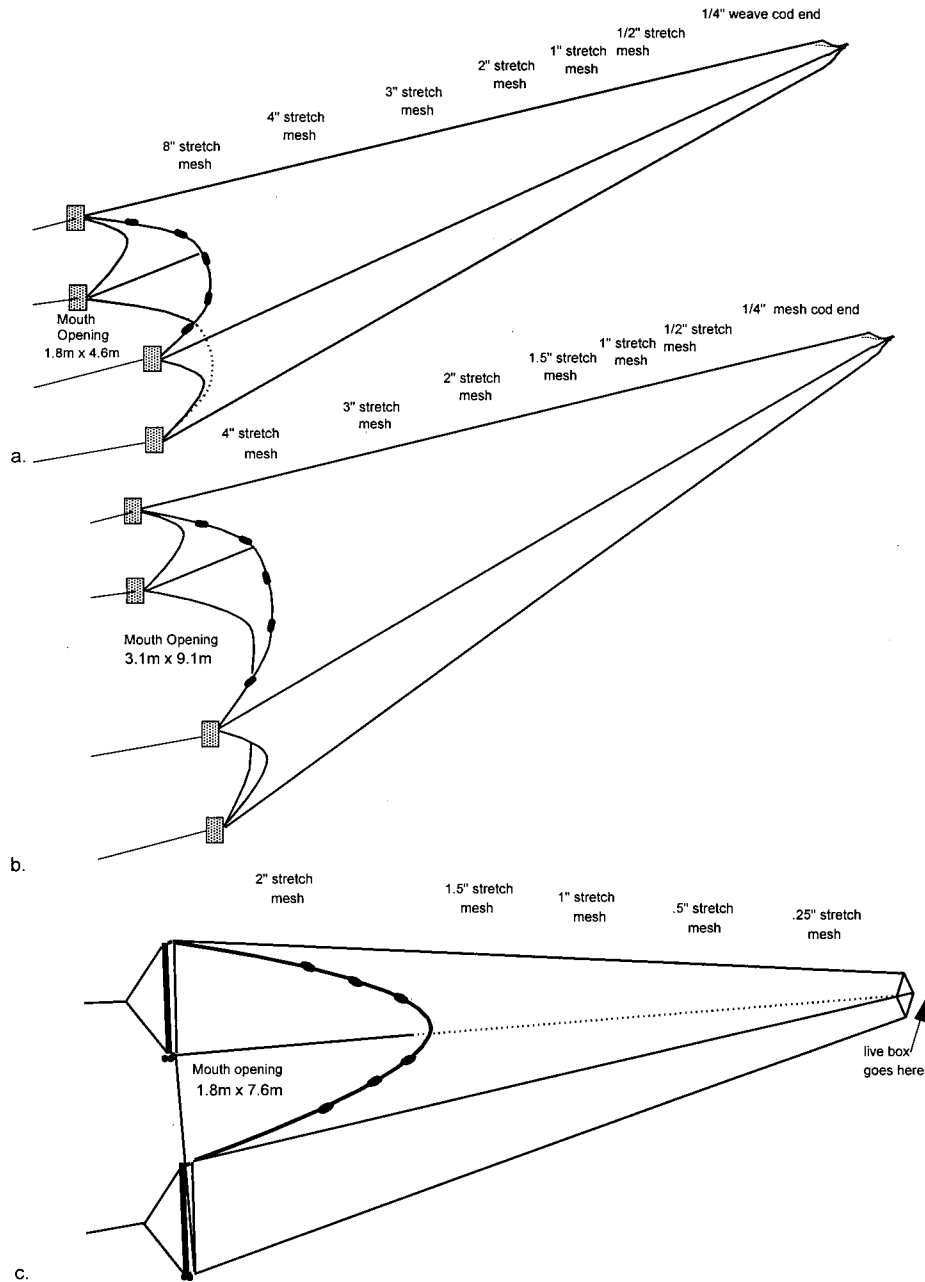


Figure 11 Schematic drawing of (a) midwater trawl net used at Sacramento, (b) midwater trawl net used at Chipps Island and in San Francisco Bay and (c) Kodiak trawl net used at Sacramento

Results and Discussion

The mean midwater trawl C/m^3 (squared) of unmarked smolts, primarily fall run, migrating past Sacramento between April and June was inversely and significantly ($r^2 = 0.88$, $P < 0.01$) related to mean Sacramento River flows in February (Figure 12). If this density measurement is a true index of abundance then it appears fewer smolts migrate into the Delta when flows are higher in the early spring (February).

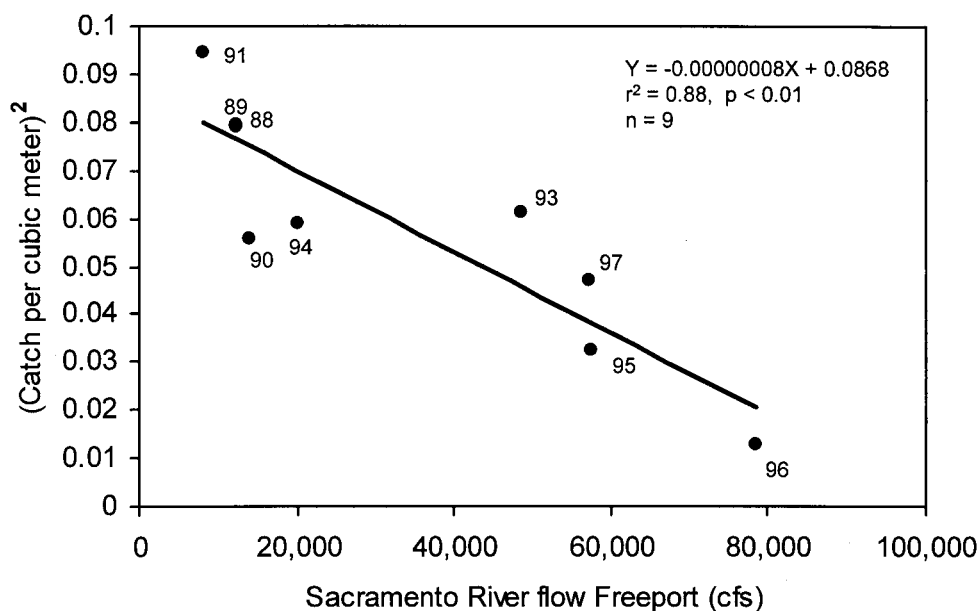


Figure 12 Mean catch of unmarked chinook salmon smolts per cubic meter (squared) in the midwater trawl at Sacramento between April and June of 1989 to 1997 versus mean daily flow (cfs) at Freeport on the Sacramento River during February. Data from 1992 were not included in the model because no sampling was done during April and late June in that year.

Catch of unmarked smolts in the midwater trawl at Chipps Island indicated that overall juvenile salmon production migrating from the Delta was greater in wet years. Mean catch per cubic meter between April and June at Chipps Island was positively correlated to flow at Rio Vista ($r^2 = 0.78$, $P < 0.01$), indicating that, overall, the density of juveniles leaving the Delta increases as flows increase (Figure 13). In addition, since many fry were observed downstream of Chipps Island in high flow years before April, the estimates of the juvenile production migrating past Chipps Island was underestimated in the high flow years. Stevens and Miller (1983) also found significant relationships between inflow and an index of abundance of fall run chinook in the Delta between April through June.

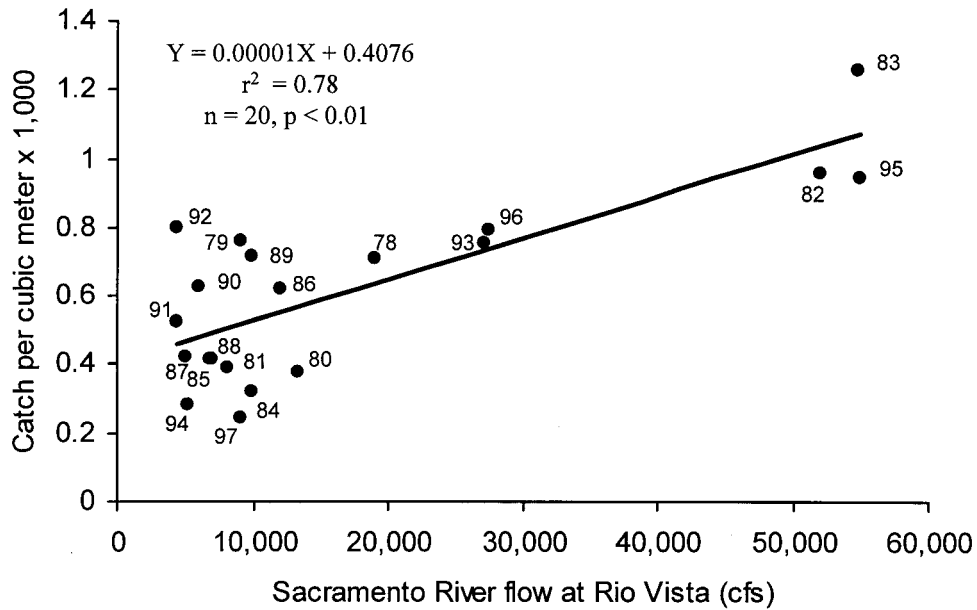


Figure 13 Mean catch of unmarked chinook salmon smolts per cubic meter (x 1,000) in the midwater trawl at Chipps Island between April and June from 1978 through 1997 versus mean daily Sacramento River flow (cfs) at Rio Vista between April and June

Catches at both Sacramento and Chipps Island include fall-run smolts released from Coleman National Fish Hatchery. Therefore, the Chipps Island abundance versus flow relationship incorporates flow effects on these hatchery fish as well as wild smolts. In recent years, about 12 million smolts have been released (Tom Nelson, personal communication, see "Notes"). Most other unmarked hatchery fish in the Central Valley are released downstream of Chipps Island.

Catches at Sacramento and Chipps Island during other months of the year indicated low abundance, until the December-January period when fall run fry enter the catches (Figure 14 and 15). Although, Figures 14 and 15 do not precisely show abundance, they show all unique lengths measured which illustrates this point.

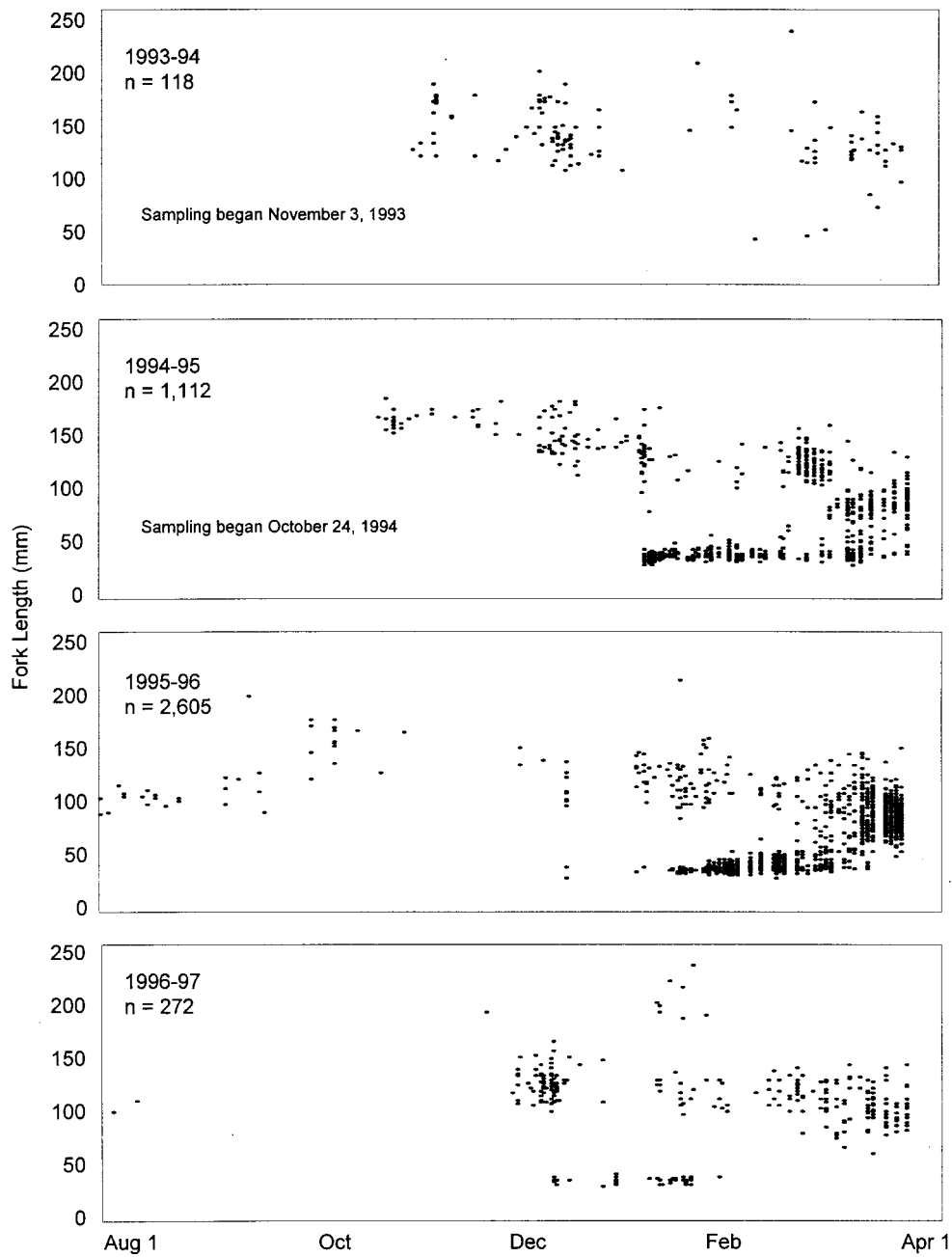


Figure 14 Measured juvenile chinook captured in the midwater trawl at Chipps Island near Pittsburg, California, between August 1 and March 31

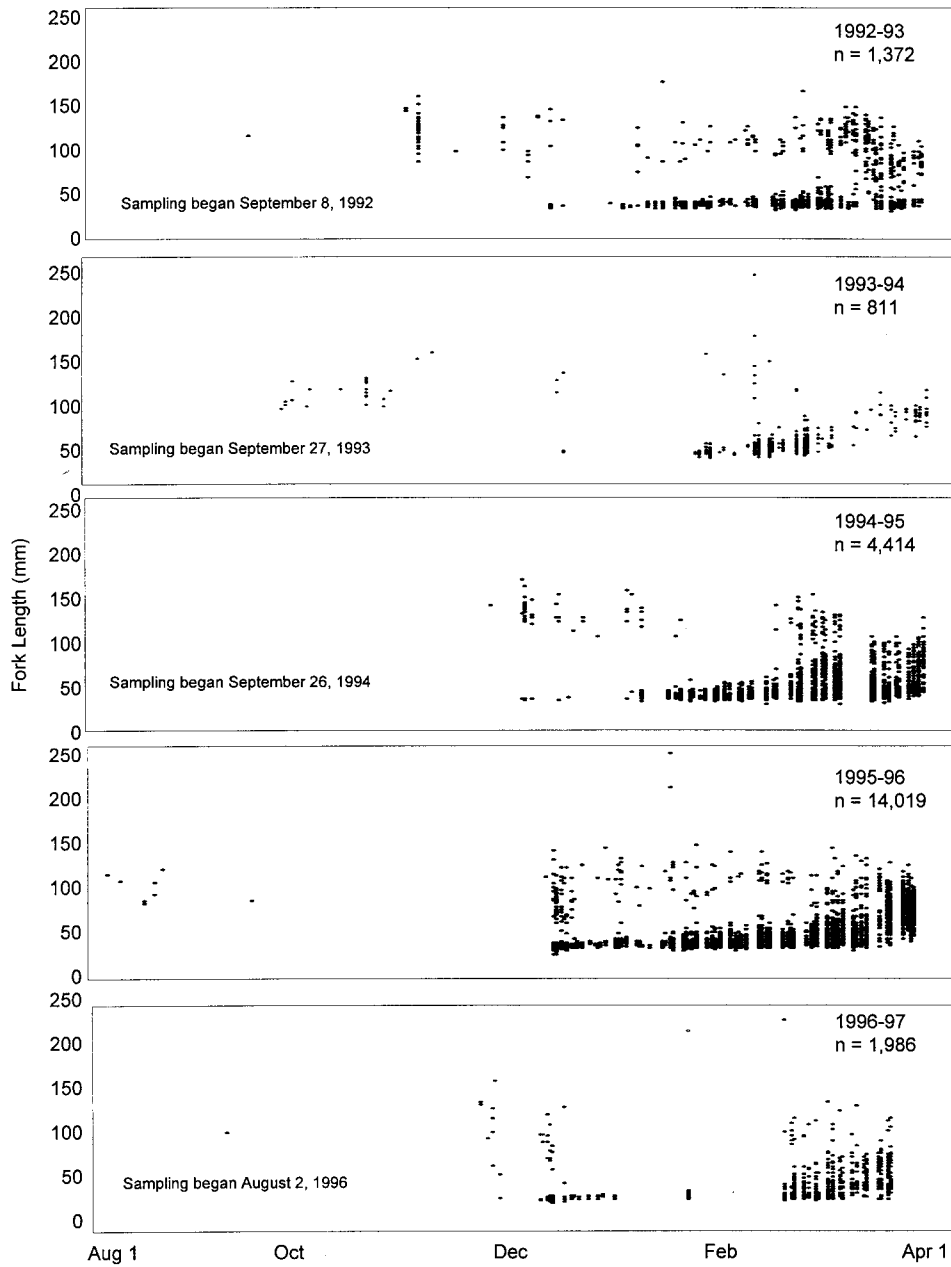


Figure 15 Measured juvenile chinook salmon captured in the midwater trawl and/or Kodiak trawl on the Sacramento River near Sacramento between August 1 and March 31

Fry Survival

Methods

Mark and recapture experiments with fry were conducted between 1980 and 1987 to (1) estimate survival in the upper Sacramento River, Delta and San Francisco Bay, under various river flows and (2) in later years, assess the impacts on survival of using existing Delta channels for water transport. Survival for fish released upstream in the Delta and in the bay was evaluated at various flows because river flows were anticipated to change with the operation of the proposed Peripheral Canal. The effects to juvenile salmon of using existing Delta channels for water transport were evaluated by estimating differential survival of marked fry released at locations in the North, Central and South Delta. Fry releases in the Delta were discontinued in 1988 to increase the number of marked smolts available for release.

Fry were obtained from Coleman National Fish Hatchery (Figure 4), adipose fin-clipped, and tagged in the snout of the fish with coded-wire half tags (CW $\frac{1}{2}$ T). Recoveries of these marked fish were made in the beach seine, at the State and federal fish salvage facilities located at the respective pumping plant intake, and in the ocean fishery.

Ocean recovery rates are relative indices that were used to compare survival between locations within a year. The ocean recovery rate is the expanded number of recoveries in the ocean fishery divided by the number released (Kjelson and Brandes 1989). Catches in the ocean sport and commercial fishery were expanded based on the percentage of sampling conducted at the various ports (PSMFC 1998).

To compare survival between years, an estimate of absolute fry-to-smolt survival was obtained by comparing the recoveries in the ocean fishery of fry released in the Delta (or upstream) to those released at Port Chicago (or Benicia) in Suisun Bay (Kjelson and Brandes 1989). In some cases releases at Ryde were used as the downstream control group. We assume that the ratio between upstream and downstream groups factors out the smolt survival downstream of Suisun Bay from the upstream release group.

Ocean recovery rates for CW $\frac{1}{2}$ T groups released on different days at the same location were averaged before analyses. Groups with different tag codes released at the same location on the same day were considered one group and recoveries were summed and divided by the total number released to represent the group. Two sample and student *t*-tests were used to test for significant differences between treatments at the 95% confidence level.

Results and Discussion

Ocean recovery rates indicated that relative survival was higher for fry released in the upper Sacramento River below Red Bluff Diversion Dam (RBDD) than for fry released in the North Delta, especially in the higher flow years (Figure 16). Those released in the bay had the lowest recovery rates in all years. The upper river release groups were recovered, on average, about five times greater than those released in the Delta in wetter years of 1980, 1982, and 1986 (Figure 16). We have defined the wetter years as those with mean February flows at "I" Street greater than 50,000 cfs. Although a dry year, 1987 also exhibited much greater survival upstream than in the Delta.

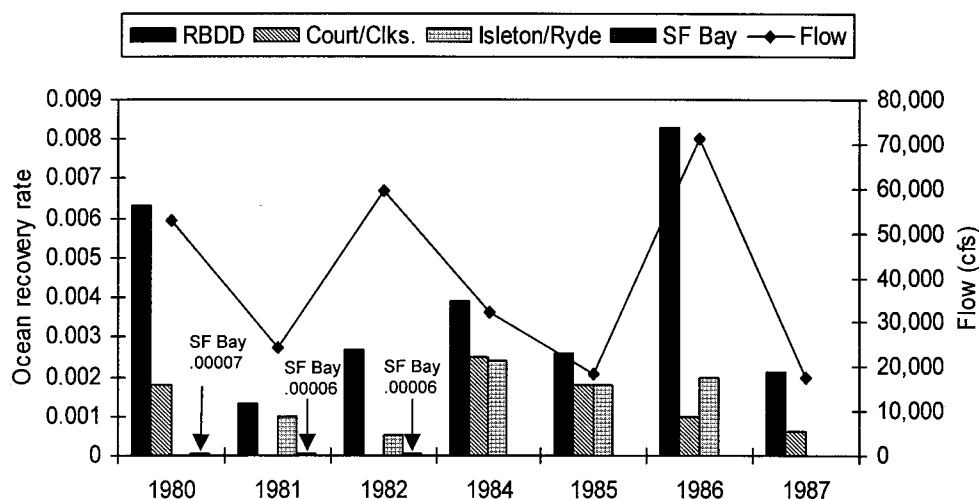


Figure 16 Ocean recovery rates of CW $\frac{1}{2}$ T fry released in the upper Sacramento River below Red Bluff Diversion Dam (RBDD), in the Delta at Courtland or Clarksburg and Isleton or Ryde, and mean daily Sacramento River flow at "I" Street in February

Estimates of absolute survival provide additional support for the conclusion that survival is higher for upstream releases in the wet years. Absolute survivals of the RBDD release groups were significantly higher than the Delta release groups in wet years (two sample *t*-test, $t = 8.28$, $n = 3$, $P = 0.014$) (Table 1). In the drier years there was not a significant difference between fry released upstream and the Delta.

Table 1 Survival estimates for CW $\frac{1}{2}$ T fry released below Red Bluff Diversion Dam in the Delta, mean daily Sacramento River flow at "I" Street during the month of February, and ocean recovery rates for smolts released at Port Chicago, Benicia or Ryde^a

| Year | Release location | | | Port Chicago, Benicia, or Ryde | Mean daily Sacramento River flow at "I" Street (cfs) |
|------|-------------------------|-------------------------|-----------------|--------------------------------|--|
| | Red Bluff Diversion Dam | Courtland or Clarksburg | Isleton or Ryde | | |
| 1980 | 0.29 | 0.08 | | 0.022 ^b | 52,576 |
| 1981 | 0.05 | | 0.04 | 0.028 ^b | 24,239 |
| 1982 | 0.39 | | 0.07 | 0.009 | 59,432 |
| 1984 | 0.51 | 0.33 | 0.32 | 0.008 ^b | 32,949 |
| 1985 | 0.26 | 0.19 | 0.18 | 0.010 ^b | 18,376 |
| 1986 | 0.29 | 0.03 | 0.07 | 0.029 ^b | 69,306 |
| 1987 | 0.10 | 0.03 | | 0.020 ^b | 17,404 |

^a A Ryde release was used in 1987 because there were no groups released at Port Chicago or Benicia that year.

^b Indicates Feather River Hatchery stock was used for the release. For all other releases, Coleman National Fish Hatchery stocks were used.

The observed wet year differences could be a result of increased survival of upstream fish or decreased survival in the Delta. The fact that Delta survival was not lower in wet years suggests that the trends are due to improved survival upstream. One hypothesis is that increased flows provide additional rearing habitat in the upper Sacramento River since there are large areas of floodplain (e.g. the Sutter and Yolo bypasses) that become accessible. Such habitat is not present along the Delta levees. Another explanation could be that some proportion of those released in the Delta moved downstream into the bay in the high flow years where observed survival was extremely poor making comparisons between those released in the Delta and those released upstream more difficult. Those released upstream also could have moved downstream into the Delta in the high flow years. Review of the recoveries by location in the beach seine survey indicated that some of those released upstream below Red Bluff Diversion Dam were recovered in the Delta soon afterwards, but recoveries were made in both dry and wet years (Table 2).

Table 2 CW^{1/2}T fry released in the Delta and upper Sacramento River below Red Bluff Diversion Dam (Below RBDD) and recovered as fry (<70 mm) downstream of the Delta (Bay) and in the Delta, respectively, between 1980 and 1982^a

| <i>Release site and date</i> | <i>Recapture site (Delta or Bay)</i> | <i>Recapture date</i> |
|------------------------------|--|-----------------------|
| Clarksburg (Delta) | | |
| 26 Feb 1980 | Crockett Marina (near Benicia) (Bay) | 03 Mar 1980 |
| 07 Mar 1980 | Montezuma Slough (Bay) | 11 Mar 1980 |
| Below RBDD | | |
| 12 Mar 1980 | American River (near Sacramento) (Delta) | 25 Mar 1980 |
| | Brannon Island (near Rio Vista) (Delta) | 02 Apr 1980 |
| Isleton (Delta) | | |
| 12 Feb 1981 | Montezuma Slough (2) | 17 Feb 1981 |
| | Montezuma Slough (2) | 04 Mar 1981 |
| 04 Mar 1981 | Montezuma Slough | 17 Mar 1981 |
| Below RBDD | | |
| 06 Feb 1981 | Steamboat Slough (Delta) | 12 Feb 1981 |
| | Isleton (Delta) | 26 Feb 1981 |
| | Montezuma Slough (2) | 04 Mar 1981 |
| Isleton (Delta) | | |
| 02 Mar 1982 | Antioch (near Chipps Island) (Bay) | 30 Mar 1982 |
| Below RBDD | | |
| 05 Feb 1982 | Discovery Park (near Sacramento) (Delta) | 09 Mar 1982 |
| 25 Feb 1982 | Ryde (Delta) | 09 Mar 1982 |
| | Discovery Park | 16 Mar 1982 |
| | Discovery Park | 30 Mar 1982 |

^a No recoveries of fry released in the Delta or in the upper Sacramento River were made downstream of the Delta or in the Delta, respectively, between 1983 and 1987.

To evaluate growth as a potential mechanism for the higher survival observed upstream in these high flow years, we looked at growth rates of the CW^{1/2}T fish released and recovered upstream and in the Delta in 1982, a high flow year. We did not find significant differences in growth between the two areas (using a student *t*-test to compare the slopes of the two lines) (Figure 17).

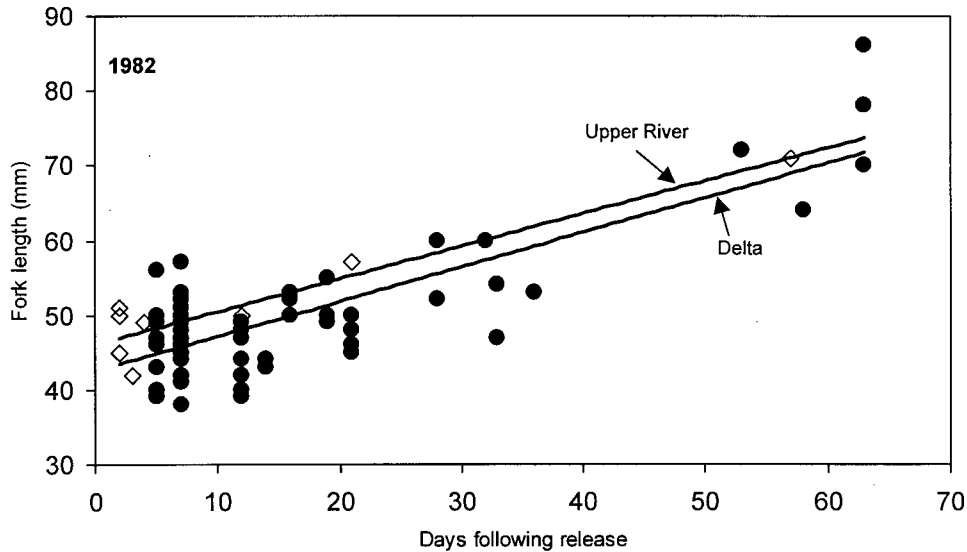


Figure 17 Growth curves for CW½T fry released and recaptured in the Delta (circles) and the upper Sacramento River (diamonds), between February 7 and April 28, 1982

Results, from additional CW½T fry released at various locations in the Delta between 1981 and 1985, indicated that in drier years survival was higher in the North Delta than in the Central Delta. Although not statistically significant, the ocean recovery rates were somewhat higher from CW½T fry released in the North Delta (Courtland, Ryde, or Isleton), relative to those released in Central Delta (at the mouth of Mokelumne River and in the North and South Forks of the Mokelumne) in the drier years (Figure 18). In the wetter years of 1982 and 1983, those released in the Central and South Delta (the mouth of the Mokelumne River) appeared to survive at a similar rate as those released at Isleton (Figure 18). The lower Old River release even seemed to survive at a relatively high rate in 1983 (Figure 18). One mechanism for the lower survival of fry released in the Central Delta in dry years could be the greater effect of the pumping plants on hydrology in these years. In dry years (1981, 1984, 1985, and 1987), CW½T fry were recovered at the fish facilities, whereas in the wetter years they were not (1980, 1982, 1983 and 1986) (Appendix A).

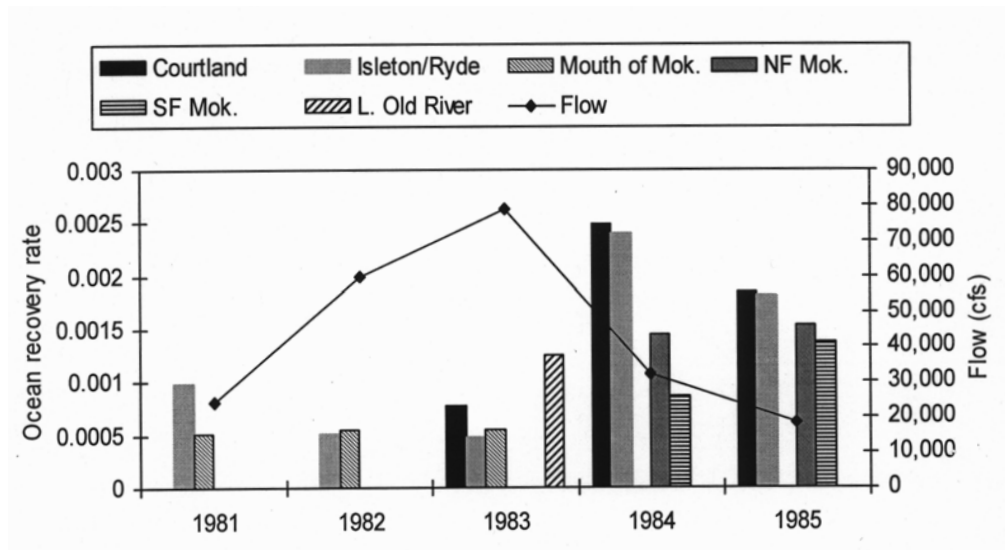


Figure 18 Ocean recovery rates for CW½T fry released at various locations in the Delta and mean daily Sacramento River flow at "I" Street in February

Smolt Survival

Methods

Mark and recapture studies also were conducted with fall run smolts starting in 1969. Survival through the Delta for smolts released near Sacramento was estimated between 1969 and 1971, 1976 and 1977, and 1978 and 1982 to document the importance of freshwater inflow on the survival of juvenile salmon migrating through the estuary (DFG 1976; Kjelson and others 1981, 1982). In 1983, the program was expanded to also examine the differential vulnerability to water project operations of marked smolts released at four locations in the Delta. These experiments were also used to evaluate the effect of movement into the Central Delta via the Delta Cross Channel and Georgiana Slough on the survival of juvenile salmon in the Delta. To separate the effects of flow from diversion into the Central Delta, experiments were conducted between 1987 and 1989 during low flows with the Delta Cross Channel gates open and/or closed. Prior to 1987, closure of the Delta Cross Channel gates only occurred in wet years. Between 1992 and 1997, survival was evaluated for fall-run smolts and late-fall-run yearlings released into Georgiana Slough in the Central Delta relative to those released on the mainstem Sacramento River. Late-fall-run yearlings were used as surrogates for winter-run juveniles to estimate the effects of diversion into the Central Delta on winter-run salmon.

Mark and recapture methodology also was used to evaluate survival in the San Joaquin Delta starting in 1985. Between 1985 and 1990, marked fish releases were made to evaluate the differential survival of smolts migrating through upper Old River relative to those continuing to migrate down the mainstem San Joaquin River. In 1992, 1994, and 1997, a temporary rock barrier was installed in upper Old River and marked smolts were released to determine if survival through the South Delta was increased with the barrier in place. In 1997, the rock barrier was changed to include two 48-inch culverts. In 1993, 1995, and 1996, the barrier was not installed because of high flows or lack of a permit, although survival through the South Delta was measured for comparison purposes. In addition, releases also were made in 1995 and 1996 to estimate the mortality associated with migration through upper Old River. Paired releases with smolts from both Feather River Hatchery and Merced River Fish Facility were made in 1996 and 1997 to address concerns that stock origin of the experimental fish had confounded previous results. In addition, physiological studies were conducted and subsets of fish were held in live cars to determine the potential cause of mortality or mortality differences between stocks if they were found. The role of exports was explored in 1989, 1990 and 1991 when releases were made at high, medium, and low exports.

Additional marked fish releases were made in the bay and upstream of the Delta. Survival through the bay was estimated to help develop outflow criteria to meet the needs of juvenile salmon migrating through San Pablo and San Francisco bays. Survival of smolts released from Coleman National Fish Hatchery into Battle Creek, at Merced River Fish Facility, and from the Feather River Hatchery released at the Feather River (Figure 4) has been measured in many years and provides an index of the survival of smolts migrating through the rivers and Delta.

For smolt and yearling mark and recapture experiments, hatchery fish were spray-dyed or fin-clipped and tagged with full sized coded-wire tags (CWT). Fall-run smolts used in the Delta experiments were obtained from Feather River Hatchery (FRH). Late-fall-run yearlings were obtained from Coleman National Fish Hatchery (CNFH). Hatchery smolts used in the San Joaquin Delta experiments originated from the Merced River Fish Facility (MRFF) between 1985 and 1987 and from the FRH between 1990 and 1995. In 1989, 1996, and 1997, both MRFF and FRH stocks were used. Smolts released at Jersey Point between 1989 and 1991, and 1994 and 1997 originated from FRH. In 1996 and 1997 releases also were made at Jersey Point with smolts from MRFF. Two groups of smolts released at Port Chicago and in San Francisco Bay in 1984 were from Nimbus Fish Hatchery. The location of the hatcheries is shown in Figure 4.

Water temperatures were measured in the transport truck (both at the hatchery and at the release site) and in the receiving water.

Recoveries of marked smolts and yearlings were made in the midwater trawl at Chipps Island, at the CVP and SWP fish salvage facilities, and as adults in the ocean fishery. (This report does not discuss inland adult recoveries.) Recoveries at the fish salvage facilities provided insight into the direct mortality of juvenile salmon within the Delta.

Sampling at the State and federal facilities generally occurred at ten-minute intervals every two hours, 24 hours per day, although the sampling protocol before 1985 was not as thorough or systematic. Marked salmon observed in the sampling were kept for tag recovery and were called unexpanded recoveries. To estimate the total number of marked salmon salvaged at the facilities (expanded salvage) those recovered in the sample are expanded by fraction of time sampled. (It should be noted that expanded salvage is not "loss." Loss would include mortality associated with pre-screen and screen efficiency losses.)

Relative and absolute survival were estimated using recoveries made at Chipps Island and in the ocean fishery. Survival indices to Chipps Island (relative survival) were estimated by dividing the number of fish recovered from each particular tag group by the number released, corrected for the fraction of time and channel width sampled using the midwater trawl at Chipps Island (Kjelson and Brandes 1989). Relative survival also was estimated using the recovery rate of marked fish as adults in the ocean fishery and was used to compare survival between locations within a year. Survival estimates (absolute survival) were obtained using the differential recovery rate of an upstream group relative to a downstream group, either at Chipps Island or in the ocean fishery and used to compare survival between years. This approach has the advantage of reducing variation due to differential gear or sampling efficiency between years. We have termed this absolute survival or a survival estimate, but it is more appropriately described as a standardized estimate of survival between two locations. The Chipps Island absolute survival estimates have the additional advantage of not incorporating the variability due to ocean residence and having the information available within months instead of years of release.

Several pieces of evidence indicate that our survival indices of hatchery fish do not have substantial bias. First, we show that smolt survival indices at Chipps Island were generally supported by similar trends of survival estimates using the ratio of ocean recovery rates. In addition, while recoveries at Chipps Island were relatively small, they seemed generally similar between separate tag codes from the same group (Appendix B). While these multiple tag codes within a group provided some assessment of the recapture variability both at Chipps Island and in the ocean fishery, true measurement of the variability in survival is not possible given the limits of releasing independent replicates each year. In addition, although in many years, especially on the San Joaquin River, survival is so low that determining true differences is prob-

lematic, we were able to detect large differences in survival between release locations, years and river basins.

Paired sample *t*-tests were used to test for significant differences with 95% confidence levels between survival indices of smolts released upstream and downstream of the Delta Cross Channel and Georgiana Slough with the cross channel gates open and closed. Simple linear regression analysis was used to explore the relationship between Georgiana Slough survival estimates and combined CVP and SWP exports. Regression analysis also was used to determine the relationship between survival estimates for smolts released at Dos Reis and river flow at Stockton.

Results and Discussion

Sacramento

Role of Flow, Temperature and Diversion into the Central Delta on Survival. Kjelson and others (1982) reported a relationship between estimated CWT salmon survival rates and river flow, which suggested that river flows influenced juvenile salmon survival during downstream migration through the Delta. In 1982, they reported that survival (based on adult recoveries in the ocean fishery) in the Delta appeared to be influenced by water temperature and/or river flow rate: smolt survival decreased as flow rates decreased and temperatures increased. For trawl recovery data, smolt survival was related to water temperature only during June (Kjelson and others 1982). Almost total mortality was observed using both methodologies in 1978 and 1981 when temperatures were about 23° C (Kjelson and others 1982).

Data gathered between 1982 and 1987, using marked smolts released near Sacramento, further supported these relationships. In presenting the "State Water Resources Control Board with the Needs of Chinook Salmon, *Oncorhynchus tshawytscha* in the Sacramento-San Joaquin Estuary," USFWS (1987) shared relationships of survival with flow and survival with temperature using both the trawl and ocean indices of Delta survival. Maximum survival was reached with calculated flows between 20,000 to 30,000 cfs at Rio Vista and with temperatures less than 17° C. It also was shown that survival of smolts released in the North Delta (Sacramento or Courtland) using differential ocean recovery rates was correlated with the percentage of water diverted into the Central Delta from the Sacramento River at Walnut Grove (USFWS 1987). Determining which factor was most important to the survival of juvenile salmon was not possible because water temperatures and the percentage of water diverted into the Central Delta were higher in dry years. Prior to 1987 the Delta Cross Channel gates were only closed when flows in the Sacramento River at Freeport were greater than about 25,000 cfs.

Data collected between 1987 and 1989, combined with the data collected in earlier years, showed that smolts released on the Sacramento River, upstream of the entrances to the Delta Cross Channel and Georgiana Slough (Courtland), survived at a significantly lower rate than those released downstream (Isleton or Ryde), with the cross channel gates open (paired *t*-test, $t = 4.11$, $n = 9$, $P = 0.003$) (Figure 19). The results of these studies indicated that smolts were diverted into the Central Delta via the Delta Cross Channel and Georgiana Slough and entering the interior Delta decreased their survival. In addition, the data also showed that survival was significantly less for smolts released upstream relative to those released downstream, when the Delta Cross Channel gates were closed (paired *t*-test, $t = 10.75$, $n = 4$, $P = 0.002$) (Figure 19), indicating that diversion into Georgiana Slough also negatively affects survival. Smolt survival information obtained from the ocean fishery showed generally the same trends but was more variable and not statistically significant (Figure 20).

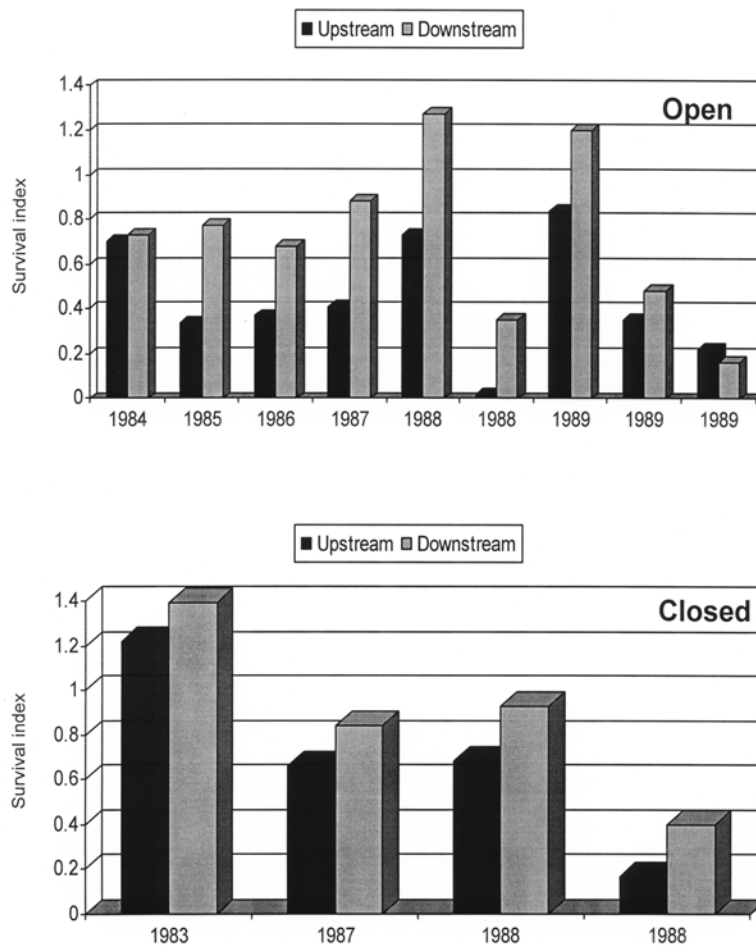


Figure 19 Survival indices of CWT fall run smolts released in the Sacramento River upstream (Courtland) and downstream (Ryde) of the Delta Cross Channel and Georgiana Slough with the gates open and closed

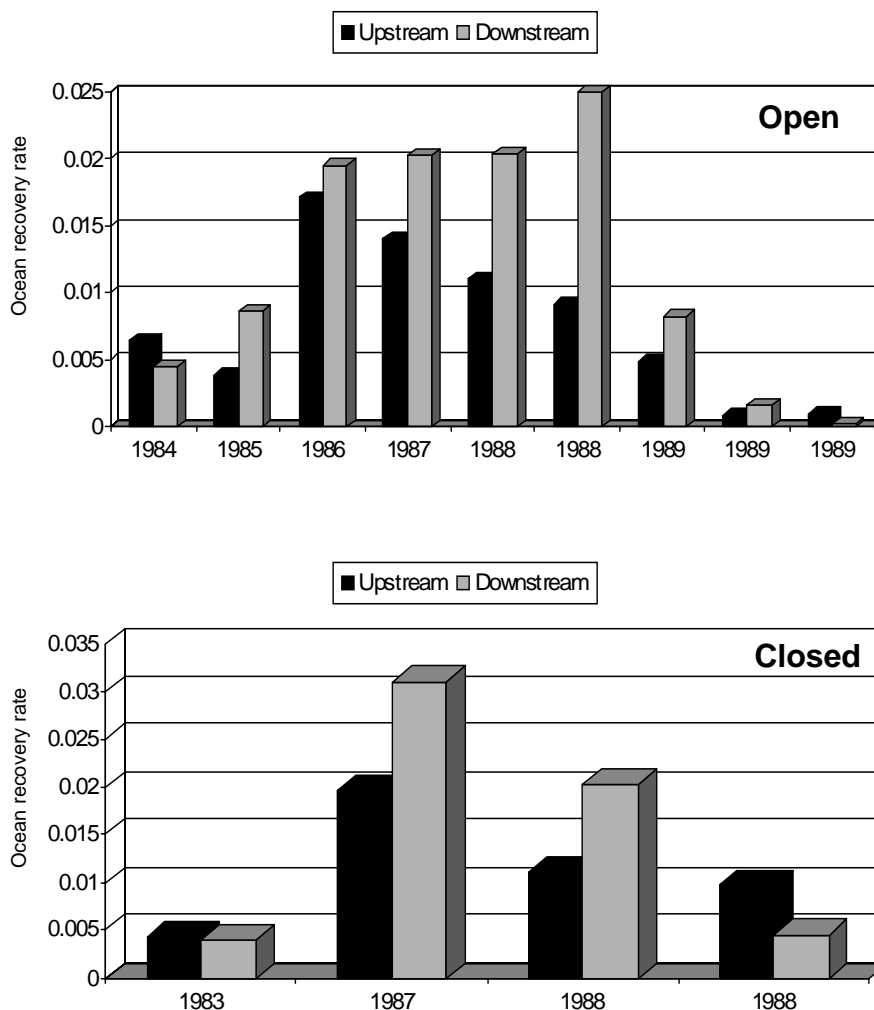


Figure 20 Recovery rates in the ocean fishery for CWT smolts released in the Sacramento River upstream (Courtland) and downstream (Ryde) of the Delta Cross Channel with the gates open and closed

The hypothesis that diversion into the Central Delta reduces juvenile salmon survival is further supported by the results of coded wire tagged, fall-run groups released into Georgiana Slough and in the main-stem Sacramento River at Ryde. The smolt survival indices and ocean recovery rates obtained from the two release locations indicated that fall run smolts survived at a significantly higher rate when released at Ryde rather than into Georgiana Slough) (Figure 21). (Paired t-tests were done for smolt survival indices ($t = 3.14, n = 7, P = 0.019$) and ocean recovery rates ($t = 4.19, n = 7, P = 0.005$).

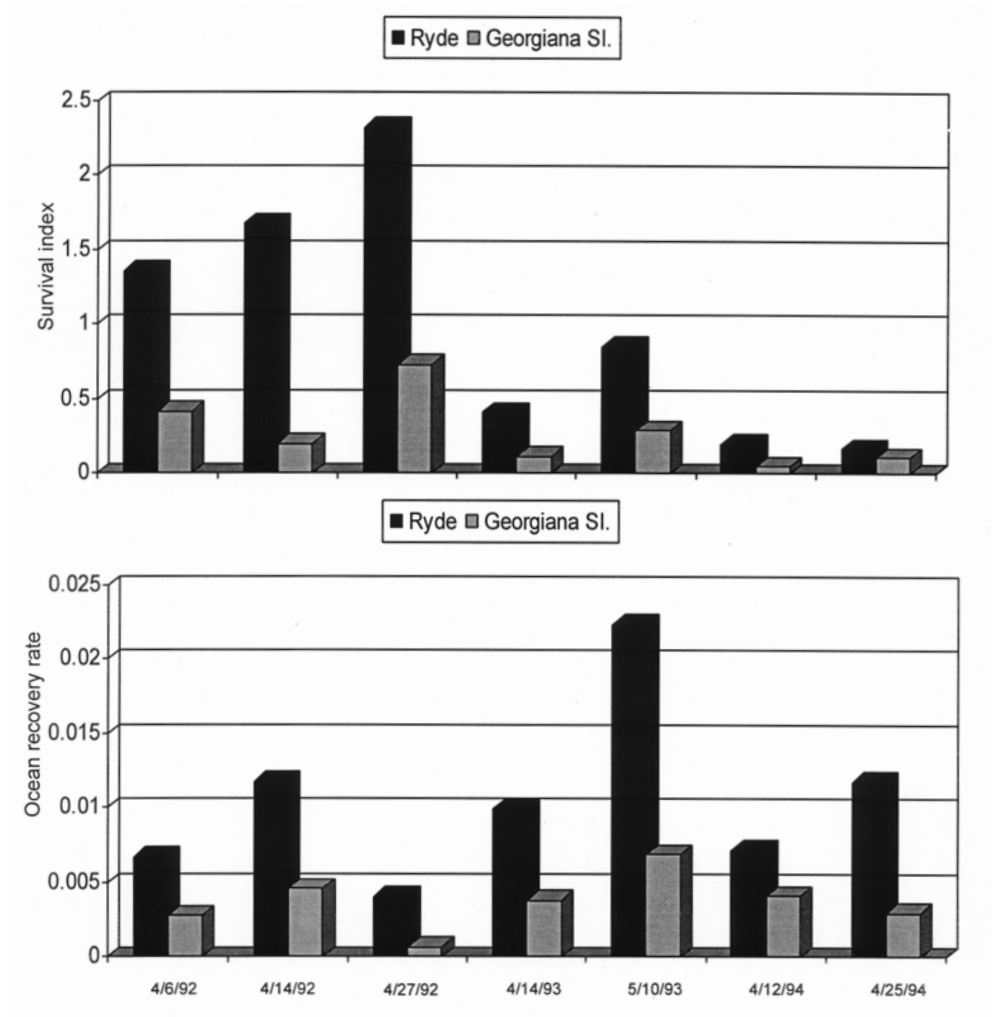


Figure 21 Survival indices to Chipps Island and ocean recovery rates for CWT fall-run smolts released at Ryde and in Georgiana Slough between 1992 and 1994

Between 1993 and 1998, studies using late-fall run juveniles were conducted to determine if survival also was higher for CWT late-fall yearlings released at Ryde than for those released into Georgiana Slough. Late-fall are larger and migrate through the Delta during the winter months when water temperatures are cooler. Despite the cooler temperatures and larger size of the fish relative to fall run smolts, the results with late-fall yearlings were similar to those obtained with fall run smolts. Results indicated that the survival indices to Chipps Island and ocean recovery rates were significantly greater for fish released at Ryde than for those released into Georgiana Slough (Figure 22). Paired *t*-tests were done for smolt survival indices ($t = 3.60, n = 6, P = 0.015$) and ocean recovery rates ($t = 3.16, n = 4, P = 0.050$). Although the ratios

between the groups released at Ryde versus those released into Georgiana Slough were similar for the fall and late-fall experiments, it is likely that true survival was less for the fall run groups which were smaller at release and experienced higher water temperatures. These data infer that once fish are diverted into the Central Delta via Georgiana Slough, high relative mortality occurs even for winter run juveniles migrating through the Delta in the late fall and winter months—a period when environmental conditions should be less stressful.

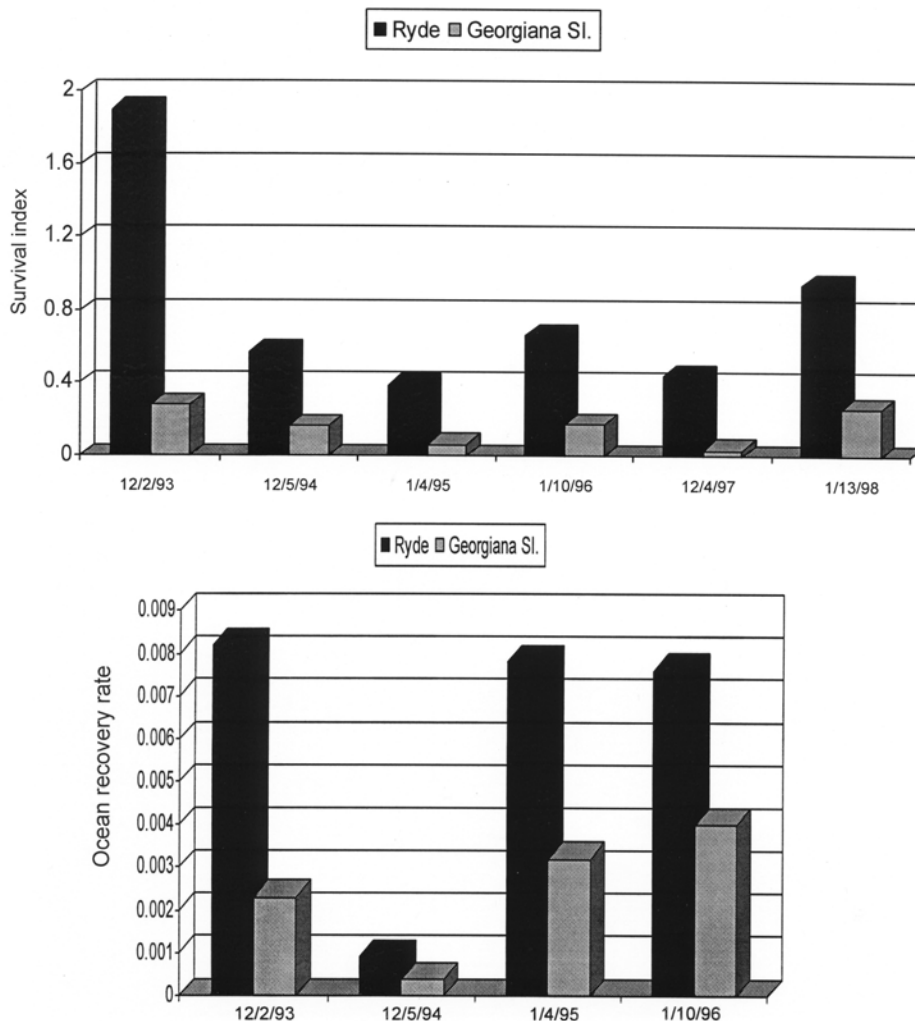


Figure 22 Survival indices to Chipps Island and ocean recovery rates for CWT late-fall-run juveniles released at Ryde/Isleton and in Georgiana Slough

Results from survival studies conducted to determine the relative vulnerability of juvenile salmon to project exports seem consistent with our hypothesis that diversion into the Central Delta is detrimental for juvenile salmon. Coded wire tagged smolts released in the North Delta (at Isleton or Ryde) appeared to have survived at higher rate than those released in the Central or South Delta (at the mouth, North and South Forks of the Mokelumne River and Lower Old River) in the drier years of 1985 and 1986 (Figure 23). This result is similar to that observed with fry released in the Central Delta relative to those released in the North Delta in the drier years.

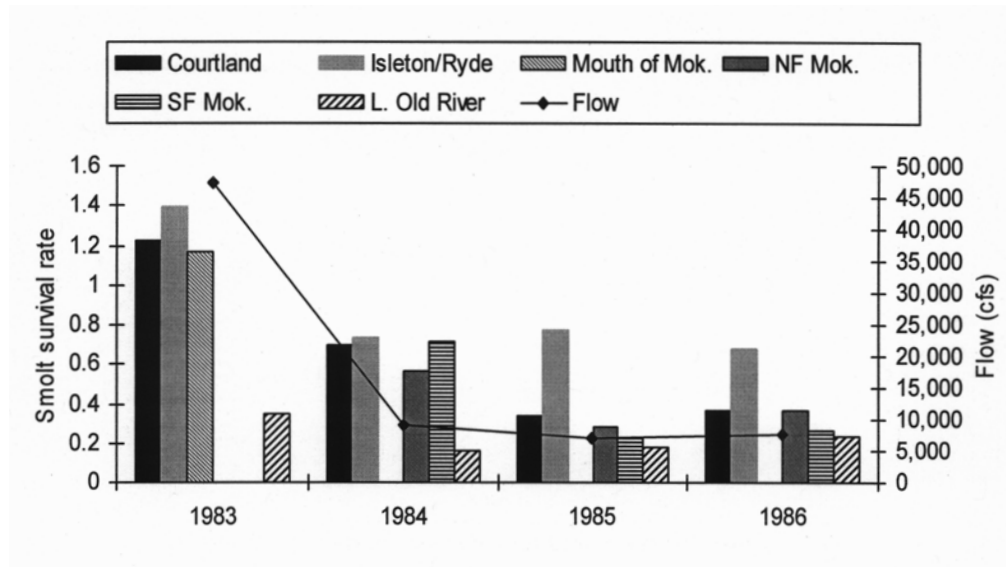


Figure 23 Survival indices of CWT smolts released at various sites in the Delta and mean Sacramento River flow (cfs) at Rio Vista. Flow at Rio Vista was the average during the recovery period of the Courtland releases at Chipps Island.

Although, we have found that diversion into the Central Delta increases juvenile salmon mortality, we have not been able to clearly separate the effects of flow and temperature from diversion impacts. The fact that relative mortality in the Central Delta appears to increase in the drier years, would indicate that there are combined effects. Two separate and independent models constructed using these coded wire tag data have found that temperature is likely the most important factor to fall run smolt survival in the Delta (Newman and Rice 1997; Kjelson and others 1989). Diversion into the central Delta via the Delta Cross Channel gates was also considered important in these models. Sacramento River flow was considered important in the Newman and Rice model (Newman and Rice 1997), but so was salinity (which was inversely correlated to Sacramento River flow) making interpretation difficult. In the Kjelson and others (1989) model Sacramento River flow was tied to the percent of water diverted into the Central Delta.

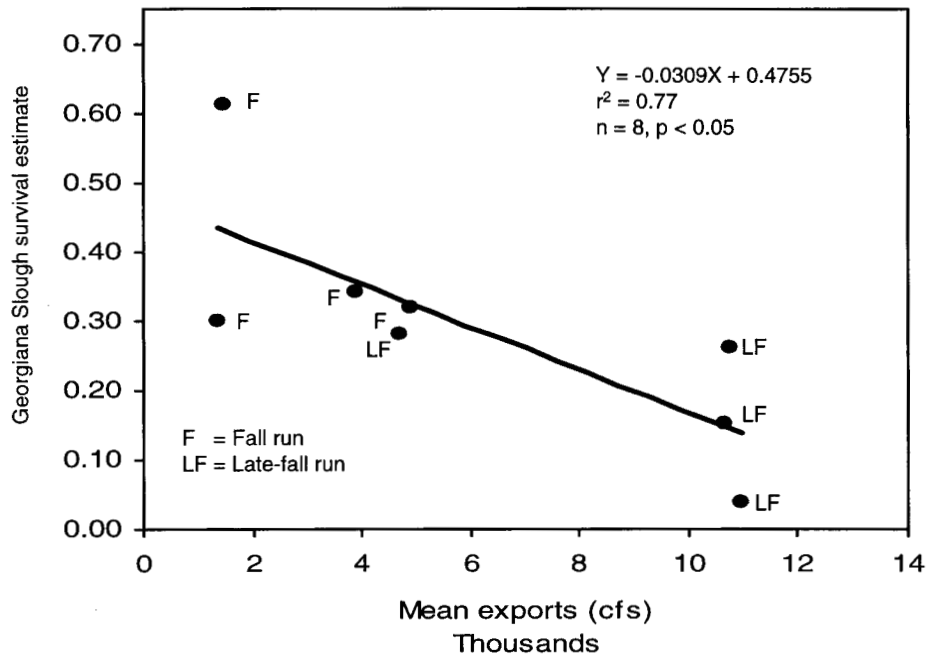


Figure 24 Estimate of survival to Chipps Island for CWT fall-run smolts and late-fall-run yearlings released into Georgiana Slough relative to those released at Ryde with the cross channel gates closed versus combined CVP+SWP exports from release date to 14 days later (fall run) or 17 days later (late-fall run).

Why survival in the Central Delta is lower than that on the main-stem Sacramento River has been hypothesized to be related to the amount of net lower San Joaquin river flow (QWEST), exports or just the longer route to the western Delta of smolts migrating through the central Delta. The survival index to Chipps Island, of fall run smolts and late-fall run yearlings released into Georgiana Slough, does not appear to be related to QWEST. However, the estimate of survival of the Georgiana Slough groups relative to the Ryde groups, for both the fall and late-fall run groups released when the cross channel gates were closed, may be related to exports, although there were large outliers in the relationship which transforming failed to resolve (Figure 24) ($r^2 = 0.77, P < 0.05$). A longer route through the Delta would expose the fish to various mortality factors for a longer period of time. However, the difference in distance, assuming the most direct routes for both groups, is only 37% greater for the Georgiana Slough group (White 1998). The Ryde groups survived between 1.5 and 22 times that observed for the Georgiana Slough groups (Table 3). Differences of between 2 and 7 times are observed in the ocean recovery rate data but some of the most recent releases have not yet been recovered in the ocean fishery (Table 4). These data would infer that the increased distance alone would not account for the differences in survival between the two groups, and exports may contribute, at least in part, to the observed differences.

Table 3 Survival indices to Chipps Island for fall-run smolts and late-fall-run yearlings released at Ryde and Georgiana Slough between 1992 and 1998 and the ratio of survival between the two paired groups

| <i>Date</i> | <i>Ryde</i> | <i>Georgiana Slough</i> | <i>Ryde:Georgiana Slough ratio</i> |
|--|-------------------|-------------------------|------------------------------------|
| Fall run | | | |
| 06 Apr 1992 | 1.36 | 0.41 | 3.3 |
| 14 Apr 1992 | 2.15 ^a | 0.71 | 3.0 |
| 27 Apr 1992 | 1.67 | 0.20 | 8.4 |
| 14 Apr 1993 | 0.41 | 0.13 | 3.2 |
| 10 May 1993 | 0.86 | 0.29 | 3.0 |
| 12 Apr 1994 | 0.20 | 0.05 | 3.7 |
| 25 Apr 1994 | 0.18 | 0.12 | 1.5 |
| Mean | | | 3.7 |
| Late-fall run | | | |
| 02 Dec 1993 | 1.91 | 0.28 | 6.8 |
| 05 Dec 1994 | 0.58 | 0.16 | 3.6 |
| 04 Jan 1995 | 0.39 | 0.06 | 6.5 |
| 10 Jan 1996 | 0.66 | 0.17 | 3.9 |
| 04 Dec 1997 | 0.67 | 0.03 | 22.3 |
| 13 Jan 1998 | 0.94 | 0.26 | 3.6 |
| Mean | | | 7.8 |
| ^a The survival index and ocean recovery rate for the 1992 release made at Ryde has been corrected to account for 10,500 marked fish inadvertently released at Georgiana Slough instead of Ryde. | | | |

Table 4 Ocean recovery rates for fall-run and late-fall-run yearlings released at Ryde and Georgiana Slough between 1992 and 1996 and the ratio of survival between the two paired groups

| <i>Date</i> | <i>Ryde</i> | <i>Georgiana Slough</i> | <i>Ryde:Georgiana Slough ratio</i> |
|---|---------------------|-------------------------|------------------------------------|
| Fall run | | | |
| 06 Apr 1992 | 0.0067 | 0.0028 | 2.4 |
| 14 Apr 1992 | 0.0107 ^a | 0.0046 | 2.3 ^a |
| 27 Apr 1992 | 0.0041 | 0.0006 | 6.8 |
| 14 Apr 1993 | 0.0099 | 0.0039 | 2.5 |
| 10 May 1993 | 0.0224 | 0.0069 | 3.2 |
| 12 Apr 1994 | 0.0074 | 0.0042 | 1.8 |
| 25 Apr 1994 | 0.0118 | 0.0030 | 3.9 |
| Mean | | | 3.3 |
| Late-fall run | | | |
| 02 Dec 1993 | 0.0082 ^b | 0.0023 | 3.6 |
| 05 Dec 1994 | 0.0009 | 0.0004 | 2.3 |
| 04 Jan 1995 | 0.0078 | 0.0033 | 2.4 |
| 10 Jan 1996 | 0.0076 | 0.0040 | 1.9 |
| Mean | | | 2.6 |
| ^a The survival index and ocean recovery rate for the 1992 release made at Ryde has been corrected to account for 10,500 marked fish inadvertently released at Georgiana Slough instead of Ryde. ^b Actual release made at Isleton, about five miles downstream of Ryde. | | | |

San Joaquin

Impacts of Migration Through Upper Old River and the Use of a Barrier in Upper Old River. Studies using marked fish released into upper Old River and on the San Joaquin River at Dos Reis found that smolts survived at a higher rate if they migrated to Chipps Island via the main-stem San Joaquin River instead of through upper Old River. Inter-annual survival rates at these two locations were highly variable and a significant difference was not found. Although not statistically significant, the survival difference is shown using both survival indices to Chipps Island and ocean recovery rates (Figure 25), suggesting that any wild smolts diverted into upper Old River have greater mortality than those migrating down the main-stem San Joaquin River.

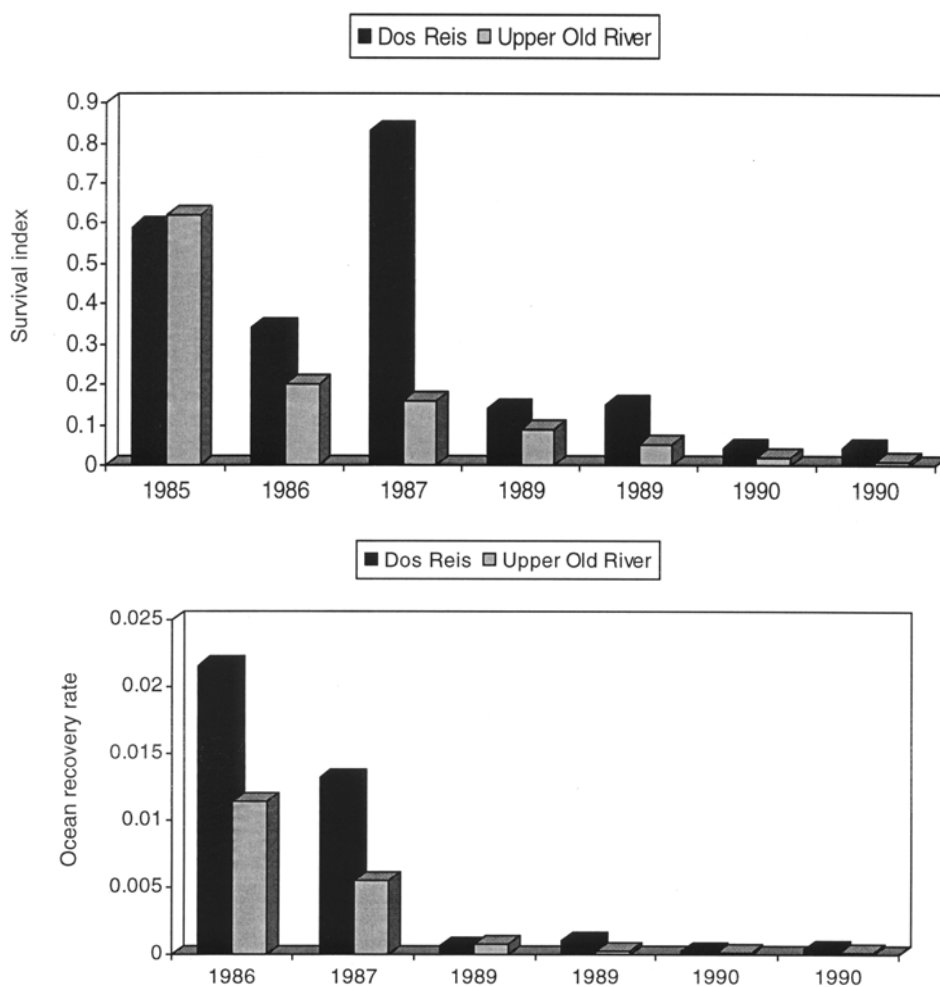


Figure 25 Smolt survival indices and ocean recovery rates of smolts released at Dos Reis on the mainstem San Joaquin River and into upper Old River. Ocean recovery rates are not available for spray-dyed smolts released in 1985.

Table 5 Results of studies comparing survival indices of Feather River Hatchery CWT juvenile chinook salmon from Mossdale to Chipps Island before and after the barrier at Old River was constructed in 1992

| <i>Date</i> | <i>Water temperature (°F)</i> | <i>Survival</i> |
|--------------------------------|-------------------------------|-----------------|
| Before barrier was constructed | | |
| 07 April 1992 | 64 | 0.17 |
| 13 April 1992 | 63 | 0.12 |
| Mean | — | 0.15 |
| After barrier was constructed | | |
| 24 April 1992 | 69 | 0.08 |
| 04 May 1992 | 71 | 0.01 |
| 12 May 1992 | 72 | 0.02 |
| Mean | — | 0.04 |

Table 6 Results of studies comparing survival indices of Feather River Hatchery CWT juvenile chinook salmon from Mossdale to Chipps Island before and after the barrier at Old River was constructed in 1994

| <i>Date</i> | <i>Water temperature (°F)</i> | <i>Survival</i> |
|--------------------------------|-------------------------------|-----------------|
| Before barrier was constructed | | |
| 11 April 1994 | 63 | 0 |
| After barrier was constructed | | |
| 26 April 1994 | 60 | 0.04 |
| 02 May 1994 | 66 | 0 |
| 09 May 1994 | 68 | 0.02 |
| Mean | — | 0.02 |

In 1992 and 1994, studies were conducted to evaluate the benefits to smolt survival of a full temporary rock barrier at the head of Old River. The study design included releasing CWT groups at Mossdale with and without the barrier in place. Due to logistical considerations, the without barrier scenario was the first experimental condition tested. In 1992, results showed survival indices to be less with the barrier in place than without counter to our hypothesis and earlier information. It is likely that the higher temperatures which occurred in the later part of the experimental period during the time the barrier was in place reduced the survival such that the benefits of the barrier were not observed (Table 5) (DWR 1992). Results in 1994 showed that smolt survival indices for all releases were extremely low and differences between the

barrier-in and barrier-out groups were not large (Table 6) (DWR 1995). Neither the 1992 nor 1994 testing was adequate to confirm benefits to smolt survival of a barrier in upper Old River.

Table 7 Release temperatures, average fish size at release, average flow at Vernalis, average Delta exports, and survival indices for Delta CWT releases in 1993, 1995, and 1996^a

| <i>Release date</i> | <i>Release location</i> | <i>Temperature at release (°F)</i> | <i>Average size at release (mm FL)</i> | <i>Average flow at Vernalis (cfs)</i> | <i>Average Delta exports (cfs)</i> | <i>Survival index</i> |
|---------------------|-------------------------|------------------------------------|--|---------------------------------------|------------------------------------|-----------------------|
| 6 Apr 1993 | Mossdale | 63 | 59 | 3,293 | 6,968 | 0.04 |
| 28 Apr 1993 | Mossdale | 64 | 71 | 4,598 | 1,518 | 0.07 |
| 4 May 1993 | Mossdale | 61 | 72 | 4,349 | 1,516 | 0.07 |
| 12 May 1993 | Mossdale | 65 | 75 | 3,167 | 1,533 | 0.07 |
| 17 Apr 1995 | Mossdale | 57 | 70 | 20,558 | 3,915 | 0.22 |
| 17 Apr 1995 | Dos Reis | 57 | 70 | 20,698 | 3,924 | 0.15 |
| 5 May 1995 | Mossdale | 62 | 75–76 | 22,772 | 4,527 | 0.12 |
| 5 May 1995 | Dos Reis | 63 | 76 | 22,397 | 5,194 | 0.39 |
| 17 May 1995 | Mossdale | 63 | 76–79 | 23,269 | 4,700 | 0.07 |
| 17 May 1995 | Dos Reis | 65 | 77 | 23,012 | 4,993 | 0.16 |
| 15 April 1996 | Mossdale | 59.5 | 78 | 6,613 | 1,687 | 0.02 |
| 30 April 1996 | Mossdale | 64 | 81 | 6,296 | 1,571 | 0.01 |
| 1 May 1996 | Dos Reis | 63 | 83–84 | 7,714 | 1,566 | 0.02 |

^a Average flows at Sacramento and Vernalis and average export values are from dayflow. Average flows at Vernalis are from date of release to last day of recovery, or for 14 days after release if no recoveries were made at Chipps Island (survival = zero). Average exports are for 14 days after release. In 1993, they were from release date to last recovery date at Chipps Island. All releases are from Feather River Hatchery stock.

Survival indices were low in 1993 and 1996, and somewhat higher in 1995, for smolts released at Mossdale, without a barrier at the head of upper Old River. Survival indices to Chipps Island ranged between 0.01 and 0.07 in 1993 and 1996 and between 0.07 to 0.22 in 1995. Complementary releases made at Dos Reis in 1995 and 1996 to estimate loss through Old River, indicated that survival was generally higher at Dos Reis than for releases made at Mossdale, suggesting that even in the higher flow years diversion into upper Old River reduces survival (Table 7).

In 1997 all releases at Mossdale were made with the barrier in place, to allow multiple measurements of survival to be generated with the barrier in place. Two 48-inch culverts included in the barrier in 1997 allowed approximately 300 cfs of water to flow from the San Joaquin River into upper Old River. Releases made at Dos Reis, relative to those released at Mossdale, were designed to evaluate the effects on smolt survival of the culverts in the barrier.

Table 8 Release temperatures, average fish size at release, average flow at Vernalis, average Delta exports, and survival indices for Delta CWT releases in 1997 with the head of Old River barrier in place^a

| <i>Release date</i> | <i>Release location</i> | <i>Temperature at release (°F)</i> | <i>Average size at release (mm FL)</i> | <i>Average flow at Vernalis (cfs)</i> | <i>Average Delta exports (cfs)</i> | <i>Survival Index</i> |
|---------------------|-------------------------|------------------------------------|--|---------------------------------------|------------------------------------|-----------------------|
| 28 Apr 1997 | Mossdale | 61 | 100 | 5,287 | 2,353 | 0.19 |
| 29 Apr 1997 | Dos Reis | 60 | 97 | 5,286 | 2,287 | 0.19 |

^a Average flows at Vernalis and average export values are from dayflow. Average flows at Vernalis are from date of release to last day of recovery, or for 14 days after release if no recoveries were made at Chipps Island (survival = zero). Average exports are for 14 days after release. All releases are from Feather River Hatchery.

Survival indices to Chipps Island of the Feather River smolts released at Dos Reis and Mossdale in 1997 were similar indicating that no difference in survival attributable to the culverts was detected (Table 8). This would suggest that the impact of the culverts was minimal to smolts passing between Mossdale and Dos Reis.

Several pieces of evidence support our conclusion that the barrier improved smolt survival through the Delta in 1997. First, the similarity between the Mossdale and Dos Reis groups provides evidence that the barrier improved survival in 1997. Without a barrier we would have expected the Mossdale group to survive at a lower rate than those released at Dos Reis. Second, the smolt survival

index, to Chipps Island for smolts released at Mossdale in 1997, was relatively high compared to past releases made at Mossdale since 1992 (Table 9). Third, the survival index to Chipps Island from smolts released at Mossdale was higher relative to past years of smolts released in the San Joaquin tributaries. In past years, survival of fish released at Mossdale was similar to that observed for fish released in the tributaries. For instance in 1996, the survival indices, to Chipps Island, of smolts released at Mossdale was 0.01 and 0.02, whereas for releases made on the upper Merced and Tuolumne it was 0.01 and 0.04, respectively - the same general magnitude (Table 9). Similarly in 1995, the survival index of smolts released at Mossdale was 0.22, and the groups released in the upper reaches of the tributaries survived at a rate of 0.15 and 0.25. Again, in the same general magnitude. In contrast, in 1997 the survival index from CWT fish released at Mossdale was 0.19 and the survival indices for upper reaches of the tributaries were 0.04, indicating that survival through the South Delta was higher relative to that in the tributaries in 1997, when the barrier was in place. Fourth, the survival index from the release made at Mossdale was closer to that of smolts released at Sacramento in 1997 than it had been in previous years. All of these data support our conclusion that the barrier improved survival in 1997.

Although it seems probable that the barrier increased survival in 1997, survival indices in the San Joaquin Delta still appeared low relative to earlier experiments conducted in 1985 and 1986 (Table 9). The use of non-basin, hatchery fish (those from FRH) or the affect of differences in water temperature between the hatchery truck and release site were hypothesized as possible causes. In both 1996 and 1997, paired releases were made at Dos Reis and Jersey Point with smolts from both FRH and MRFF to assess the potential affect of different stocks on the results of past experiments. Results showed that the survival estimate to Chipps Island, of the Dos Reis group relative to the Jersey Point group, was higher for the MRFF group in both 1996 and 1997 (Table 10). In 1997, smolts from FRH were significantly larger (average 88 mm fork length) and heavier than Merced River stock (average 74 mm fork length). However by standardizing survival, bias associated with recapture efficiency of the different sized fish between stocks should be factored out as long as sizes within a stock were similar, which they were in this case. Results from physiological tests conducted in 1996 and 1997, on subsets of fish (approximately 30) from paired groups released at Dos Reis, indicated there were no physiological reasons for the differences in survival between the two stocks (MRFF and FRH). In 1996 pathologists determined that the Merced stock was at an early infection stage of PKX, a myxosporean parasite, but it should not have affected their survival through the Delta, but could be a factor in adult survival of this stock (True 1996). Physiological tests conducted included those for internal parasites and bacterium and various other analyses (organosomatic analyses, ATPase assay, triglyceride level analyses and stress glucose response analyses). An additional group of 12 was used to assess osmoregulatory ability. In 1996 these tests were made on fish at release, while in 1997 they were made on fish that had been held in live cars for 48 hours.

Table 9 Survival indices of Merced Fish Facility, Feather River Hatchery, and Tuolumne River Fish Facility smolts released in the San Joaquin Delta and tributaries between 1982 and 1997

| Year | Release sites | | | | | | | | | |
|------|---------------------|--------------------------------------|--------------------------------------|--------------------|------------------------------|------------------------------|--------------------------------|--------------------------------|----------------------------------|----------------------------------|
| | Dos Reis | Mossdale w/o HORB ^a | Mossdale w/o HORB ^a | Upper Old River | Upper Merced ^b | Lower Merced ^b | Upper Tuolumne ^b | Lower Tuolumne ^b | Upper Stanislaus ^b | Lower Stanislaus ^b |
| 1997 | 0.19 ^a | | | | | | | | | |
| 1997 | 0.14 ^b | – | 0.19 | – | 0.04 | 0.14 | 0.04 | 0.17 | – | – |
| 1997 | | – | – | – | 0 | 0.01 | – | – | – | – |
| 1996 | 0.02 ^a | | | | | | | | | |
| 1996 | 0.09 ^b | 0.01 | | – | 0.01 | 0.01 | 0.04 | 0.07 | – | – |
| 1996 | | 0.02 | – | – | – | – | – | – | – | – |
| 1995 | 0.15 ^a | 0.22 | – | – | 0.15 | 0.20 | 0.25 | 0.22 | – | – |
| 1995 | 0.39 ^a | 0.12 | – | – | – | – | – | – | – | – |
| 1995 | 0.16 ^a | 0.07 | – | – | – | – | – | – | – | – |
| 1994 | – | 0.00 | 0.02 | – | 0.06 | 0.02 | 0.03 | 0.04 | – | – |
| 1994 | – | – | 0.04 | – | – | – | – | – | – | – |
| 1994 | – | – | 0 | – | – | – | – | – | – | – |
| 1993 | – | 0.04 | – | – | – | – | – | – | – | – |
| 1993 | – | 0.07 | – | – | – | – | – | – | – | – |
| 1993 | – | 0.07 | – | – | – | – | – | – | – | – |
| 1993 | – | 0.07 | – | – | – | – | – | – | – | – |
| 1992 | – | 0.18 | 0.08 | – | – | – | – | – | – | – |
| 1992 | – | 0.12 | 0.01 | – | – | – | – | – | – | – |
| 1992 | – | – | 0.02 | – | – | – | – | – | – | – |
| 1991 | 0.16 ^a | – | – | – | – | – | – | – | – | – |
| 1990 | 0.04 ^a | – | – | 0.02 ^a | – | – | 0.04 | 0.01 ^c | – | – |
| 1990 | 0.04 ^a | | – | 0.01 ^a | – | – | – | – | – | – |
| 1989 | 0.14 ^a | – | – | 0.09 ^a | – | 0.05 | – | – | 0.05 | 0.21 |
| 1989 | 0.15 ^b | – | – | 0.05 ^b | – | – | – | – | – | 0 |
| 1988 | – | – | – | – | – | – | – | – | 0.07 | 0.09 |
| 1987 | 0.83 ^{a,d} | – | – | 0.16 ^b | – | – | 0.05 | 0.18 | – | – |
| 1986 | 0.34 ^b | – | – | 0.2 ^b | – | – | 0.40 | 0.27 | 0.34 | 0.56 |
| 1985 | 0.59 ^{b,e} | – | – | 0.62 ^b | – | – | – | – | – | – |
| 1984 | – | – | – | – | – | – | – | – | – | – |
| 1983 | – | – | – | – | – | – | – | – | – | – |
| 1982 | 0.6 ^{b,f} | – | – | – | 0.62 | – | – | – | – | – |

^a Stock source: Feather River Hatchery.

^b Stock source: Merced River Fish Facility.

^c Stock source: TRFF.

^d Release temperature of 70 °F.

^e Spray-dyed fish.

^f May be biased low due to the lack of sampling at Chipps Island during the first week after release.

Table 10 Ratio of survival indices (absolute smolt survival) of smolts released at Dos Reis and Jersey Point and recovered at Chipps Island using Feather River Hatchery and Merced River Fish Facility stock in 1996 and 1997

| <i>Release date</i> | <i>Hatchery stock</i> | <i>Release site</i> | <i>Survival index to Chipps Island</i> | <i>Absolute smolt survival</i> |
|---------------------|-----------------------|---------------------|--|--------------------------------|
| 01 May 1996 | Feather River | Dos Reis | 0.02 | 0.06 |
| 03 May 1996 | Feather River | Jersey Point | 0.35 | |
| 01 May 1996 | Merced River FF | Dos Reis | 0.10 | 0.14 |
| 03 May 1996 | Merced River FF | Jersey Point | 0.72 | |
| 29 Apr 1997 | Feather River | Dos Reis | 0.19 | 0.18 |
| 02 May 1997 | Feather River | Jersey Point | 1.03 | |
| 29 Apr 1997 | Merced River FF | Dos Reis | 0.14 | 0.27 |
| 02 May 1997 | Merced River FF | Jersey Point | 0.51 | |
| 08 May 1997 | Merced River FF | Dos Reis | 0.12 | 0.30 |
| 12 May 1997 | Merced River FF | Jersey Point | 0.40 | |

To address the concern that temperature shock reduced the survival of smolts released in the South Delta, smolts were held in live cars in 1996 and 1997. Approximately 200 fish from the paired Dos Reis releases in 1996 were held in live cages for 48 hours to assess immediate and short term mortality within and between groups. In 1997, this was expanded to include all release sites. Sub-samples of the 200 fish (25) were closely evaluated immediately after each release and after they had been held for 48 hours to assess their condition. Fish were evaluated based on eye condition, body color, fin condition, scale loss and gill color. All fish looked healthy both immediately after release and after 48 hours. Only minor mortality (6 dead fish) was observed, of which most (4) was attributed to one location in one year. Mortality (less than 1%) was observed at the release site for this group, which was released on May 12, 1997, at Jersey Point (Brandes 1996; Brandes and Pierce 1998). Considering that most of the fish were healthy after being held for 48 hours in the live cars, it did not appear that acute temperature shock or any other factor at the release site caused mortality within the holding period. Increased predation as a result of reduced avoidance to predators due to temperature stress or other factors can not be assessed holding fish in live cars.

The Role of Flow on Survival. To separate the role of flow in the San Joaquin River from the impacts of diversion into upper Old River, survival estimates of smolts released at Dos Reis relative to those released at Jersey Point were plotted against river flow at Stockton (Figure 26). The relationship between sur-

vival and river flow was statistically significant ($r^2 = 0.65$, $P < 0.01$), using stock from both Feather River Hatchery and Merced River Fish Facility. In 1989, a release was made at Dos Reis with Merced River stock. Since there was no corresponding Jersey Point release using Merced stock, a Feather River stock was used instead. Although the intercept changed slightly (0.0581), the slope of the relationship did not change when the data point was deleted from the regression ($r^2 = 0.82$, $P < 0.01$). If smolts from Dos Reis survive at a higher rate because of increased flows at Stockton, the barrier may have served as the mechanism to increase the flows. It could be that survival is improved via the barrier because of the shorter migration path, but also because it increases the flows down the main-stem San Joaquin River.

The relative importance of flow and the barrier to smolt survival through the Delta between Mossdale and Jersey Point is shown in Figure 27. The rock barrier cannot presently be installed at Vernalis flows of greater than 7000 cfs. To put the improvement in survival resulting from the barrier in perspective, survival indices were compared between 1996 and 1995 and 1996 and 1997. In 1995, the high flows, without a barrier, increased survival by about 16 times that of 1996. The barrier in 1997 improved the 1996 survival index about 4.5 times. The barrier improves survival at flows of less than 7000 cfs but flows greater than 10,000 cfs appear to improve survival even further (Figure 27).

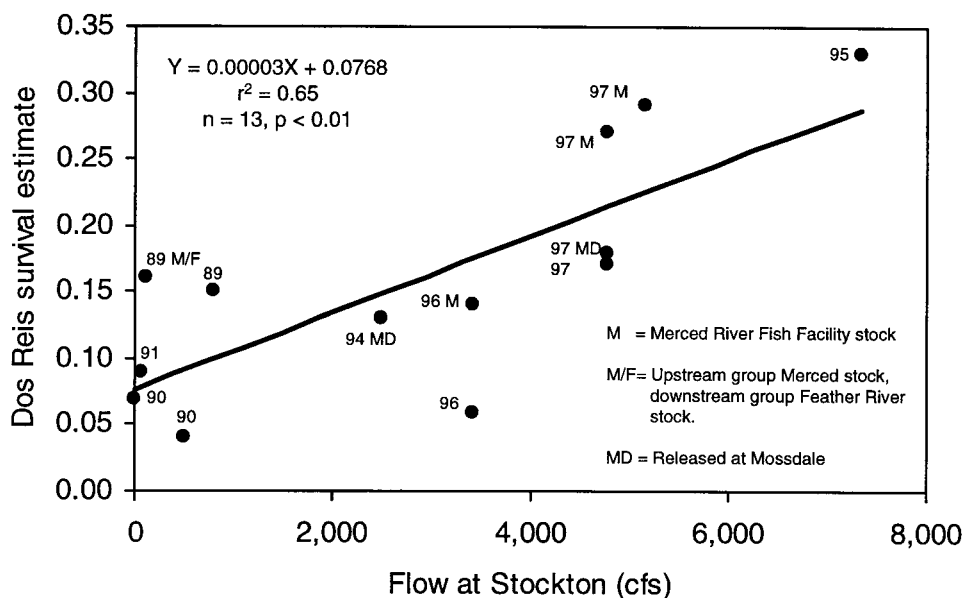


Figure 26 Estimate of survival between Dos Reis and Jersey Point or Mossdale and Jersey Point with the barrier in place using CWT smolts from Feather River Hatchery and Merced River Fish Facility

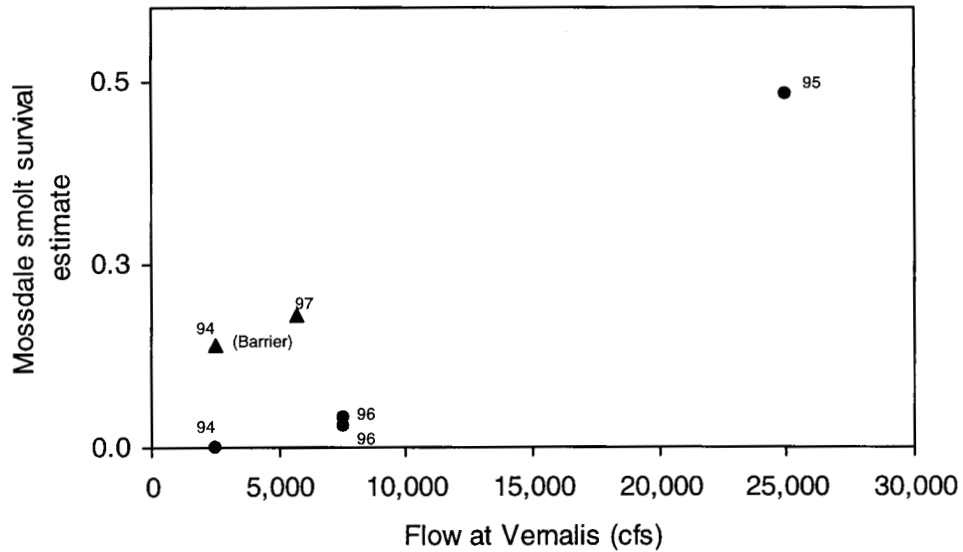


Figure 27 Absolute smolt survival for smolts released at Mossdale in relation to those released at Jersey Point versus flow (cfs) at Vernalis

The Role of Exports and Direct Entrainment on Survival. To determine if exports influenced the survival of smolts in the San Joaquin Delta, experiments were conducted in 1989, 1990 and 1991 at medium/high and low export levels. Results were mixed showing in 1989 and 1990 that survival estimates between Dos Reis and Jersey Point were higher with higher exports whereas in 1991 between Stockton and the mouth of the Mokelumne River (Tables 11 and 12) survival was shown to be lower (0.008 compared to 0.15) when exports were higher. One potential bias in the 1989 and 1990 data is that as mentioned earlier, smolts released at Dos Reis in 1989 were from the Merced River Fish Facility while those released at Jersey Point were from Feather River hatchery. Using different stocks to estimate smolt survival between two locations may introduce bias. In addition, results in 1989 and 1990 also showed that survival indices of the upper Old River groups relative to the Jersey Point groups were also higher during the higher export period, but overall still about half that of the survival of smolts released at Dos Reis (Table 11).

Table 11 Survival indices of smolts released at Dos Reis on the mainstem San Joaquin River, upper Old River, and Jersey Point based on Chipps Island recoveries^a

| Year | Flow at Vernalis (cfs) ^b | CVP + SWP exports (cfs) ^c | Dos Reis | Upper Old River | Jersey Pt. | Dos Reis-Jersey Pt. ratio | Upper Old River:Jersey Pt. ratio |
|------|-------------------------------------|--------------------------------------|----------|-----------------|------------|---------------------------|----------------------------------|
| 1989 | 2,274 | 10,247 | 0.14 | 0.09 | 0.88 | 0.16 | 0.10 |
| 1989 | 2,289 | 1,797 | 0.14 | 0.05 | 0.96 | 0.14 | 0.05 |
| 1990 | 1,290 | 9,618 | 0.04 | 0.02 | 0.61 | 0.06 | 0.03 |
| 1990 | 1,665 | 2,462 | 0.04 | 0.01 | 1.05 | 0.04 | 0.01 |

^a The ratio of survival indices between Dos Reis to Jersey Point and upper Old River to Jersey Point are included to compare absolute survival between years.

^b Flows at Vernalis are ten-day averages in cubic feet per second after the Dos Reis groups were released.

^c Exports are daily averages in cubic feet per second five days after release of upper Old River groups.

Contrary to the mixed results between survival and exports, direct entrainment losses at the fish facilities has been identified as a cause of juvenile salmon mortality in the Delta. Kjelson (1981) reported that records of salmon observed in salvage and respective spring export rates between 1959 and 1967 and 1968 to 1979 indicated that as exports increased more downstream migrating salmon are observed in the salvage. In USFWS Exhibit 31 (1987), it was reported that on average only 0.36% of the CWT smolts, released in the Sacramento River (above the Walnut Grove diversion) or in the forks of the Mokelumne River, were estimated to have been salvaged (expanded salvage) at the export facilities in the south Delta. These percentages are small, even when further expanded for screen efficiency and predation losses in Clifton Court Forebay, relative to the indirect mortality in the Delta that would occur to juveniles drawn off their normal migration path and exposed to other mortality factors for a longer period of time.

Table 12 Survival indices for CWT chinook released at various locations along the San Joaquin and Mokelumne rivers in the Delta in April and May 1991^a

| <i>Month (mean exports) and release site</i> | <i>River mile</i> | <i>Temp. (°F)</i> | <i>Survival index to Chipps Island</i> | <i>Survival rate per mile^a</i> |
|--|-----------------------|-----------------------|--|---|
| April (4,283 cfs) | | | | |
| Dos Reis | 50 | 60 | 0.16 | |
| Dos Reis to Stockton | | | | 0.06 |
| Stockton | 39 | 59 | 0.25 | |
| Stockton to Empire Tract | | | | 0.05 |
| Empire Tract | 29 | 61 | 0.54 | |
| Empire Tract to mouth of Mokelumne River | | | | 0.03 |
| Mouth of the Mokelumne River | 19 | 61 | 1.56 | |
| Stockton to the mouth of Mokelumne River | | | | 0.008 |
| Mouth of the Mokelumne River to Jersey Point | | | | 0.13 |
| Jersey Point | 12 | 63 | 1.70 | |
| May (2,613 cfs) | | | | |
| Stockton | | 65 | 0.19 | |
| Stockton to the mouth of Mokelumne River | | | | 0.015 |
| Mouth of the Mokelumne River | | 64.5 | 0.640 | |
| Mouth of the Mokelumne River to Jersey Point | | | | 0.05 |
| Jersey Point | | 61 | 1.69 | |

^a Survival rate per mile and river miles to Chipps Island also are included for the reaches between Stockton and the mouth of the Mokelumne River and between the mouth of the Mokelumne River and Jersey Point.

Recoveries at the fish salvage facilities were much greater from releases made in the South Delta than in the North Delta. Many marked fish were observed at the fish facilities when they were released into upper Old River (average 19%). Smolts released at Dos Reis on the main-stem San Joaquin River had a lower salvage rate (averaged 3%) (USFWS 1990). These differences in salvage may, in part, account for the lower survival observed for the upper Old River group.

The number of marked fish recovered at the fish facilities from releases made in the San Joaquin Delta seems to be related to release location, whether or not there is a barrier in place and the rate of exports. In 1991, the greatest number of fish recovered at the fish facilities was from Dos Reis, Stockton and Empire Tract groups. The fewest recoveries were from the Mokelumne release groups and those released at Jersey Point (Table 13) (USFWS 1992b). Recoveries at the fish facilities from releases made at Mossdale were greatest when there was no barrier at the head of Old River (Table 14). This is further illustrated by the greater recoveries at both the CVP and SWP of smolts released at Mossdale relative to those released at Dos Reis (Table 15). In 1997, the number of expanded recoveries from two Dos Reis groups and the Mossdale group, were similar with the barrier in place (Table 16).

Table 13 Expanded fish facility recoveries during high (April) and low (May) export levels during spring 1991

| <i>Release location</i> | <i>Release date</i> | <i>Number released</i> | <i>Mean daily exports^a</i> | <i>Expanded fish facility recoveries</i> | |
|-------------------------|---------------------|------------------------|---------------------------------------|--|------------|
| | | | | <i>CVP</i> | <i>SWP</i> |
| Dos Reis | 15 April | 102,999 | 4,283 | 5,472 | 2,526 |
| Stockton | 16 April | 99,341 | 4,283 | 338 | 2,635 |
| Empire Tract | 17 April | 95,602 | 4,283 | 131 | 1,401 |
| L. Mokelumne | 18 April | 47,289 | 4,283 | 0 | 276 |
| Jersey Point | 19 April | 52,139 | 4,283 | 20 | 274 |
| Stockton | 06 May | 99,820 | 2,613 | 52 | 64 |
| L. Mokelumne | 09 May | 45,706 | 2,613 | 22 | 13 |
| Jersey Point | 13 May | 49,184 | 2,613 | 6 | 0 |

^a Mean daily exports (CVP and SWP combined) for April (16 April to 6 May) and May (6 May to 30 May) are the mean between the release date and final capture.

Table 14 Expanded SWP and CVP fish facility recoveries for fish released at Mossdale with and without the head of Old River barrier in place in 1992 and 1994

| <i>Release date</i> | <i>Barrier status</i> | <i>Number released</i> | <i>Expanded fish facility recoveries</i> | |
|---------------------|-----------------------|------------------------|--|------------|
| | | | <i>SWP</i> | <i>CVP</i> |
| 07 April 1992 | No barrier | 107,103 | 71 | 5,380 |
| 13 April 1992 | No barrier | 103,712 | 106 | 3,385 |
| 11 April 1994 | No barrier | 51,084 | 100 | 648 |
| 04 May 1992 | Barrier | 99,717 | 8 | 28 |
| 12 May 1992 | Barrier | 105,385 | 6 | 0 |
| 26 April 1994 | Barrier | 50,259 | 0 | 0 |
| 02 May 1994 | Barrier | 51,632 | 24 | 12 |
| 09 May 1994 | Barrier | 53,880 | 13 | 0 |

Table 15 Expanded SWP and CVP fish facility recoveries for fish released at Dos Reis and Mossdale without the upper Old River barrier in place in 1995 and 1996

| <i>Release location</i> | <i>Release date</i> | <i>Number released</i> | <i>Expanded fish facility recoveries</i> | |
|-------------------------|---------------------|------------------------|--|------------|
| | | | <i>SWP</i> | <i>CVP</i> |
| Mossdale | 17 April 1995 | 100,969 | 36 | 2,732 |
| Dos Reis | 17 April 1995 | 50,848 | 0 | 1 |
| Mossdale | 05 May 1995 | 102,562 | 74 | 1,859 |
| Dos Reis | 05 May 1995 | 52,097 | 0 | 0 |
| Mossdale | 17 May 1995 | 104,125 | 128 | 1,452 |
| Dos Reis | 17 May 1995 | 51,665 | 0 | 24 |
| Mossdale | 30 April 1996 | 99,656 | 24 | 110 |
| Dos Reis | 01 May 1996 | 206,780 | 0 | 0 |

In 1989 and 1990 expanded recoveries at the fish salvage facilities for both CWT groups released in upper Old River and Dos Reis during the high export were greater than those during the low export experiments (USFWS 1990) (Table 17). In 1991, it was observed that there were 25 times more marked fish recovered at the fish facilities from the Stockton group during the period of higher exports, than the releases made during the lower export period (USFWS 1992b) (Table 13). These pieces of information indicate that direct mortality is higher when exports are higher.

Table 16 Expanded SWP and CVP fish facility recoveries for fish released at Dos Reis and Mossdale in 1997 with the upper Old River barrier in place using Feather River Hatchery or Merced River Fish Facility stock

| <i>Release location</i> | <i>Stock</i> | <i>Release date</i> | <i>Number released</i> | <i>Expanded fish facility recoveries</i> | |
|-------------------------|----------------------------|---------------------|------------------------|--|------------|
| | | | | <i>SWP</i> | <i>CVP</i> |
| Mossdale | Feather River Hatchery | 28 April | 48,774 | 34 | 204 |
| Dos Reis | Feather River Hatchery | 29 April | 49,830 | 31 | 96 |
| Dos Reis | Merced River Fish Facility | 29 April | 102,480 | 130 | 288 |

Table 17 Expanded SWP and CVP fish facility recoveries for smolts released in the San Joaquin River at Dos Reis and into upper Old River in 1989 and 1990 and mean daily exports five days after release of the upper Old River group

| <i>Release location</i> | <i>Release date</i> | <i>CVP + SWP mean daily exports (cfs)</i> | <i>Number released</i> | <i>Expanded fish facility recoveries</i> | |
|-------------------------|---------------------|---|------------------------|--|------------|
| | | | | <i>SWP</i> | <i>CVP</i> |
| Dos Reis | 20 Apr 1989 | 10,247 | 52,962 | 2,286 | 428 |
| Upper Old River | 21 Apr 1989 | 10,247 | 51,972 | 2,916 | 658 |
| Dos Reis | 02 May 1989 | 1,797 | 75,983 | 344 | 84 |
| Upper Old River | 03 May 1989 | 1,797 | 74,309 | 215 | 1,256 |
| Dos Reis | 16 Apr 1990 | 9,618 | 105,742 | 1,044 | 722 |
| Upper Old River | 17 Apr 1990 | 9,618 | 106,269 | 1,729 | 948 |
| Dos Reis | 02 May 1990 | 2,462 | 103,533 | 96 | 54 |
| Upper Old River | 03 May 1990 | 2,462 | 103,595 | 920 | 426 |

Bay Survival. In 1984, 1985 and 1986 smolts were released at Port Chicago in Suisun Bay and in San Francisco Bay near the Golden Gate Bridge to estimate survival through the Bay. The survival indices of marked fish released at Port Chicago and recovered in the midwater trawl at the Golden Gate were highly variable and ranged from 0.75 to 2.39 (Table 18). The extreme tidal fluctuations in San Francisco Bay most likely had a significant effect on the variability of the indices. Survival estimates through the Bay, from Port Chicago to the Golden Gate measured using the differential ocean recovery rates from the two release groups, showed survival ranged between 0.76 and 0.84 in the three years (Table 18). Delta outflows were low, and ranging from 6,690 cfs to 13,507 cfs, and did not appear to effect survival rates through the Bay. Since survival was observed to be relatively high through the Bay in the three years measured, CWT experiments in the Bay were discontinued to free up marked fish for use in the Delta where survival had been shown to be less and the need for information greater.

Table 18 San Francisco Bay (Golden Gate Bridge) tag summary, survival calculations and expanded ocean recoveries

| <i>Tag code</i> | <i>Release site (stock)</i> | <i>Release date</i> | <i>Number released</i> | <i>Size (mm)</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Ocean recoveries</i> |
|-----------------|-----------------------------|---------------------|------------------------|------------------|----------------------------|---------------------------|-------------------------|-----------------------|-------------------------|
| 6-62-51 | Port Chicago (FRH) | 06/02/86 | 47,995 | 75 | 06/05/86 | 06/18/86 | 15 | 0.75 | 1,382 |
| 6-62-52 | Fort Baker (FRH) | 06/03/86 | 49,583 | 73 | --- | --- | 0 | | 1,807 |
| 6-62-45 | Port Chicago (FRH) | 05/13/85 | 48,143 | 76 | 05/17/85 | 05/29/85 | 22 | 1.54 | 465 |
| 6-62-44 | Fort Baker (FRH) | 05/14/85 | 47,158 | N/A | --- | --- | 0 | | 537 |
| 6-54-51 | Port Chicago (NFH) | 07/23/84 | 50,114 | N/A | 07/26/84 | 07/31/84 | 36 | 2.39 | 1,159 |
| 6-54-52 | Fort Baker (NFH) | 07/25/84 | 48,677 | N/A | --- | --- | 0 | | 1,461 |

Annual Indices of Survival. The survival indices to Chipps Island and survival estimates using differential ocean recovery rates, of smolts released near Sacramento, in the upper Sacramento River and in the San Joaquin tributaries, allows survival through the Delta and upstream to be compared between years.

Survival indices to Chipps Island of hatchery smolts released near Sacramento were compared to those released upstream in Battle Creek in Figure 28. The survival indices to Chipps Island from releases made into Battle Creek would include survival in the Delta as well as that in the upper river. Survival appeared to be relatively high between Battle Creek and Chipps Island in 1984 and 1993. Smolt survival through the Delta appeared highest in 1982 and 1983.

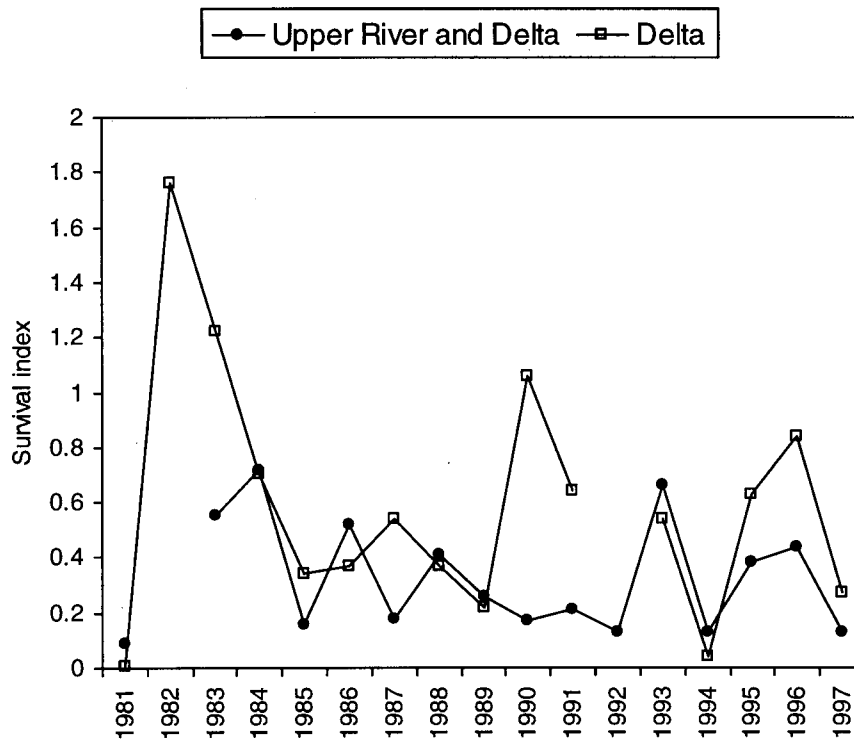


Figure 28 Survival indices of smolts released in the upper river (Battle Creek) and those released in the northern Delta (Courtland, Sacramento, Miller Park, Discovery Park) between 1981 and 1997. No release upstream in 1982 or at Sacramento in 1992.

Survival estimates using ocean recovery rates of smolts released at Battle Creek, relative to those released at Princeton, Knights Landing or Sacramento, were compared to the survival estimates of fish released at Sacramento, relative to those released at Port Chicago/Benicia, to allow upriver survival estimates to be separated from those in the Delta (Figure 29). These data show that survival was greatest upstream in 1987 and 1990, contrary to the conclusions based on Chipps Island survival indices. Variability in the ocean recovery rates or the poor survival of the downstream groups relative to the upstream groups likely account for the ratios of greater than 1.0 observed for several of the groups. Both sets of survival indices/estimates provide a rough estimate of the survival of smolts migrating through the River and Delta over time.

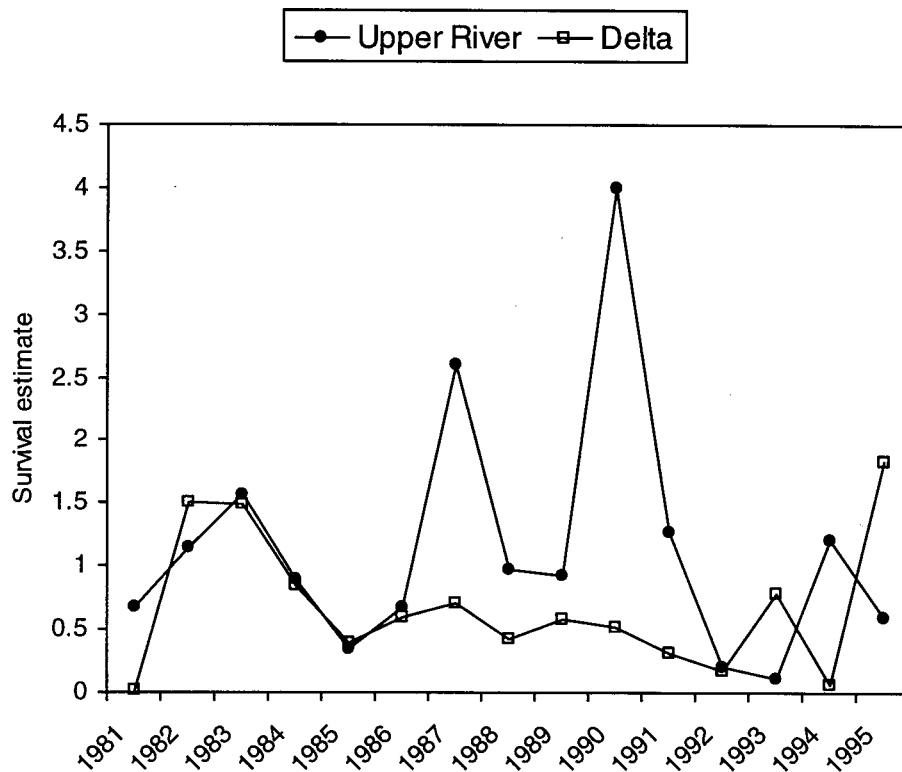


Figure 29 Estimates of survival in the upper river and Delta. A Ryde release was used as a downstream control in 1987 because a release was not made at Port Chicago or Benicia that year. In 1992, Princeton was used for the Delta survival estimate.

Marked releases have been made at sites in the San Joaquin tributaries during many years since 1982 and similar upstream and Delta comparisons were made between years. The survival indices from releases made in the lower reach of the tributaries would provide an index of survival through the lower San Joaquin River and Delta. Survival indices to Chipps Island from releases made in the upstream reaches of the tributaries would include both tributary and Delta survival. In many years (1986, 1988, 1994, 1995, and 1996) survival to Chipps Island from the upper reaches of the tributaries were similar to that from the releases made in the lower reaches indicating that most of the mortality occurred in the San Joaquin River main-stem and Delta (Figure 30). In other years, such as in 1987, 1989 and 1997, survival from releases made in the upper reaches of the tributaries was much less than that in the lower reaches, indicating that mortality in the tributaries was higher relative to that in the Delta and San Joaquin River.

Survival for smolts released in the lower reaches of the San Joaquin River tributaries also can be compared to that for smolts released near Sacramento. Survival is generally, substantially higher for smolts released at Sacramento than for those released in the lower tributaries of the San Joaquin River. Exceptions were in 1986, 1994 and 1997 when survival through the Delta from both basins was similar (Figure 30).

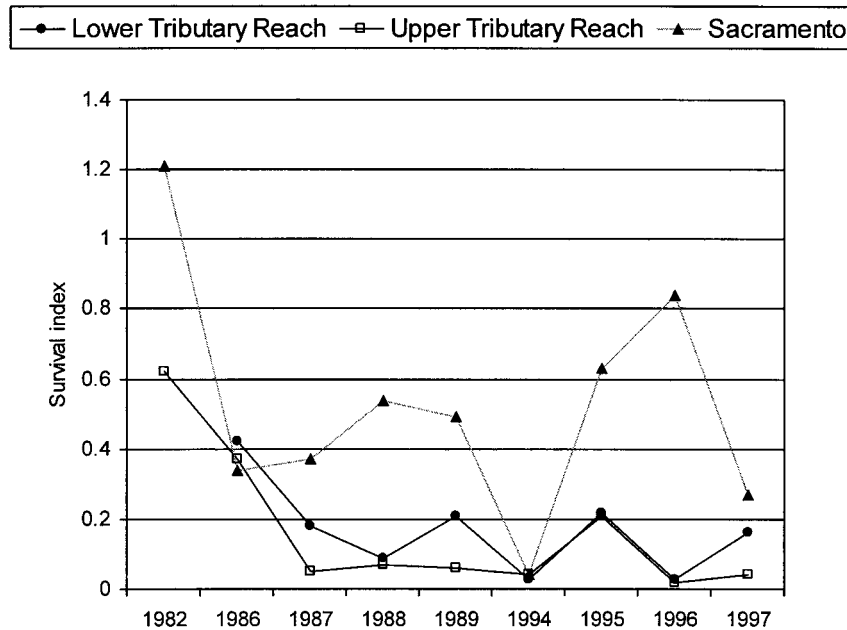


Figure 30 Survival indices for CWT smolts released at sites in the lower (L. Trib.) and upper (U. Trib.) reaches of the San Joaquin tributaries and near Sacramento (Sac.)

Summary and Recommendations

Analyses of the lower river and Delta beach seine data and the trawl data at Sacramento and Chipps Island, indicates that many juveniles enter the Delta as fry in wet years and that overall, juvenile production leaving the Delta is higher in wet years. The increase in juvenile production in wet years could be partially due to survival increases of fry upstream. Increased river flows appeared to increase fry survival upstream, but likely caused a greater proportion of them to migrate to the estuary where fry survival appears lower than upriver in the higher flow years. The survival of marked fry and smolts in the Central Delta appeared lower than in the North Delta, especially in the drier years. Both fry and smolts in the Central Delta may be more vulnerable to exports than those released in the North Delta in the drier years.

Studies using marked smolts in the Sacramento Delta indicated that migration into the Central Delta via the Delta Cross Channel or Georgiana Slough negatively affected the survival of juveniles migrating through the Delta not only in the spring, but in the winter months as well. Migration through upper Old River in the south Delta also appeared to negatively affect the survival of smolts originating from the San Joaquin basin. Direct losses, as indexed using expanded salvage recoveries, due to export pumping were generally low for smolts migrating through the Delta on the Sacramento River. Direct losses were higher for marked fish released in the San Joaquin Delta, with the greatest salvage from smolts released in upper Old River. Salvage also was higher for releases made at the same location when exports were increased. These long-term studies have helped identify actions that could improve juvenile salmon survival through the Delta.

Long-term systematic releases to measure survival through the Delta can be used as the basis for future modeling to further define ways to improve survival. Some models have been developed from CWT data generated from the Sacramento Delta (Newman and Rice 1997; Kjelson and others 1989). Additional models using this data are in the process of being generated. In such a complex system, it will take consistent releases over many years to refine models that will further define the factors important to juvenile salmon abundance and survival and identify additional ways to improve survival through the Delta.

Acknowledgements

The authors recognize and appreciate all of the seasonal aides, biological technicians, junior biologists and boat operators that have helped gather the data over the past 20 years. We would also like to thank those who analyzed and summarized aspects of the data presented in this report, especially Erin Sauls, Mark Pierce, and Chris Alexander. Mary Sommer, from California Department of Fish and Game, assisted us in generating the maps. Russ Gartz and Ken Newman gave advice regarding some of the statistics. Martin Kjelson has been the project leader for this program since 1977 and was responsible for most aspects of the program design and implementation. Ted Sommer and Colin Levings gave helpful suggestions on an earlier draft. The IEP funding used to support these studies was primarily from California Department of Water Resources and the U.S. Bureau of Reclamation.

References

- Brandes PL. 1996. Results of 1996 coded-wire tag smolt survival experiment in the San Joaquin River Delta. Interagency Ecological Program Newsletter 9(4):13-6. Sacramento (CA): California Department of Water Resources.
- Brandes PL, Pierce M. 1998. 1997 Salmon smolt survival studies in the South Delta. Interagency Ecological Program Newsletter 11(1):29-38. Sacramento (CA): California Department of Water Resources.
- [DFG] California Department of Fish and Game. 1976. Exhibit 3: Report to the State Water Resources Control Board on the impact of water development on fish and wildlife resources in the Sacramento-San Joaquin Estuary.
- [DWR] California Department of Water Resources. 1992. South Delta Temporary Barriers Project: monitoring, evaluation, and management program. Sacramento (CA): California Department of Water Resources.
- [DWR] California Department of Water Resources. 1995. Temporary barriers project fishery, water quality, and vegetation monitoring, 1994. Sacramento (CA): California Department of Water Resources.
- Fisher FW. 1994. Past and present status of Central Valley chinook salmon. *Conser Biol* 8(3):870-3.
- Healy MC. 1980. Utilization of the Nanaimo River Estuary by juvenile chinook salmon, *Oncorhynchus tshawytscha*. *Fish Bull* 77(3):653-68.
- Healy MC. 1991. Life history of chinook salmon (*Oncorhynchus tshawytscha*). In: Groot C, Margolis L, editors. Pacific salmon life histories. Vancouver: UBC Press. p 313-93.
- Junge CO. 1970. The effect of superimposed mortalities on reproduction curves. *Research Reports of the Fish Commission of Oregon* 2:56-63.
- Kjelson MA, Brandes PL. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento-San Joaquin Rivers, California. In: Levings CD, Holtby LB, Henderson MA, editors. Proceedings of the National Workshop on the Effects of Habitat Alteration on Salmonid Stocks. *Can Spec Publ Fish Aquatic Sci* 105:100-15.
- Kjelson MA, Greene S, Brandes PL. 1989. A model for estimating mortality and survival of fall-run chinook salmon smolts in the Sacramento River Delta between Sacramento and Chipps Island. Stockton (CA): US Fish and Wildlife Service. 50 p.
- Kjelson MA, Raquel PF, Fisher FW. 1981. Influences of freshwater inflow on chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento-San Joaquin Estuary. In: Cross RD, Williams DL, editors. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. US Fish and Wildlife Service. FWS/OBS-81-04. p 88-108.

- Kjelson MA, Raquel PF, Fisher FW. 1982. Life history of fall-run juvenile chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento-San Joaquin Estuary, California, In: Kennedy VS, editor. Estuarine comparisons. New York (NY): Academic Press. p 393-411.
- McLain JS. 1998. Relative efficiency of the midwater and kodiak trawl at capturing juvenile chinook salmon in the Sacramento River. Interagency Ecological Program Newsletter 11(4):26-9. Sacramento (CA): California Department of Water Resources.
- [NMFS] National Marine Fisheries Service. 1999. West coast salmon and the endangered species act listing status: chinook. Available at <http://www.nwr.noaa.gov/1salmon/salmesa/chinswit.htm>. Accessed in 1999.
- Newman K, Rice J. 1997. Statistical model for survival of chinook salmon smolts outmigrating through the lower Sacramento-San Joaquin system. Interagency Ecological Program Technical Report 59. Sacramento (CA): California Department of Water Resources.
- Oltmann R. 1995. Continuous flow measurements using ultrasonic velocity meters: an update. Interagency Ecological Program Newsletter Autumn 1995. Sacramento (CA): California Department of Water Resources.
- [PSMFC] Pacific States Marine Fisheries Commission. 1998. Regional Mark Information System web page. Available at <http://www.psmfc.org/rmpc>. Accessed in 1999.
- Reisenbichler RR, McIntyre JD, Solazzi MF, Landino SW. 1992. Genetic variation in steelhead of Oregon and northern California. *Trans Am Fish Soc* 121(2):158-69.
- Snider WM, Titus RB, Payne BA. 1998. Lower American River emigration survey, October 1995 - September 1996. California Department of Fish and Game, Environmental Services Division, Stream Evaluation Program.
- Sommer T, McEwan D, Brown R. 2000. Factors affecting chinook salmon spawning in the lower Feather River. In: Brown R, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 1*. Sacramento (CA): California Department of Fish and Game.
- Stevens DE, Miller LW. 1983. Effects of river flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. *N Am J Fish Manag* 3:425-37.
- True K. 1996. Health monitoring component of South Delta salmon study - spring 1996. Anderson (CA): California-Nevada Fish Health Center. 10 p.
- [USFWS] US Fish and Wildlife Service. 1982. *Fish hatchery management*. Washington, DC: Department of the Interior, US Fish and Wildlife Service. 517 p.

- [USFWS] US Fish and Wildlife Service. 1987. Exhibit 31: the needs of chinook salmon, *Oncorhynchus tshawytscha* in the Sacramento-San Joaquin Estuary. Presented to the State Water Resources Control Board for the 1987 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento-San Joaquin Delta.
- [USFWS] US Fish and Wildlife Service. 1990. 1990 annual progress report: abundance and survival of juvenile chinook salmon in the Sacramento-San Joaquin Estuary. Stockton (CA): US Fish and Wildlife Service.
- [USFWS] US Fish and Wildlife Service. 1992a. Measures to improve the protection of chinook salmon in the Sacramento-San Joaquin River Delta. Presented to the State Water Resources Control Board for the 1992 Water Quality/Water Rights Proceedings on the San Francisco Bay/Sacramento-San Joaquin Delta.
- [USFWS] US Fish and Wildlife Service. 1992b. 1991 annual progress report: abundance and survival of juvenile chinook salmon in the Sacramento-San Joaquin Estuary. Stockton (CA): US Fish and Wildlife Service.
- [USFWS] US Fish and Wildlife Service. 1994. 1993 annual progress report: abundance and survival of juvenile chinook salmon in the Sacramento-San Joaquin Estuary. Stockton (CA): US Fish and Wildlife Service.
- [USFWS] US Fish and Wildlife Service. 1995. Working paper: habitat restoration actions to double natural production of anadromous fish in the Central Valley of California. Volume 2. Prepared for the US Fish and Wildlife Service under the direction of the Anadromous Fish Restoration Core Group. Stockton (CA): US Fish and Wildlife Service.
- White J. 1998. State of California Department of Fish and Game testimony of Jim White, Bay-Delta Water Rights Hearings Before the State Water Resources Control Board. Phase 6: The Petition of the United States Bureau of Reclamation and the California Department of Water Resources for joint points of diversion in the southern Delta. Submitted 23 November 1998.
- Wickwire RH, Stevens DE. 1971. Migration and distribution of young king salmon, *Oncorhynchus tshawytscha*, in the Sacramento River near Collinsville. Anadromous Fisheries Branch Administrative Report No. 71-4. Stockton (CA): California Department of Fish and Game.

Notes

- Nelson, Tom (Coleman National Fish Hatchery). Phone conversation with author in October 1999.

**Appendix A:
Unexpanded Fish Facility Recoveries for Coded Wire Half Tagged Fry
Released in the Sacramento-San Joaquin Delta**

Table A-1 Unexpanded fish facility recoveries for CW1/2T fry released in the Sacramento-San Joaquin Delta^a

| Year | Tag code | Release site (stock) ^b | Release date | Number released | Size (mm) | Unexpanded recoveries | |
|------|----------|-----------------------------------|--------------|-----------------|-----------|-----------------------|------------------|
| | | | | | | CVP | SWP ^c |
| 1987 | H6-7-7 | Below RBDD (CNFH) | 13-Mar-87 | 52,977 | 52 | 0 | 1 |
| 1987 | B5-4-13 | Battle Creek (CNFH) | 12-Mar-87 | 51,075 | 51 | 1 | 0 |
| 1986 | H6-7-6 | Courtland (NFH) | 05-Mar-87 | 48,733 | 50 | 4 | 3 |
| 1986 | H6-7-5 | Below RBDD (CNFH) | 19-Mar-86 | 51,426 | 50 | 0 | 0 |
| 1986 | H5-7-7 | Battle Creek (CNFH) | 18-Mar-86 | 51,371 | 50 | 0 | 0 |
| 1986 | H6-6-7 | Courtland (CNFH) | 27-Feb-86 | 50,961 | 45 | 0 | 0 |
| 1986 | H6-7-3 | Courtland (CNFH) | 10-Mar-86 | 53,831 | 50 | 0 | 0 |
| 1986 | H6-7-2 | Ryde (CNFH) | 14-Mar-86 | 52,635 | 47 | 0 | 0 |
| 1986 | H6-7-4 | Ryde (CNFH) | 12-Mar-86 | 52,748 | 53 | 0 | 0 |
| 1985 | H6-5-5 | Below RBDD (CNFH) | 14-Feb-85 | 49,155 | 47 | 0 | 2 |
| 1985 | H6-6-5 | Below RBDD (CNFH) | 14-Mar-85 | 52,313 | 48 | 0 | 0 |
| 1985 | H6-5-6 | Courtland (CNFH) | 19-Feb-85 | 51,201 | 48 | 0 | 0 |
| 1985 | H6-6-4 | Courtland (CNFH) | 07-Mar-85 | 51,985 | 46 | 0 | (3) 6 |
| 1985 | H6-6-1 | South Fork Mokelumne (CNFH) | 26-Feb-85 | 50,052 | 48 | 2 | (2) 1 |
| 1985 | H6-6-2 | North Fork Mokelumne (CNFH) | 28-Feb-85 | 51,145 | 46 | 0 | (1) 3 |
| 1985 | H6-5-7 | Ryde (CNFH) | 21-Feb-85 | 49,183 | 47 | 0 | 0 |
| 1985 | H6-6-3 | Ryde (CNFH) | 05-Mar-85 | 50,550 | 47 | 1 | (2) 8 |
| 1984 | H6-4-4 | Below RBDD (CNFH) | 01-Mar-84 | 43,883 | 45 | 1 | 0 |
| 1984 | H6-5-4 | Below RBDD (CNFH) | 24-Mar-84 | 47,855 | 50 | 0 | 0 |
| 1984 | H6-4-5 | Courtland (CNFH) | 05-Mar-84 | 48,460 | 45 | 0 | 0 |
| 1984 | H6-5-3 | Courtland (CNFH) | 21-Mar-84 | 48,157 | 48 | 0 | 0 |
| 1984 | H6-4-6 | Ryde (CNFH) | 08-Mar-84 | 45,465 | 49 | 4 | 0 |
| 1984 | H6-5-2 | Ryde (CNFH) | 19-Mar-84 | 46,767 | 49 | 4 | 0 |
| 1984 | H6-5-1 | South Fork Mokelumne (CNFH) | 14-Mar-84 | 45,036 | 49 | 3 | 0 |
| 1984 | H6-4-7 | North Fork Mokelumne (CNFH) | 12-Mar-84 | 42,165 | 50 | 5 | 0 |
| 1983 | H6-3-3 | Isleton (FRH) | 04-Mar-83 | 45,775 | 44 | 0 | 0 |
| 1983 | H6-4-2 | Isleton (FRH) | 29-Mar-83 | 47,518 | 49 | 0 | 0 |
| 1983 | H6-3-4 | Courtland (FRH) | 09-Mar-83 | 48,541 | 47 | 0 | 0 |
| 1983 | H6-4-3 | Courtland (FRH) | 31-Mar-83 | 48,501 | 51 | 0 | 0 |
| 1983 | H6-3-5 | Mouth of Mokelumne (FRH) | 14-Mar-83 | 45,960 | N/A | 0 | 0 |

^a In some cases, average size was calculated from number of fish per pound using a conversion table (Source: USFWS 1982, Table I-6).

^b CNFH = Coleman National Fish Hatchery, FRH = Feather River Hatchery.

^c Salvage numbers in parentheses have an unknown location (either CVP or SWP).

Table A-1 Unexpanded fish facility recoveries for CW1/2T fry released in the Sacramento-San Joaquin Delta^a (Continued)

| Year | Tag code | Release site (stock) ^b | Release date | Number released | Size (mm) | Unexpanded recoveries | |
|-------------|--------------|-----------------------------------|------------------|-----------------|-----------|-----------------------|------------------|
| | | | | | | CVP | SWP ^c |
| 1983 | H6-4-1 | Mouth of Mokelumne (FRH) | 24-Mar-83 | 47,367 | 48 | 0 | 0 |
| 1983 | H6-3-6 | Lower Old River (FRH) | 17-Mar-83 | 47,677 | 49 | 0 | 0 |
| 1983 | H6-3-7 | Lower Old River (FRH) | 22-Mar-83 | 48,580 | 48 | 0 | 0 |
| 1982 | H6-2-2 | Below RBDD (CNFH) | 05-Feb-82 | 41,753 | 44 | 0 | 0 |
| 1982 | H6-2-6 | Below RBDD (CNFH) | 25-Feb-82 | 43,673 | 44 | 0 | 0 |
| 1982 | H6-2-3 | Isleton (CNFH) | 11-Feb-82 | 43,248 | 44 | 0 | 0 |
| 1982 | H6-2-7 | Isleton (CNFH) | 02-Mar-82 | 40,508 | 45 | 0 | 0 |
| 1982 | H6-2-4 | Mouth of Mokelumne (CNFH) | 17-Feb-82 | 43,849 | 43 | 0 | 0 |
| 1982 | H6-3-2 | Mouth of Mokelumne (CNFH) | 10-Mar-82 | 41,470 | 44 | 0 | 0 |
| 1982 | H6-2-5 | Berkeley (CNFH) | 22-Feb-82 | 40,699 | 44 | 0 | 0 |
| 1982 | H6-3-1 | Berkeley (CNFH) | 08-Mar-82 | 39,321 | 44 | 0 | 0 |
| 1981 | H6-1-1 | Below RBDD (CNFH) | 06-Feb-81 | 35,905 | 41 | 0 | 0 |
| 1981 | H6-1-5 | Below RBDD (CNFH) | 28-Feb-81 | 47,019 | 40 | 0 | 0 |
| 1981 | H6-1-4 | Berkeley (CNFH) | 25-Feb-81 | 49,705 | 44 | 0 | 0 |
| 1981 | H6-2-1 | Berkeley (CNFH) | 08-Mar-81 | 36,901 | 43 | 0 | 0 |
| 1981 | H6-1-3 | Mouth of Mokelumne (CNFH) | 20-Feb-81 | 45,193 | 44 | 2 | 0 |
| 1981 | H6-1-7 | Mouth of Mokelumne (CNFH) | 06-Mar-81 | 45,796 | 43 | 2 | 0 |
| 1981 | H6-1-2 | Isleton (CNFH) | 12-Feb-81 | 40,916 | 45 | 3 | 0 |
| 1981 | H6-1-6 | Isleton (CNFH) | 04-Mar-81 | 45,949 | 43 | 0 | 0 |
| 1981 | H5-2-4 | Berkeley (CNFH) | | 21,939 | 46 | 0 | 0 |
| 1981 | H5-2-5 | Berkeley (CNFH) | | 20,788 | 46 | 0 | 0 |
| 1981 | Total | | 28-Feb-80 | 42,727 | | | |
| 1981 | H5-2-6 | Clarksburg (CNFH) | | 22,121 | 50 | 0 | 0 |
| 1981 | H5-2-7 | Clarksburg (CNFH) | | 21,624 | 50 | 0 | 0 |
| 1981 | Total | | 28-Feb-80 | 43,745 | | | |
| 1981 | H5-3-3 | Clarksburg (CNFH) | | 23,908 | 46 | 0 | 0 |
| 1981 | H5-3-4 | Clarksburg (CNFH) | | 22,829 | 44 | 0 | 0 |
| 1981 | Total | | 31-Mar-80 | 46,737 | | | |

^a In some cases, average size was calculated from number of fish per pound using a conversion table (Source: USFWS 1982, Table I-6).

^b CNFH = Coleman National Fish Hatchery, FRH = Feather River Hatchery.

^c Salvage numbers in parentheses have an unknown location (either CVP or SWP).

**Appendix B:
Chippis Island Tag Summary and Survival Calculations
for Coded Wire Tagged Fish Groups with Multiple Tag Codes**

Table B-1 1997 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-6-2-11 | West Sacramento (FRH) | | 25,641 | 22-Apr-97 | 07-May-97 | 14 | 0.52 | |
| 6-1-6-2-12 | West Sacramento (FRH) | | 25,032 | 22-Apr-97 | 08-May-97 | 9 | 0.34 | |
| | Total | 15-Apr-97 | 50,673 | 22-Apr-97 | 08-May-97 | 23 | | 0.43 |
| 6-1-6-3-2 | Mossdale (w/ barrier) (FRH) | | 23,701 | 03-May-97 | 07-May-97 | 2 | 0.08 | |
| 6-1-6-3-3 | Mossdale (w/ barrier) (FRH) | | 25,073 | 05-May-97 | 18-May-97 | 8 | 0.31 | |
| | Total | 28-Apr-97 | 48,774 | 03-May-97 | 18-May-97 | 10 | | 0.19 |
| 6-1-6-3-4 | Dos Reis (FRH) | | 25,084 | 06-May-97 | 11-May-97 | 7 | 0.27 | |
| 6-1-6-3-5 | Dos Reis (FRH) | | 24,746 | 06-May-97 | 11-May-97 | 3 | 0.12 | |
| | Total | 29-Apr-97 | 49,830 | 06-May-97 | 11-May-97 | 10 | | 0.19 |
| 6-25-45 | Dos Reis (MRFF) | | 49,005 | 08-May-97 | 16-May-97 | 9 | 0.18 | |
| 6-25-46 | Dos Reis (MRFF) | | 53,475 | 10-May-97 | 15-May-97 | 7 | 0.13 | |
| | Total | 29-Apr-97 | 102,480 | 08-May-97 | 16-May-97 | 16 | | 0.15 |
| 6-1-6-2-13 | West Sacramento (FRH) | | 25,829 | 05-May-97 | 15-May-97 | 15 | 0.55 | |
| 6-1-6-2-14 | West Sacramento (FRH) | | 26,315 | 07-May-97 | 10-May-97 | 7 | 0.25 | |
| | Total | 01-May-97 | 52,144 | 05-May-97 | 15-May-97 | 22 | | 0.40 |
| 6-1-6-2-7 | Jersey Point (FRH) | | 24,815 | 03-May-97 | 10-May-97 | 27 | 1.03 | |
| 6-1-6-2-8 | Jersey Point (FRH) | | 25,049 | 04-May-97 | 11-May-97 | 28 | 1.05 | |
| | Total | 02-May-97 | 49,864 | 03-May-97 | 11-May-97 | 55 | | 1.03 |
| 6-1-6-2-9 | West Sacramento (FRH) | | 25,152 | --- | --- | 0 | | |
| 6-1-6-2-10 | West Sacramento (FRH) | | 25,069 | 21-May-97 | 21-May-97 | 1 | 0.04 | |
| | Total | 15-May-97 | 50,221 | 21-May-97 | 21-May-97 | 1 | | 0.02 |

^a FRH = Feather River Hatchery, MRFF = Merced River Fish Facility.

Table B-2 1997 Upper San Joaquin River Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-11-5-11 | Upper Merced (MRFF) | | 26,045 | 06-May-97 | 06-May-97 | 1 | 0.04 | |
| 6-1-11-5-12 | Upper Merced (MRFF) | | 27,683 | 06-May-97 | 08-May-97 | 3 | 0.10 | |
| 6-1-11-5-13 | Upper Merced (MRFF) | | 31,930 | 09-May-97 | 09-May-97 | 1 | 0.03 | |
| 6-1-11-6-12 | Upper Merced (MRFF) | | 24,880 | --- | --- | 0 | | |
| | Total | 20-Apr-97 | 110,538 | 06-May-97 | 09-May-97 | 5 | | 0.04 |
| 6-1-11-5-15 | Lower Merced (MRFF) | | 24,398 | 04-May-97 | 14-May-97 | 6 | 0.23 | |
| 6-1-11-6-1 | Lower Merced (MRFF) | | 29,011 | 04-May-97 | 09-May-97 | 3 | 0.10 | |
| 6-1-11-6-2 | Lower Merced (MRFF) | | 25,761 | 03-May-97 | 12-May-97 | 7 | 0.25 | |
| 6-1-11-6-3 | Lower Merced (MRFF) | | 25,317 | --- | --- | 0 | | |
| | Total | 22-Apr-97 | 104,487 | 03-May-97 | 14-May-97 | 16 | | 0.14 |
| 6-1-11-6-7 | Upper Tuolumne (MRFF) | | 31,112 | 18-May-97 | 18-May-97 | 1 | 0.04 | |
| 6-1-11-6-8 | Upper Tuolumne (MRFF) | | 29,947 | --- | --- | 0 | | |
| 6-1-11-6-9 | Upper Tuolumne (MRFF) | | 24,551 | 24-May-97 | 24-May-97 | 1 | 0.04 | |
| 6-1-11-6-10 | Upper Tuolumne (MRFF) | | 7,897 | 18-May-97 | 18-May-97 | 1 | 0.14 | |
| | Total | 22-Apr-97 | 93,507 | 18-May-97 | 24-May-97 | 3 | | 0.036 |
| 6-1-11-6-4 | Lower Tuolumne (MRFF) | | 25,241 | 11-May-97 | 18-May-97 | 6 | 0.23 | |
| 6-1-11-6-5 | Lower Tuolumne (MRFF) | | 25,692 | 11-May-97 | 18-May-97 | 2 | 0.07 | |
| 6-1-11-6-6 | Lower Tuolumne (MRFF) | | 21,531 | 08-May-97 | 21-May-97 | 4 | 0.19 | |
| | Total | 23-Apr-97 | 72,464 | 08-May-97 | 21-May-97 | 12 | | 0.17 |
| 6-1-11-6-14 | Lower Merced (MRFF) | | 33,064 | --- | --- | 0 | | |
| 6-1-11-6-15 | Lower Merced (MRFF) | | 28,294 | 28-May-97 | 28-May-97 | 1 | 0.03 | |
| 6-1-11-7-1 | Lower Merced (MRFF) | | 24,943 | --- | --- | 0 | | |
| 6-1-11-7-2 | Lower Merced (MRFF) | | 5,856 | --- | --- | 0 | | |
| | Total | 14-May-97 | 92,157 | 28-May-97 | 28-May-97 | 1 | | 0.01 |

^a MRFF = Merced River Fish Facility.

Contributions to the Biology of Central Valley Salmonids

Table B-3 1996 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-01-06-01-14 | Mossdale (FRH) | | 49,024 | --- | --- | 0 | | |
| 6-01-06-01-15 | Mossdale (FRH) | | 51,718 | 25-Apr-96 | 27-Apr-96 | 2 | 0.04 | |
| | Total | 15-Apr-96 | 100,742 | 25-Apr-96 | 27-Apr-96 | 2 | | 0.02 |
| 6-01-06-02-01 | Mossdale (FRH) | | 50,462 | 07-May-96 | 07-May-96 | 1 | 0.02 | |
| 6-01-06-02-05 | Mossdale (FRH) | | 49,194 | --- | --- | 0 | | |
| | Total | 30-Apr-96 | 99,656 | 07-May-96 | 07-May-96 | 1 | | 0.01 |
| 6-01-06-02-03 | Dos Reis (FRH) | | 49,868 | 09-May-96 | 23-May-96 | 2 | 0.04 | |
| 6-01-06-01-10 | Dos Reis (FRH) | | 48,770 | 11-May-96 | 11-May-96 | 1 | 0.02 | |
| | Total | 01-May-96 | 98,819 | 09-May-96 | 23-May-96 | 2 | | 0.02 |
| 6-01-11-04-12 | Dos Reis (MRFF) | | 25,530 | 08-May-96 | 10-May-96 | 2 | 0.07 | |
| 6-01-11-04-13 | Dos Reis (MRFF) | | 28,079 | 05-May-96 | 07-May-96 | 2 | 0.07 | |
| 6-01-11-04-14 | Dos Reis (MRFF) | | 18,459 | 06-May-96 | 06-May-96 | 1 | 0.05 | |
| 6-01-11-04-15 | Dos Reis (MRFF) | | 35,893 | 08-May-96 | 12-May-96 | 5 | 0.13 | |
| | Total | 01-May-96 | 107,961 | 05-May-96 | 12-May-96 | 10 | | 0.09 |

^a FRH = Feather River Hatchery, MRFF = Merced River Fish Facility.

Table B-4 1996 Upper San Joaquin River Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-01-11-04-08 | Upper Merced (MRFF) | | 21,011 | --- | --- | 0 | | |
| 6-01-11-04-09 | Upper Merced (MRFF) | | 21,069 | --- | --- | 0 | | |
| 6-01-11-04-10 | Upper Merced (MRFF) | | 22,638 | 08-May-96 | 08-May-96 | 1 | 0.04 | |
| 6-01-11-04-11 | Upper Merced (MRFF) | | 21,693 | --- | --- | 0 | | |
| | Total | 25-Apr-96 | 86,411 | 08-May-96 | 08-May-96 | 1 | | 0.01 |
| 6-01-11-05-03 | Lower Merced (MRFF) | | 21,705 | --- | --- | 0 | | |
| 6-01-11-05-04 | Lower Merced (MRFF) | | 22,019 | 05-May-96 | 05-May-96 | 1 | 0.04 | |
| 6-01-11-05-05 | Lower Merced (MRFF) | | 20,613 | --- | --- | 0 | | |
| | Total | 26-Apr-96 | 64,337 | 05-May-96 | 05-May-96 | 1 | | 0.01 |
| 6-01-11-05-06 | Upper Tuolumne (MRFF) | | 21,601 | --- | --- | 0 | | |
| 6-01-11-05-07 | Upper Tuolumne (MRFF) | | 22,861 | 02-May-96 | 06-May-96 | 2 | 0.08 | |
| 6-01-11-05-08 | Upper Tuolumne (MRFF) | 26-Apr-96 | 22,984 | 06-May-96 | 06-May-96 | 1 | 0.04 | |
| | Total | | 67,446 | 02-May-96 | 06-May-96 | 3 | | 0.04 |
| 6-01-11-05-09 | Upper Tuolumne (MRFF) | | 22,789 | 02-May-96 | 02-May-96 | 1 | 0.04 | |
| 6-01-11-05-10 | Upper Tuolumne (MRFF) | | 27,819 | 01-May-96 | 08-May-96 | 3 | 0.10 | |
| | Total | 27-Apr-96 | 50,608 | 01-May-96 | 08-May-96 | 4 | | 0.07 |

^a MRFF = Merced River Fish Facility.

Contributions to the Biology of Central Valley Salmonids

Table B-5 1995 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-14-5-1 | Mossdale (FRH) | | 50,849 | 25-Apr-95 | 24-May-95 | 10 | 0.19 | |
| 6-1-14-4-14 | Mossdale (FRH) | | 50,120 | 26-Apr-95 | 17-May-95 | 10 | 0.19 | |
| | Total | 17-Apr-95 | 100,969 | 25-Apr-95 | 24-May-95 | 20 | | 0.19 |
| 6-31-50 | Mossdale (FRH) | | 52,297 | 12-May-95 | 24-May-95 | 10 | 0.19 | |
| 6-31-51 | Mossdale (FRH) | | 50,265 | 12-May-95 | 02-Jun-95 | 3 | 0.06 | |
| | Total | 05-May-95 | 102,562 | 12-May-95 | 02-Jun-95 | 13 | | 0.12 |
| 6-1-14-5-4 | Mossdale (FRH) | | 52,703 | 29-May-95 | 29-May-95 | 1 | 0.02 | |
| 6-31-48 | Mossdale (FRH) | | 51,422 | 21-May-95 | 29-May-95 | 7 | 0.13 | |
| | Total | 17-May-95 | 104,125 | 21-May-95 | 29-May-95 | 8 | | 0.07 |

^a FRH = Feather River Hatchery.

Table B-6 1995 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-11-4-1 | Upper Merced (MRFF) | | 28,349 | 08-May-95 | 29-May-95 | 5 | 0.17 | |
| 6-1-11-4-2 | Upper Merced (MRFF) | | 27,961 | 21-May-95 | 13-Jun-95 | 3 | 0.10 | |
| 6-1-11-4-3 | Upper Merced (MRFF) | | 26,839 | 28-May-95 | 12-Jun-95 | 4 | 0.14 | |
| 6-1-11-4-4 | Upper Merced (MRFF) | | 28,138 | 23-May-95 | 06-Jun-95 | 6 | 0.20 | |
| | Total | 03-May-95 | 111,287 | 08-May-95 | 13-Jun-95 | 18 | | 0.16 |
| 6-1-11-4-5 | Lower Merced (MRFF) | | 27,318 | 21-May-95 | 03-Jun-95 | 7 | 0.24 | |
| 6-1-11-4-6 | Lower Merced (MRFF) | | 27,643 | 21-May-95 | 09-Jun-95 | 4 | 0.14 | |
| 6-1-11-4-7 | Lower Merced (MRFF) | | 28,054 | 20-May-95 | 29-May-95 | 7 | 0.23 | |
| | Total | 04-May-95 | 83,015 | 20-May-95 | 09-Jun-95 | 18 | | 0.20 |
| 6-1-11-3-11 | Upper Tuolumne (MRFF) | | 28,068 | 31-May-95 | 13-Jun-95 | 8 | 0.27 | |
| 6-1-11-3-12 | Upper Tuolumne (MRFF) | | 27,132 | 21-May-95 | 25-Jun-95 | 6 | 0.22 | |
| 6-1-11-3-13 | Upper Tuolumne (MRFF) | | 28,347 | 29-May-95 | 14-Jun-95 | 8 | 0.27 | |
| | Total | 04-May-95 | 83,547 | 21-May-95 | 25-Jun-95 | 22 | | 0.26 |

^a MRFF = Merced River Fish Facility.

Contributions to the Biology of Central Valley Salmonids

Table B-7 1994 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-11-2-10 | Upper Merced (MRFF) | | 28,315 | 01-May-94 | 02-May-94 | 2 | 0.07 | |
| 6-1-11-2-11 | Upper Merced (MRFF) | | 25,328 | 01-May-94 | 01-May-94 | 1 | 0.04 | |
| 6-1-11-2-12 | Upper Merced (MRFF) | | 28,532 | 01-May-94 | 08-May-94 | 2 | 0.07 | |
| 6-1-11-2-13 | Upper Merced (MRFF) | | 17,390 | 15-May-94 | 15-May-94 | 1 | 0.05 | |
| | Total | 22-Apr-94 | 99,565 | 01-May-94 | 15-May-94 | 6 | | 0.06 |
| 6-1-11-2-14 | Lower Merced (MRFF) | | 35,017 | --- | --- | 0 | | |
| 6-1-11-2-15 | Lower Merced (MRFF) | | 23,324 | 01-May-94 | 03-May-94 | 2 | 0.08 | |
| 6-1-11-3-1 | Lower Merced (MRFF) | | 23,750 | --- | --- | 0 | | |
| | Total | 22-Apr-94 | 82,091 | 01-May-94 | 03-May-94 | 2 | | 0.02 |
| 6-1-11-3-2 | Upper Tuolumne (MRFF) | | 58,859 | 05-May-94 | 14-May-94 | 2 | 0.03 | |
| 6-1-11-3-3 | Upper Tuolumne (MRFF) | | 4,281 | 12-May-94 | 12-May-94 | 1 | 0.22 | |
| 6-1-11-3-4 | Upper Tuolumne (MRFF) | | 20,274 | --- | --- | 0 | | |
| | Total | 23-Apr-94 | 83,414 | 05-May-94 | 14-May-94 | 3 | | 0.03 |
| 6-1-11-3-5 | Lower Tuolumne (MRFF) | | 36,429 | 06-May-94 | 06-May-94 | 1 | 0.03 | |
| 6-1-11-3-6 | Lower Tuolumne (MRFF) | | 13,626 | 08-May-94 | 08-May-94 | 1 | 0.07 | |
| | Total | 24-Apr-94 | 50,055 | 06-May-94 | 08-May-94 | 2 | | 0.04 |

^a MRFF = Merced River Fish Facility.

Table B-8 1992 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-14-2-12 | Mossdale (FRH) | | 54,073 | 13-Apr-92 | 05-May-92 | 9 | 0.16 | |
| 6-1-14-2-13 | Mossdale (FRH) | | 53,030 | 13-Apr-92 | 01-May-92 | 11 | 0.20 | |
| | Total | 07-Apr-92 | 107,103 | 13-Apr-92 | 05-May-92 | 20 | | 0.18 |
| 6-1-14-2-14 | Mossdale (FRH) | | 53,754 | 16-Apr-92 | 27-Apr-92 | 10 | 0.17 | |
| 6-1-14-2-15 | Mossdale (FRH) | | 49,958 | 21-Apr-92 | 01-May-92 | 3 | 0.06 | |
| | Total | 13-Apr-92 | 103,712 | 16-Apr-92 | 01-May-92 | 13 | | 0.12 |
| 6-1-14-3-3 | Mossdale (w/barrier) (FRH) | | 53,294 | 03-May-92 | 06-May-92 | 7 | 0.12 | |
| 6-1-14-3-4 | Mossdale (w/barrier) (FRH) | | 51,445 | 04-May-92 | 19-May-92 | 2 | 0.04 | |
| | Total | 24-Apr-92 | 104,739 | 03-May-92 | 19-May-92 | 9 | | 0.08 |
| 6-31-31 | Mossdale (w/barrier) (FRH) | | 51,262 | 16-May-92 | 16-May-92 | 1 | 0.02 | |
| 6-31-32 | Mossdale (w/barrier) (FRH) | | 48,455 | --- | --- | 0 | | |
| | Total | 04-May-92 | 99,717 | 16-May-92 | 16-May-92 | 1 | 0.01 | 0.01 |
| 6-31-33 | Mossdale (w/barrier) (FRH) | | 52,454 | --- | --- | 0 | | |
| 6-31-34 | Mossdale (w/barrier) (FRH) | | 52,931 | 21-May-92 | 23-May-92 | 2 | 0.04 | |
| | Total | 12-May-92 | 105,385 | 21-May-92 | 23-May-92 | 2 | | 0.02 |

^a FRH = Feather River Hatchery, w/barrier = with barrier in upper Old River.

Contributions to the Biology of Central Valley Salmonids

Table B-9 1991 Upper Sacramento River, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 5-18-45 | Princeton (CNFH) | | 12,474 | 14-May-91 | 19-May-91 | 4 | 0.30 | |
| 5-18-47 | Princeton (CNFH) | | 18,713 | 11-May-91 | 21-May-91 | 10 | 0.50 | |
| 5-18-48 | Princeton (CNFH) | | 20,792 | 10-May-91 | 30-May-91 | 10 | 0.46 | |
| | Total | 03-May-91 | 51,979 | 10-May-91 | 30-May-91 | 24 | | 0.44 |

^a CNFH = Coleman National Fish Hatchery.

Table B-10 1991 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-14-1-14 | Dos Reis (FRH) | | 52,097 | 23-Apr-91 | 11-May-91 | 8 | 0.15 | |
| 6-1-14-1-15 | Dos Reis (FRH) | | 50,902 | 23-Apr-91 | 02-May-91 | 9 | 0.17 | |
| | Total | 15-Apr-91 | 102,999 | 23-Apr-91 | 11-May-91 | 17 | | 0.16 |
| 6-1-14-2-1 | Buckley Cove (FRH) | | 51,128 | 24-Apr-91 | 06-May-91 | 15 | 0.28 | |
| 6-1-14-2-2 | Buckley Cove (FRH) | | 48,213 | 25-Apr-91 | 02-May-91 | 11 | 0.21 | |
| | Total | 16-Apr-91 | 99,341 | 24-Apr-91 | 06-May-91 | 26 | | 0.24 |
| 6-1-14-2-3 | Empire Tract (FRH) | | 48,255 | 24-Apr-91 | 09-May-91 | 25 | 0.48 | |
| 6-1-14-2-4 | Empire Tract (FRH) | | 47,347 | 24-Apr-91 | 12-May-91 | 29 | 0.58 | |
| | Total | 17-Apr-91 | 95,602 | 24-Apr-91 | 12-May-91 | 54 | | 0.54 |
| 6-1-14-2-7 | Sacramento (Miller Park) (FRH) | | 51,392 | 01-May-91 | 06-May-91 | 34 | 0.62 | |
| 6-1-14-2-8 | Sacramento (Miller Park) (FRH) | | 51,272 | 30-Apr-91 | 09-May-91 | 50 | 0.91 | |
| | Total | 25-Apr-91 | 102,664 | 30-Apr-91 | 09-May-91 | 84 | | 0.77 |
| 6-1-14-2-9 | Sacramento (Miller Park) (FRH) | | 53,430 | 27-Apr-91 | 16-May-91 | 21 | 0.37 | |
| 6-31-24 | Sacramento (Miller Park) (FRH) | | 51,086 | 04-May-91 | 10-May-91 | 34 | 0.64 | |
| | Total | 29-Apr-91 | 104,516 | 27-Apr-91 | 16-May-91 | 55 | | 0.50 |
| 6-31-25 | Buckley Cove (FRH) | | 49,393 | 11-May-91 | 30-May-91 | 7 | 0.13 | |
| 6-31-26 | Buckley Cove (FRH) | | 50,427 | 11-May-91 | 16-May-91 | 13 | 0.24 | |
| | Total | 06-May-91 | 99,820 | 11-May-91 | 30-May-91 | 20 | | 0.19 |

^a FRH = Feather River Hatchery.

Table B-11 1990 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-14-1-8 | Dos Reis (FRH) | | 53,254 | 26-Apr-90 | 13-May-90 | 2 | 0.04 | |
| 6-1-14-1-7 | Dos Reis (FRH) | | 52,488 | 12-May-90 | 15-May-90 | 2 | 0.04 | |
| | Total | 16-Apr-90 | 105,742 | 26-Apr-90 | 15-May-90 | 4 | | 0.04 |
| 6-1-14-1-6 | Upper Old River (FRH) | | 52,954 | --- | --- | 0 | | |
| 6-1-14-1-5 | Upper Old River (FRH) | | 53,313 | 24-Apr-90 | 01-May-90 | 2 | 0.041 | |
| | Total | 17-Apr-90 | 106,267 | 24-Apr-90 | 01-May-90 | 2 | | 0.02 |
| 6-1-14-1-12 | Upper Old River (FRH) | | 51,521 | 16-May-90 | 16-May-90 | 1 | 0.02 | |
| 6-1-14-1-13 | Upper Old River (FRH) | | 52,074 | --- | --- | 0 | | |
| | Total | 03-May-90 | 103,595 | 16-May-90 | 16-May-90 | 1 | | 0.01 |

^a FRH = Feather River Hatchery.

Table B-12 1990 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-11-1-14 | Upper Tuolumne (MRFF) | | 24,134 | 12-May-90 | 12-May-90 | 1 | 0.04 | |
| 6-1-11-1-15 | Upper Tuolumne (MRFF) | | 24,259 | 16-May-90 | 16-May-90 | 1 | 0.04 | |
| 6-1-11-2-1 | Upper Tuolumne (MRFF) | | 23,494 | 12-May-90 | 12-May-90 | 1 | 0.04 | |
| 6-1-11-2-2 | Upper Tuolumne (MRFF) | | 21,766 | 08-May-90 | 08-May-90 | 1 | 0.04 | |
| | Total | 30-Apr-90 | 93,653 | 08-May-90 | 16-May-90 | 4 | | 0.04 |
| 6-1-11-2-3 | Lower Tuolumne (TRFF) | | 27,263 | 12-May-90 | 12-May-90 | 1 | 0.03 | |
| 6-1-11-2-4 | Lower Tuolumne (TRFF) | | 26,067 | --- | --- | 0 | | |
| 6-1-11-2-5 | Lower Tuolumne (TRFF) | | 24,905 | --- | --- | 0 | | |
| | Total | 01-May-90 | 78,235 | 12-May-90 | 12-May-90 | 1 | | 0.01 |

^a MRFF = Merced River Fish Facility, TRFF = Tuolumne River Fish Facility.

Table B-13 1989 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-1-11-1-11 | Jersey Point (FRH) | | 27,758 | 29-Apr-89 | 15-May-89 | 24 | 0.81 | |
| 6-1-11-1-12 | Jersey Point (FRH) | | 29,058 | 29-Apr-89 | 12-May-89 | 29 | 0.94 | |
| | Total | 24-Apr-89 | 56,816 | 29-Apr-89 | 15-May-89 | 53 | | 0.88 |
| 6-1-11-1-7 | Dos Reis (MRFF) | | 25,089 | 10-May-89 | 30-May-89 | 3 | 0.12 | |
| 6-1-11-1-8 | Dos Reis (MRFF) | | 25,631 | 08-May-89 | 24-May-89 | 7 | 0.26 | |
| 6-1-11-1-13 | Dos Reis (MRFF) | | 25,353 | 10-May-89 | 10-May-89 | 1 | 0.04 | |
| | Total | 02-May-89 | 76,073 | 08-May-89 | 30-May-89 | 11 | | 0.15 |
| 6-1-11-1-4 | Upper Old River (MRFF) | | 25,087 | 08-May-89 | 08-May-89 | 1 | 0.04 | |
| 6-1-11-1-5 | Upper Old River (MRFF) | | 24,472 | 09-May-89 | 09-May-89 | 1 | 0.04 | |
| 6-1-11-1-6 | Upper Old River (MRFF) | | 24,782 | 08-May-89 | 15-May-89 | 2 | 0.08 | |
| | Total | 03-May-89 | 74,341 | 08-May-89 | 15-May-89 | 4 | | 0.05 |
| 6-1-11-1-9 | Jersey Point (FRH) | | 27,525 | 08-May-89 | 25-May-89 | 33 | 1.13 | |
| 6-1-11-1-10 | Jersey Point (FRH) | | 28,708 | 08-May-89 | 22-May-89 | 25 | 0.82 | |
| | Total | 05-May-89 | 56,233 | 08-May-89 | 25-May-89 | 58 | | 1.0 |
| 6-31-15 | Sacramento (Miller Park) (FRH) | | 44,695 | 17-Jun-89 | 19-Jun-89 | 11 | 0.23 | |
| 6-31-17 | Sacramento (Miller Park) (FRH) | | 49,909 | 17-Jun-89 | 19-Jun-89 | 9 | 0.17 | |
| | Total | 14-Jun-89 | 94,604 | 17-Jun-89 | 19-Jun-89 | 20 | | 0.20 |

^a FRH = Feather River Hatchery, MRFF = Merced River Fish Facility.

Table B-14 1989 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| B6-14-9 | Upper Stanislaus (MRFF) | | 52,445 | 29-Apr-89 | 11-May-89 | 3 | 0.05 | |
| B6-14-10 | Upper Stanislaus (MRFF) | | 51,506 | 30-Apr-89 | 16-May-89 | 4 | 0.07 | |
| | Total | 20-Apr-89 | 103,951 | 29-Apr-89 | 16-May-89 | 7 | | 0.06 |
| B6-1-1 | Lower Stanislaus (MRFF) | | 25,525 | 24-Apr-89 | 02-May-89 | 11 | 0.40 | |
| B6-14-11 | Lower Stanislaus (MRFF) | | 48,695 | 24-Apr-89 | 27-Apr-89 | 6 | 0.12 | |
| | Total | 19-Apr-89 | 74,220 | 24-Apr-89 | 2-May-89 | 17 | | 0.21 |
| 6-1-11-1-1 | Lower Merced (MRFF) | | 25,357 | 03-May-89 | 10-May-89 | 3 | 0.11 | |
| 6-1-11-1-2 | Lower Merced (MRFF) | | 25,276 | 15-May-89 | 15-May-89 | 1 | 0.04 | |
| 6-1-11-1-3 | Lower Merced (MRFF) | | 23,832 | --- | --- | 0 | | |
| | Total | 21-Apr-89 | 74,465 | 03-May-89 | 15-May-89 | 4 | | 0.05 |

^a MRFF = Merced River Fish Facility.

Table B-15 1988 Sacramento-San Joaquin Estuary Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| B6-14-2 | Courtland (FRH) | | 51,388 | 07-May-88 | 21-May-88 | 71 | 0.65 | |
| B6-14-3 | Courtland (FRH) | | 55,861 | 07-May-88 | 25-May-88 | 83 | 0.70 | |
| | Total | 03-May-88 | 107,249 | 07-May-88 | 25-May-88 | 154 | | 0.68 |
| B6-14-6 | Sacramento (Miller Park) (FRH) | | 51,005 | 08-May-88 | 23-May-88 | 77 | 0.71 | |
| B6-14-7 | Sacramento (Miller Park) (FRH) | | 51,731 | 09-May-88 | 21-May-88 | 65 | 0.59 | |
| | Total | 05-May-88 | 102,736 | 08-May-88 | 23-May-88 | 142 | | 0.65 |
| B6-14-4 | Courtland (FRH) | | 51,274 | 08-May-88 | 27-May-88 | 67 | 0.67 | |
| B6-14-5 | Courtland (FRH) | | 51,206 | 10-May-88 | 21-May-88 | 80 | 0.73 | |
| | Total | 06-May-88 | 102,480 | 08-May-88 | 27-May-88 | 147 | | 0.73 |
| 6-62-59 | Courtland (FRH) | | 54,997 | 23-Jun-88 | 29-Jun-88 | 25 | 0.21 | |
| 6-62-60 | Courtland (FRH) | | 51,904 | 23-Jun-88 | 03-Jul-88 | 14 | 0.13 | |
| | Total | 21-Jun-88 | 106,901 | 23-Jun-88 | 03-Jul-88 | 39 | | 0.17 |
| 6-62-61 | Sacramento (Miller Park) (FRH) | | 49,245 | 26-Jun-88 | 07-Jul-88 | 7 ^b | 0.08 | |
| 6-62-62 | Sacramento (Miller Park) (FRH) | | 48,647 | 26-Jun-88 | 03-Jul-88 | 7 ^b | 0.07 | |
| | Total | 23-Jun-88 | 97,892 | 26-Jun-88 | 07-Jul-88 | 14 | | 0.08 |

^a FRH = Feather River Hatchery.

^b Total number recovered for both tag code 6-62-61 and 6-62-62 is reduced by 1, as they were recorded as being recovered at Chipps Island on the day of release.

Table B-16 1988 Upper San Joaquin River and Tributaries Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| B6-11-5 | Upper Stanislaus (MRFF) | | 36,769 | 04-May-88 | 11-May-88 | 6 | 0.08 | |
| B6-11-6 | Upper Stanislaus (MRFF) | | 34,906 | 12-May-88 | 21-May-88 | 5 | 0.07 | |
| | Total | 26-Apr-88 | 71,675 | 04-May-88 | 21-May-88 | 11 | | 0.07 |
| B6-11-3 | Lower Stanislaus (MRFF) | | 35,249 | 03-May-88 | 19-May-88 | 6 | 0.08 | |
| B6-11-4 | Lower Stanislaus (MRFF) | | 33,539 | 07-May-88 | 22-May-88 | 7 | 0.10 | |
| | Total | 26-Apr-88 | 68,788 | 03-May-88 | 22-May-88 | 13 | | 0.09 |

^a MRFF = Merced River Fish Facility.

Table B-17 1987 Sacramento San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-45-3 | Upper Old River (MRFF) | | 31,099 | 30-Apr-87 | 06-May-87 | 8 | 0.23 | |
| 6-45-4 | Upper Old River (MRFF) | | 29,253 | 30-Apr-87 | 05-May-87 | 5 | 0.16 | |
| 6-45-5 | Upper Old River (MRFF) | | 30,600 | 30-Apr-87 | 03-May-87 | 3 | 0.07 | |
| | Total | 27-Apr-87 | 90,952 | 30-Apr-87 | 06-May-87 | 16 | | 0.16 |
| 6-45-6 | Dos Reis (MRFF) | | 30,919 | 05-May-87 | 13-May-87 | 30 | 0.93 | |
| 6-45-7 | Dos Reis (MRFF) | | 31,634 | 05-May-87 | 20-May-87 | 22 | 0.66 | |
| 6-45-8 | Dos Reis (MRFF) | | 30,059 | 05-May-87 | 12-May-87 | 28 | 0.89 | |
| | Total | 27-Apr-87 | 92,612 | 05-May-87 | 20-May-87 | 80 | | 0.83 |
| 6-62-53 | Courtland (FRH) | | 49,781 | 01-May-87 | 12-May-87 | 32 | 0.60 | |
| 6-62-54 | Courtland (FRH) | | 50,521 | 01-May-87 | 14-May-87 | 39 | 0.72 | |
| | Total | 28-Apr-87 | 100,302 | 01-May-87 | 14-May-87 | 71 | | 0.66 |
| 6-62-56 | Courtland (FRH) | | 49,083 | 04-May-87 | 15-May-87 | 20 | 0.39 | |
| 6-62-57 | Courtland (FRH) | | 51,836 | 05-May-87 | 22-May-87 | 23 | 0.42 | |
| | Total | 01-May-87 | 100,919 | 04-May-87 | 22-May-87 | 43 | | 0.41 |

^a MRFF = Merced River Fish Facility, FRH = Feather River Hatchery.

Table B-18 1987 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-46-60 | Upper Tuolumne (MRFF) | | 29,959 | 25-Apr-87 | 01-May-87 | 2 | 0.06 | |
| 6-46-61 | Upper Tuolumne (MRFF) | | 30,601 | --- | --- | 0 | | |
| 6-46-62 | Upper Tuolumne (MRFF) | | 29,040 | 28-Apr-87 | 30-Apr-87 | 3 | 0.10 | |
| | Total | 16-Apr-87 | 89,600 | 25-Apr-87 | 01-May-87 | 5 | | 0.05 |
| 6-45-1 | Lower Tuolumne (MRFF) | | 31,866 | 22-Apr-87 | 04-May-87 | 5 | 0.14 | |
| 6-45-2 | Lower Tuolumne (MRFF) | | 30,936 | 22-Apr-87 | 05-May-87 | 9 | 0.27 | |
| 6-46-63 | Lower Tuolumne (MRFF) | | 30,709 | 26-Apr-87 | 05-May-87 | 4 | 0.12 | |
| | Total | 16-Apr-87 | 93,511 | 22-Apr-87 | 05-May-87 | 18 | | 0.18 |

^a MRFF = Merced River Fish Facility.

Table B-19 1986 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| H5-4-2 | Battle Creek (CNFH) | | 24,933 | 21-May-86 | 26-May-86 | 11 | 0.41 | |
| H5-4-3 | Battle Creek (CNFH) | | 28,659 | 21-May-86 | 27-May-86 | 19 | 0.62 | |
| | Total | 13-May-86 | 53,592 | 21-May-86 | 27-May-86 | 30 | | 0.52 |
| H5-4-4 | Below RBDD (CNFH) | | 26,900 | 21-May-86 | 31-May-86 | 9 | 0.31 | |
| H5-4-5 | Below RBDD (CNFH) | | 27,606 | 20-May-86 | 01-Jun-86 | 17 | 0.58 | |
| | Total | 13-May-86 | 54,506 | 20-May-86 | 01-Jun-86 | 26 | | 0.45 |
| H5-4-6 | Princeton (CNFH) | | 23,669 | 23-May-86 | 27-May-86 | 3 | 0.12 | |
| H5-4-7 | Princeton (CNFH) | | 22,719 | 19-May-86 | 22-May-86 | 7 | 0.29 | |
| | Total | 14-May-86 | 56,388 | 19-May-86 | 27-May-86 | 10 | | 0.17 |

^a CNFH = Coleman National Fish Hatchery.

Table B-20 1986 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-46-58 | Dos Reis (MRFF) | | 47,954 | 02-Jun-86 | 08-Jun-86 | 13 | 0.25 | |
| B6-11-1 | Dos Reis (MRFF) | | 47,641 | 02-Jun-86 | 07-Jun-86 | 22 | 0.43 | |
| | Total | 29-May-86 | 95,595 | 02-Jun-86 | 08-Jun-86 | 35 | | 0.34 |
| 6-46-59 | Upper Old River (MRFF) | | 49,434 | 01-Jun-86 | 06-Jun-86 | 10 | 0.19 | |
| B6-11-2 | Upper Old River (MRFF) | | 50,747 | 01-Jun-86 | 03-Jun-86 | 11 | 0.20 | |
| | Total | 30-May-86 | 100,181 | 01-Jun-86 | 06-Jun-86 | 21 | | 0.20 |

^a MRFF = Merced River Fish Facility.

Table B-21 1986 Upper San Joaquin River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-46-54 | Upper Tuolumne (MRFF) | | 49,630 | 25-Apr-86 | 27-May-86 | 17 | 0.38 | |
| 6-46-55 | Upper Tuolumne (MRFF) | | 49,518 | 23-Apr-86 | 21-May-86 | 18 | 0.43 | |
| | Total | 14-Apr-86 | 99,148 | 23-Apr-86 | 27-May-86 | 35 | | 0.40 |
| 6-46-56 | Lower Tuolumne (MRFF) | | 51,300 | 23-Apr-86 | 7-May-86 | 10 | 0.31 | |
| 6-46-57 | Lower Tuolumne (MRFF) | | 52,174 | 25-Apr-86 | 10-May-86 | 10 | 0.26 | |
| | Total | 14-Apr-86 | 103,474 | 23-Apr-86 | 10-May-86 | 20 | | 0.27 |
| 6-46-48 | Upper Stanislaus (MRFF) | | 31,120 | 03-May-86 | 16-Jun-86 | 17 | 0.55 | |
| 6-46-49 | Upper Stanislaus (MRFF) | | 31,148 | 05-May-86 | 20-May-86 | 11 | 0.33 | |
| 6-46-50 | Upper Stanislaus (MRFF) | | 24,751 | 07-May-86 | 07-Jun-86 | 4 | 0.15 | |
| 6-46-53 | Upper Stanislaus (MRFF) | | 21,254 | 08-May-86 | 11-Jun-86 | 5 | 0.22 | |
| | Total | 28-Apr-86 | 108,273 | 03-May-86 | 16-Jun-86 | 37 | | 0.34 |
| 6-46-45 | Lower Stanislaus (MRFF) | | 31,491 | 05-May-86 | 15-May-86 | 16 | 0.48 | |
| 6-46-46 | Lower Stanislaus (MRFF) | | 31,310 | 05-May-86 | 25-May-86 | 18 | 0.54 | |
| 6-46-47 | Lower Stanislaus (MRFF) | | 30,530 | 03-May-86 | 18-May-86 | 20 | 0.66 | |
| 6-46-52 | Lower Stanislaus (MRFF) | | 12,768 | 05-May-86 | 18-May-86 | 6 | 0.44 | |
| | Total | 29-Apr-86 | 106,169 | 03-May-86 | 25-May-86 | 60 | | 0.56 |

^a MRFF = Merced River Fish Facility.

Table B-22 1985 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 5-39-4 | Battle Creek (CNFH) | | 11,484 | 21-May-85 | 23-May-85 | 2 | 0.16 | |
| 5-40-4 | Battle Creek (CNFH) | | 10,698 | 22-May-85 | 25-May-85 | 2 | 0.17 | |
| 5-41-4 | Battle Creek (CNFH) | | 10,330 | 21-May-85 | 23-May-85 | 3 | 0.27 | |
| H5-1-5 | Battle Creek (CNFH) | | 22,558 | 20-May-85 | 22-May-85 | 3 | 0.12 | |
| 5-6-16 | Battle Creek (CNFH) | | 10,209 | 24-May-85 | 24-May-85 | 1 | 0.09 | |
| | Total | 14-May-85 | 65,279 | 20-May-85 | 25-May-85 | 11 | | 0.16 |
| 5-9-47 | Below RBDD (CNFH) | | 21,871 | 21-May-85 | 24-May-85 | 2 | 0.09 | |
| 5-42-4 | Below RBDD (CNFH) | | 10,610 | 21-May-85 | 31-May-85 | 5 | 0.44 | |
| 5-43-4 | Below RBDD (CNFH) | | 9,756 | 22-May-85 | 23-May-85 | 3 | 0.29 | |
| H5-1-6 | Below RBDD (CNFH) | | 23,378 | 22-May-85 | 24-May-85 | 9 | 0.36 | |
| | Total | 14-May-85 | 65,615 | 21-May-85 | 31-May-85 | 19 | | 0.27 |
| 5-9-48 | Princeton (CNFH) | | 21,943 | 21-May-85 | 24-May-85 | 3 | 0.13 | |
| 5-9-49 | Princeton (CNFH) | | 20,460 | 21-May-85 | 22-May-85 | 3 | 0.14 | |
| H5-1-7 | Princeton (CNFH) | | 23,519 | 20-May-85 | 22-May-85 | 3 | 0.12 | |
| | Total | 15-May-85 | 65,922 | 20-May-85 | 24-May-85 | 9 | | 0.13 |

^a CNFH = Coleman National Fish Hatchery.

Contributions to the Biology of Central Valley Salmonids

Table B-23 1985 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-62-38 | Courtland (FRH) | | 54,457 | 14-May-85 | 25-May-85 | 23 | 0.40 | |
| 6-62-39 | Courtland (FRH) | | 14,731 | 14-May-85 | 25-May-85 | 2 | 0.13 | |
| 6-62-40 | Courtland (FRH) | | 10,887 | 14-May-85 | 25-May-85 | 3 | 0.26 | |
| 6-62-41 | Courtland (FRH) | | 20,551 | 14-May-85 | 25-May-85 | 9 | 0.41 | |
| | Total | 10-May-85 | 100,626 | 14-May-85 | 25-May-85 | 37 | | 0.34 |

^a FRH = Feather River Hatchery.

Table B-24 1984 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-60-42 | Battle Creek (CNFH) | | 50,742 | 16-May-84 | 23-May-84 | 19 | 0.77 | |
| 6-60-43 | Battle Creek (CNFH) | | 49,479 | 16-May-84 | 23-May-84 | 16 | 0.66 | |
| | Total | 09-May-84 | 100,221 | 16-May-84 | 23-May-84 | 35 | | 0.72 |
| 6-60-40 | Below RBDD (CNFH) | | 51,948 | 15-May-84 | 23-May-84 | 29 | 1.06 | |
| 6-60-41 | Below RBDD (CNFH) | | 50,921 | 15-May-84 | 23-May-84 | 29 | 1.08 | |
| | Total | 09-May-84 | 102,869 | 15-May-84 | 23-May-84 | 58 | | 1.07 |
| 6-60-38 | Knights Landing (CNFH) | | 49,400 | 13-May-84 | 23-May-84 | 19 | 0.85 | |
| 6-60-39 | Knights Landing (CNFH) | | 49,351 | 15-May-84 | 23-May-84 | 17 | 0.65 | |
| | Total | 09-May-84 | 98,751 | 13-May-84 | 23-May-84 | 36 | | 0.81 |

^a CNFH = Coleman National Fish Hatchery.

Table B-25 1984 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-62-28 | South Fork Mokelumne (FRH) | | 41,371 | 16-Jun-84 | 26-Jun-84 | 25 | 0.72 | |
| 6-42-8 | South Fork Mokelumne (FRH) | | 14,916 | 17-Jun-84 | 22-Jun-84 | 9 | 0.66 | |
| | Total | 12-Jun-84 | 56,287 | 16-Jun-84 | 26-Jun-84 | 34 | | 0.72 |
| 6-62-29 | Ryde (FRH) | | 44,818 | 16-Jun-84 | 26-Jun-84 | 30 | 0.66 | |
| 6-42-9 | Ryde (FRH) | | 15,180 | 17-Jun-84 | 28-Jun-84 | 8 | 0.62 | |
| | Total | 13-Jun-84 | 59,998 | 16-Jun-84 | 28-Jun-84 | 38 | | 0.73 |

^a FRH = Feather River Hatchery.

Table B-26 1983 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-60-36 | Battle Creek (CNFH) | | 44,382 | 07-Jun-83 | 24-Jun-83 | 15 | 0.65 | |
| 6-60-37 | Battle Creek (CNFH) | | 43,508 | 07-Jun-83 | 17-Jun-83 | 10 | 0.34 | |
| | Total | 02-Jun-83 | 87,890 | 07-Jun-83 | 24-Jun-83 | 25 | | 0.55 |
| 6-60-34 | Below RBDD (CNFH) | | 44,498 | 07-Jun-83 | 15-Jun-83 | 16 | 0.51 | |
| 6-60-35 | Below RBDD (CNFH) | | 45,343 | 07-Jun-83 | 21-Jun-83 | 10 | 0.40 | |
| | Total | 02-Jun-83 | 89,841 | 07-Jun-83 | 21-Jun-83 | 26 | | 0.52 |
| 6-60-32 | Knights Landing (CNFH) | | 45,986 | 05-Jun-83 | 15-Jun-83 | 45 | 1.26 | |
| 6-60-33 | Knights Landing (CNFH) | | 46,099 | 05-Jun-83 | 21-Jun-83 | 31 | 1.10 | |
| | Total | 02-Jun-83 | 92,085 | 05-Jun-83 | 21-Jun-83 | 76 | | 1.34 |

^a CNFH = Coleman National Fish Hatchery.

Table B-27 1982 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-60-26 | Battle Creek (CNFH) | | 42,964 | 13-May-82 | 07-Jun-82 | 37 | 1.65 | |
| 6-60-27 | Battle Creek (CNFH) | | 41,738 | 13-May-82 | 24-May-82 | 27 | 0.76 | |
| | Total | 05-May-82 | 84,702 | 13-May-82 | 07-Jun-82 | 64 | | 1.45 |
| 6-60-28 | Below RBDD (CNFH) | | 44,308 | 13-May-82 | 15-Jun-82 | 34 | 1.24 | |
| 6-60-29 | Below RBDD (CNFH) | | 43,817 | 10-May-82 | 24-May-82 | 35 | 1.06 | |
| | Total | 05-May-82 | 88,125 | 10-May-82 | 15-Jun-82 | 69 | | 1.25 |
| 6-60-30 | Knights Landing (CNFH) | | 44,735 | 10-May-82 | 24-May-82 | 50 | 1.48 | |
| 6-60-31 | Knights Landing (CNFH) | | 44,540 | 10-May-82 | 24-May-82 | 41 | 1.22 | |
| | Total | 05-May-82 | 89,275 | 10-May-82 | 24-May-82 | 91 | | 1.35 |

^a CNFH = Coleman National Fish Hatchery.

Table B-28 1981 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-60-20 | Knights Landing (CNFH) | | 43,059 | 28-May-81 | 28-May-81 | 3 | 0.08 | |
| 6-60-21 | Knights Landing (CNFH) | | 43,562 | 28-May-81 | 04-Jun-81 | 2 | 0.14 | |
| | Total | 18-May-81 | 86,621 | 28-May-81 | 04-Jun-81 | 5 | | 0.18 |

^a CNFH = Coleman National Fish Hatchery.

Table B-29 1981 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> | <i>Survival index</i> | <i>Group survival</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|-----------------------|-----------------------|
| 6-62-14 | Discovery Park (FRH) | | 71,932 | 10-Jun-81 | 10-Jun-81 | 1 | 0.02 | |
| 6-62-17 | Discovery Park (FRH) | | 68,318 | --- | --- | 0 | 0 | |
| | Total | 04-Jun-81 | 140,249 | 10-Jun-81 | 10-Jun-81 | 1 | | 0.01 |

^a FRH = Feather River Hatchery.

Table B-30 1980 Upper Sacramento River and Tributaries, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|
| H5-3-1 | Below RBDD (CNFH) | | 25,618 | --- | --- | 0 |
| H5-3-2 | Below RBDD (CNFH) | | 22,560 | --- | --- | 0 |
| | Total | 28-Feb-80 | 48,178 | | | |
| H5-3-5 | Below RBDD (CNFH) | | 21,786 | 15-May-80 | 15-May-80 | 1 |
| H5-3-6 | Below RBDD (CNFH) | | 21,836 | --- | --- | 0 |
| | Total | 31-Mar-80 | 43,622 | | | |

^a CNFH = Coleman National Fish Hatchery.

Table B-31 1980 Sacramento-San Joaquin Estuary, Fall-run Releases

| <i>Tag code</i> | <i>Release site (stock)^a</i> | <i>Date released</i> | <i>Number released</i> | <i>First day recovered</i> | <i>Last day recovered</i> | <i>Number recovered</i> |
|-----------------|---|----------------------|------------------------|----------------------------|---------------------------|-------------------------|
| H5-2-4 | Berkeley (CNFH) | | 21,939 | --- | --- | 0 |
| H5-2-5 | Berkeley (CNFH) | | 20,788 | --- | --- | 0 |
| | Total | 28-Feb-80 | 42,727 | | | |
| H5-2-6 | Clarksburg (CNFH) | | 22,121 | --- | --- | 0 |
| H5-2-7 | Clarksburg (CNFH) | | 21,624 | --- | --- | 0 |
| | Total | 28-Feb-80 | 43,745 | | | |
| H5-3-3 | Clarksburg (CNFH) | | 23,908 | 17-Apr-80 | 01-May-80 | 2 |
| H5-3-4 | Clarksburg (CNFH) | | 22,829 | 24-Apr-80 | 01-May-80 | 2 |
| | Total | 31-Mar-80 | 46,737 | | | |

^a CNFH = Coleman National Fish Hatchery.

The Effects of San Joaquin River Flows and Delta Export Rates During October on the Number of Adult San Joaquin Chinook Salmon that Stray

Carl Mesick

Abstract

This report describes a two-part investigation of the effects of fall make-up pumping on straying of adult San Joaquin chinook salmon. The first part is a reevaluation of 1964 to 1967 data collected by Hallock and others (1970) on the migratory behavior of tagged and untagged adult San Joaquin salmon in the Delta. The second part is an evaluation of the recovery of adult salmon that were released in the San Joaquin basin as coded-wire tagged juveniles reared at the Merced River Fish Facility.

There are three important results from Hallock and others (1970) regarding their migration analysis. First, adult salmon are migrating through the San Joaquin Delta near Prisoners Point primarily during October, the period when they are probably most susceptible to low flows and high exports. Second, the fish migrate slowly and do not arrive in the San Joaquin tributaries until about four weeks after they pass Prisoners Point, even when flows, exports, and dissolved oxygen concentrations near Stockton are suitable for migration. And third, migration rates of adult salmon are substantially higher when Vernalis flows exceed about 3,000 cfs and total exports are less than 100% of Vernalis flows. Although most of the tagged fish migrated into the Sacramento and Mokelumne basins when Vernalis flows were less than about 2,000 cfs and total exports exceeded 150% of Vernalis flows, there is uncertainty as to whether these were San Joaquin fish that strayed or Sacramento River fish that were captured in the San Joaquin on their way to the Sacramento River.

The coded-wire-tag (CWT) recovery data may not have been appropriate for a straying analysis because there are no clear records of the number of fish examined for tags during the carcass surveys. Not all fish counted for the carcass survey were examined for tags. These recovery data are necessary to accurately compute the total number of adult salmon with tags in each river. A casual inspection of the CWT recovery data suggests that: (1) straying rates increased as the percentage of San Joaquin flow exported by the CVP and SWP pump-

ing facilities increased and (2) the critical period is between 1 and 21 October. Furthermore, pulse flows from the San Joaquin tributaries, or a reduction of Delta exports that result in no more than a 300% export rate of San Joaquin flows at Vernalis for eight to twelve days in mid-October, are sufficient to keep straying rates below 3%.

The results of these correlation analyses suggest that when more than 300% of Vernalis flow is exported over a ten-day period in mid-October adult San Joaquin chinook salmon stray to the Sacramento and eastside basins. However, further tests are needed due to the limitations of the existing data.

Introduction

To increase production of fall-run chinook salmon (*Oncorhynchus tshawytscha*) in the San Joaquin tributaries, exports at the State Water Project (SWP) and the Central Valley Project (CVP) and San Joaquin River flows were managed to provide a 1:4 ratio of exports to flow at Vernalis during spring 1996 when the salmon smolts were migrating through the Delta. The State Water Resources Control Board Order 96-6 permitted the SWP and the CVP to "make-up" the reduced volume of springtime exports by pumping at near maximum rates during fall, primarily October and November. Sustained high export rates during October and November were cause for concern, since this is the period when adult San Joaquin chinook salmon migrate upstream through the Delta to their spawning grounds. To do this, the salmon require the scent of San Joaquin River flow to return to their natal river. In October 1996, the combined SWP and CVP exports averaged about 9,600 cfs, whereas San Joaquin River flows at Vernalis averaged 2,650 cfs. Fall make-up pumping occurred again in fall 1997, and the combined SWP and CVP exports averaged about 9,700 cfs, while San Joaquin River flows at Vernalis averaged about 1,950 cfs. It is likely that when exports are relatively high compared to Vernalis flows, little if any San Joaquin River water reaches the San Francisco Bay where it is needed to help guide the salmon (see the literature review that follows). If true, a substantial portion of the adult salmon population of the San Joaquin tributaries could stray into the Sacramento and Mokelumne rivers, which provide a majority of the flow through the Central Delta during the fall, particularly when the ratio of exports to San Joaquin River flow is high.

This report describes a two-part evaluation of the possible effects of fall make-up pumping on the straying of adult San Joaquin chinook salmon. The first part is a reevaluation of the data collected by Hallock and others (1970) from 1964 to 1967 on the migratory behavior of tagged and untagged adult San Joaquin salmon in the Delta. The second part is an evaluation of the recovery of adult salmon that were released in the San Joaquin basin as coded-wire

tagged juveniles reared at the Merced River Fish Facility. The recovery data are from Department of Fish and Game surveys made between 1983 and 1996.

A Literature Review of Homing Behavior of Adult Pacific Salmon

Adult Pacific salmon rely on olfactory cues to guide their upriver migration to their natal stream, although other factors may be involved (Quinn 1990). It is generally believed that juveniles rearing and migrating downriver acquire a series of olfactory waypoints at every major confluence and retrace the sequence as adults when they return to spawn (Harden Jones 1968; Quinn and others 1989; Quinn 1990). Few adult coho (Wisby and Hasler 1954) and chinook salmon (Groves and others 1968) that had their olfactory pits plugged (to prevent them from sensing waterborne odors) were able to home to their natal stream. Most (67% and 89%) of the control fish in those studies were able to home to their natal stream. During both of these studies, blinded fish were able to home more successfully than were fish with occluded olfactory pits. Normal homing rates for chinook salmon probably range between 84% for 17,671 recovered fish that were reared at a New Zealand hatchery (Unwin and Quinn 1993) and 98.6% for 41,085 recovered fish that were reared at the Cowlitz River Hatchery, Washington (Quinn and Fresh 1984). Experiments have also shown that juvenile coho salmon exposed to artificial waterborne odors while they were reared in hatcheries, homed to waters that contained those artificial odors (Cooper and others 1976; Johnsen and Hasler 1980; Brannon and Quinn 1990; Dittman and others 1994; Dittman and others 1996).

Besides olfactory cues, there is evidence that compass orientation helps adult salmon to home to their natal stream. Adult Pacific salmon, particularly those that migrate long distances in the ocean to feed (stream-type populations), use compass orientation in ocean and coastal waters to locate the mouth of their natal stream, where they switch to olfactory clues (Quinn 1990). However, the mechanism of compass orientation and the transition from compass orientation in coastal waters and estuaries to olfactory-based upriver homing appear to be very complicated and not well understood (Quinn 1990). Furthermore, ocean-type populations of Pacific salmon, such as the fall-run chinook populations in the San Joaquin tributaries, may not have a well-developed means of navigation by compass orientation since they do not migrate far from the coast to feed. This would explain why most sockeye salmon, a stream-type population, that had their olfactory nerves severed in an experiment could still migrate in a homeward direction (Craigie 1926), whereas chinook salmon with plugged olfactory pits could not migrate homeward (Groves and others 1968).

There is contradictory evidence that hereditary factors also influence homing behavior. Bams (1976) and McIsaac and Quinn (1988) provided proof that a high proportion of displaced chinook salmon offspring homed to their ances-

tral spawning area even though the juvenile fish were never exposed to their ancestral waters. However, Donaldson and Allen (1957) provided evidence that coho juveniles relocated to two different locations prior to smolting would home to their release sites and not to their original hatchery site. The scent from siblings (population-specific odors) did not affect adult coho salmon homing behavior in Lake Washington (Brannon and Quinn 1990), and no other mechanism to account for a hereditary factor has been discovered.

When adult Pacific salmon do not return to their natal stream, they appear to select a new river for spawning based on the magnitude of streamflow. Two field studies conducted by Quinn and Fresh (1984) in Washington and Unwin and Quinn (1993) in New Zealand determined that adult chinook salmon strays selected rivers with the highest streamflow. An experimental study conducted by Wisby and Hasler (1954) also showed that when the scent of the fishes' natal river was not present, coho salmon moved into the arm of a Y-maze with the greatest flow. If true, then adult San Joaquin salmon that cannot use olfaction due to an absence of scent from their natal river would probably return to the Sacramento River, where flows are substantially greater.

A Review of Hallock's Study

The migration of adult fall-run chinook salmon in the Delta and lower San Joaquin River was studied by the Department of Fish and Game between 1964 and 1967. Adult salmon were captured with a trammel net (floating gill net, 23 feet deep and 1,378 to 1,804 feet long) at Prisoners Point in the San Joaquin River, which is about 2.5 miles upstream of the confluence with the Mokelumne River. The daily catch rate was recorded during each year except 1965. Sonic tags were attached to the dorsal surface of the fish just anterior to the dorsal fin with straps and pins. Stationary monitors that recorded the presence of the tags were used in the Sacramento River, Mokelumne River, San Joaquin River, and throughout the Delta to help determine the destination and migration rate of the tagged fish. The authors also presented the number of salmon captured at a trap operated in the Stanislaus River for hatchery stock from 1965 to 1967.

Results

For 1966 and 1967, when catch rates were estimated at both Prisoners Point and the Stanislaus trap, most fish arrived at Prisoners Point between 1 October and 20 October (some were caught through 21 November), whereas most fish were not caught at the Stanislaus River trap until after 5 November (Figures 1 and 2). Hallock reported that few of the tagged fish migrated past Stockton when dissolved oxygen (DO) levels were less than about 5 ppm (4.5 in 1967 and 5.5 in 1965). Furthermore, the catch at the Stanislaus trap tended

to increase about one week after DO levels at Stockton stabilized at or above the critical level. The fish usually remained in the Delta for at least three weeks prior to entering the Stanislaus and Hallock reported that some remained in the Delta for up to two months. Therefore, an evaluation of fall make-up pumping on straying of adult fish must be conducted by monitoring fish in the Delta, not the San Joaquin tributaries.

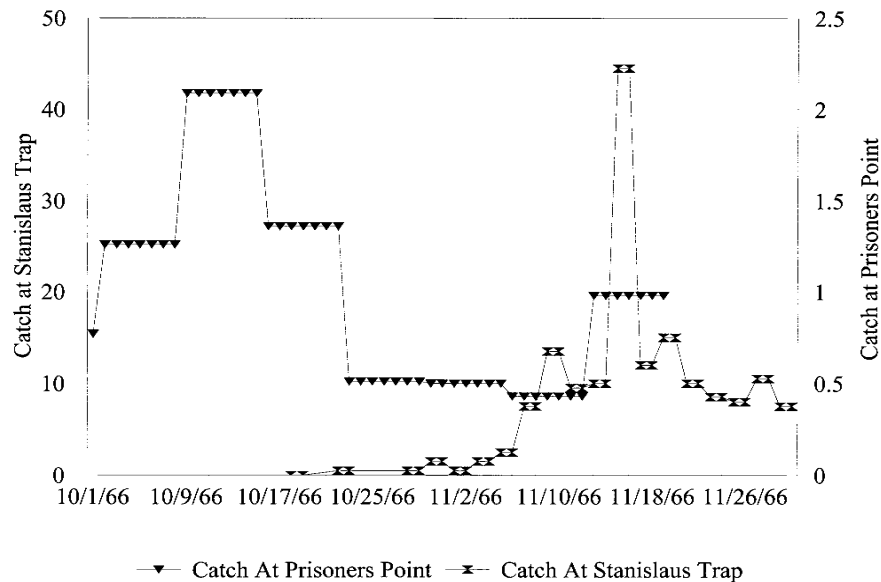


Figure 1 Catch rates of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River (about 2.5 miles upstream of the confluence with the Mokelumne River) and at the Orange Blossom trap in the Stanislaus River in October and November 1966

I evaluated the effects of exports and San Joaquin flow on the number of strays using two sets of data collected by Hallock and others (1970). The first data set evaluated were straying rates for 35 to 77 adult salmon tagged at Prisoners Point each year and the second data set evaluated were catch rates of adult salmon at Prisoners Point relative to flows and exports.

During the first three weeks of October in 1965 and 1967, only 15% of the tagged fish migrated into the Sacramento and Mokelumne rivers when Vernalis flows ranged between 2,000 and 4,000 cfs and the proportion of Vernalis flows exported at Tracy ranged between 45% and 120%. In contrast, during the first three weeks of October, 54% of the tagged fish (35) strayed into the Sacramento and Mokelumne rivers in 1964 and 71% of the tagged fish (52) strayed in 1966 when Vernalis flow ranged between 700 and 1,500 cfs and the proportion of Vernalis flows exported at Tracy ranged between 150% and 250%. A solid rock barrier was installed at the head of Old River in 1964, but not during the other study years, and it is likely that the barrier increased the amount of San Joaquin flow that remained in the San Joaquin River.

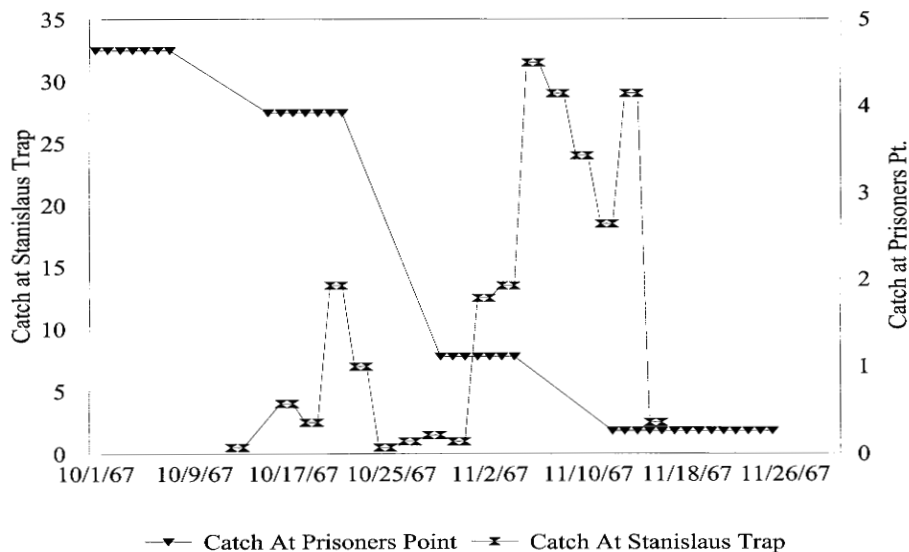


Figure 2 Catch rates of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River, which is about 2.5 miles upstream of the confluence with the Mokelumne River and at the Orange Blossom trap in the Stanislaus River in October and November 1967

Hallock and others (1970) could not verify whether the adult salmon caught at Prisoners Point were actually of San Joaquin origin. They speculated the tagged fish that migrated into the Sacramento and Mokelumne rivers were not San Joaquin basin strays but were Sacramento basin fish guided 2.5 miles upstream of the mouth of the Mokelumne in the Delta (to Prisoners Point) by strong tidal flows. However, they could not reasonably explain why a high number of tagged fish migrated into the Sacramento and Mokelumne rivers in 1964 and 1966 when there was a high proportion of exported San Joaquin flow, but a low number of tagged fish migrated into the same rivers in 1965 and 1967 when there was a low proportion of exported San Joaquin flow.

The effects of Vernalis flows and exports on straying were also evaluated using the catch rate at Prisoners Point determined by Hallock and others (1970). In 1964, catch rates ranged between 0.63 and 1.25 fish/hour between 5 and 25 October, when Vernalis flow ranged between 1,100 and 1,500 cfs (Figure 3) and exports ranged between 130 and 225% of Vernalis flows (Figure 4). After Vernalis flows rapidly increased to about 2,000 cfs and exports began to decline to less than 100% of Vernalis flows on 29 October, catch rates at Prisoners Point increased to 5.36 fish/hour on 4 and 5 November.

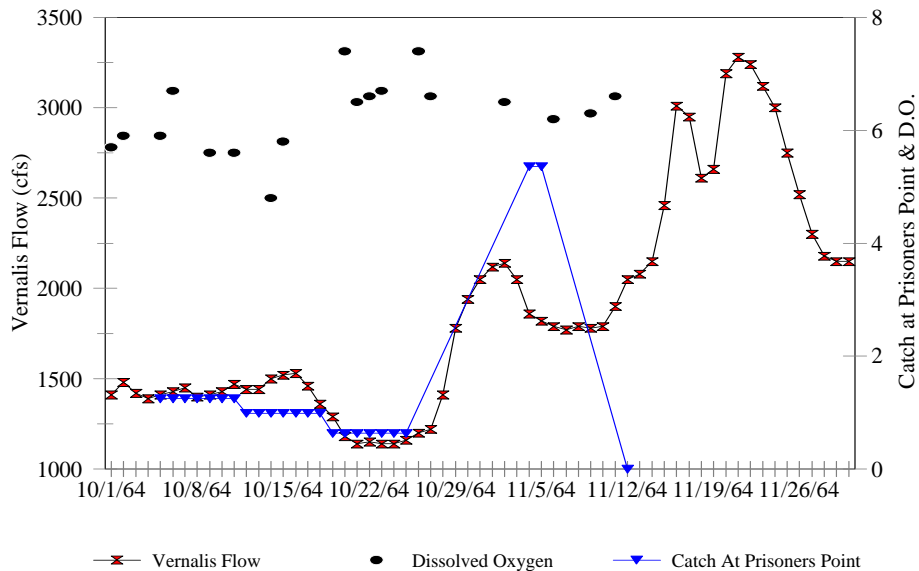


Figure 3 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to the flow in the San Joaquin River at Vernalis and DO levels (ppm) near Stockton in October and November 1964

In 1966, catch rates at Prisoners Point remained low throughout October and November when the straying rates of tagged fish were high (71%). A gradual increase in Vernalis flow from 700 cfs from 1 October to 1,350 cfs on 24 October had no obvious effect on catch rates (Figure 5). Likewise, declining export rates from 250% on 1 October to 100% of Vernalis flows on 24 October also had no effect on catch rates (Figure 6). When Vernalis flows increased to about 1,500 cfs on 8 November and exports decreased to 60% between 8 and 19 November, catch rates increased from a steady 0.5 fish/hour to 0.96 fish/hour on 14 November. This small increase in catch rates suggests most of the adults had already migrated into the Delta, and flow releases and/or export reductions after 8 November were already too late to substantially affect straying rates.

In 1967, catch rates at Prisoners Point remained high between 1 and 17 October when straying rates of tagged fish were low (15%). During high catch rates in early October, Vernalis flows ranged between 2,250 and 2,750 cfs (Figure 7), and exports ranged between 80% and 120% of Vernalis flows (Figure 8). When Vernalis flows increased to about 3,500 cfs and exports declined to 25% of Vernalis flows after 27 October, catch rates remained low suggesting most fish had completed their migration through the Delta.

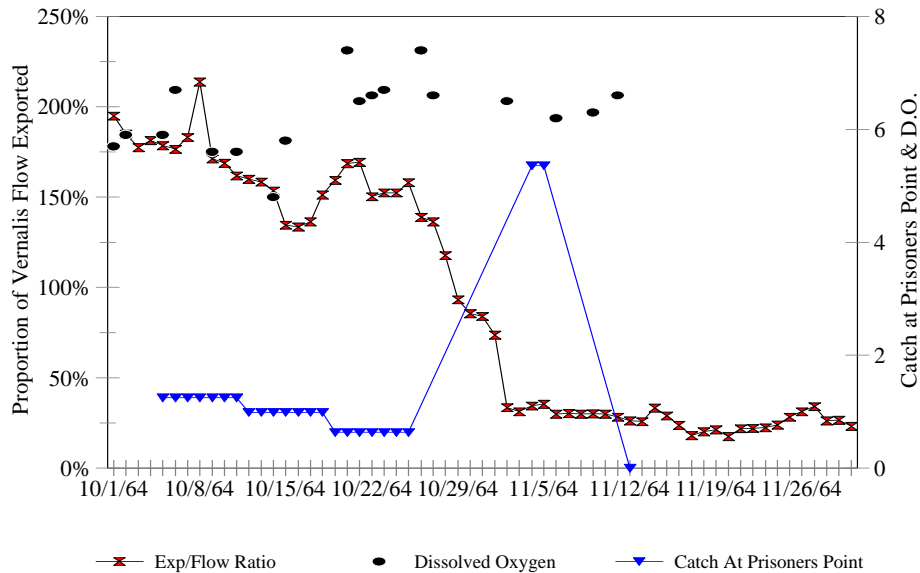


Figure 4 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to the proportion of the flow in the San Joaquin River at Vernalis that was exported at the SWP and CVP Delta pumping facilities and DO levels (ppm) near Stockton in October and November 1964

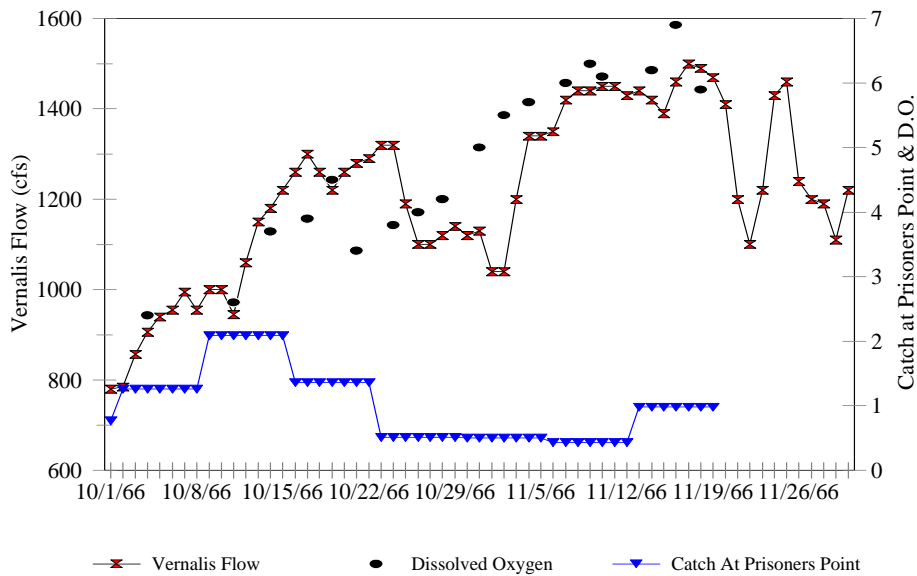


Figure 5 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to flow in the San Joaquin River at Vernalis and DO levels (ppm) near Stockton in October and November 1966

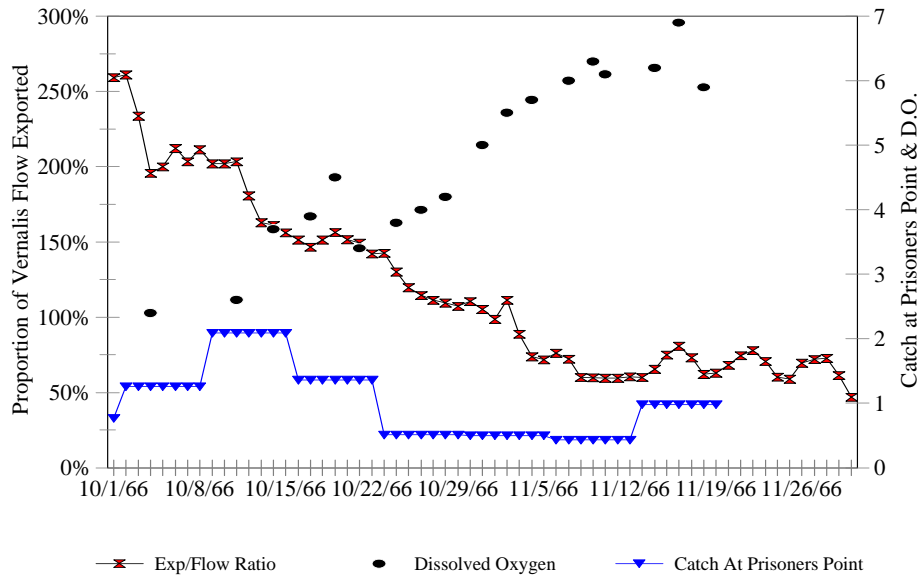


Figure 6 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to proportion of the flow in the San Joaquin River at Vernalis that was exported at the SWP and CVP Delta pumping facilities and DO levels (ppm) near Stockton in October and November 1966

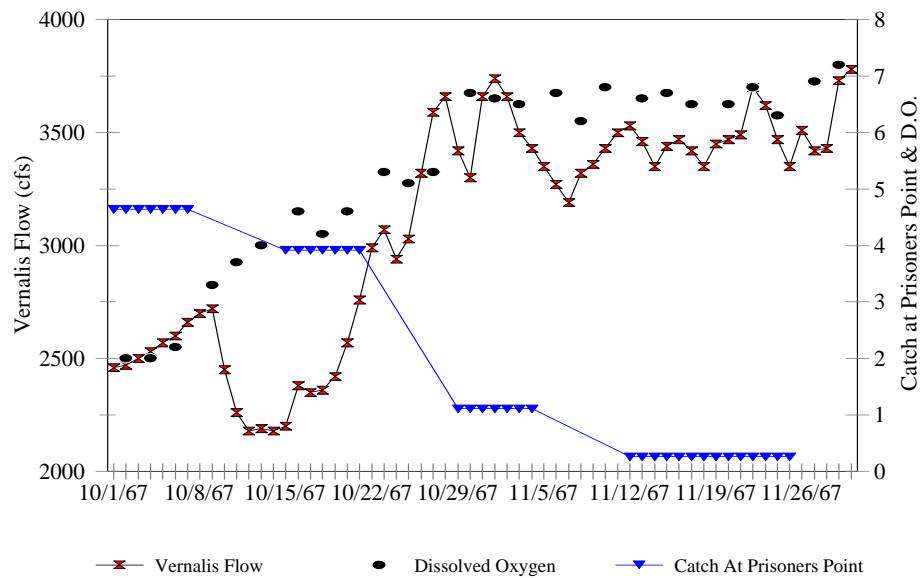


Figure 7 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to flow in the San Joaquin River at Vernalis and DO levels (ppm) near Stockton in October and November 1967

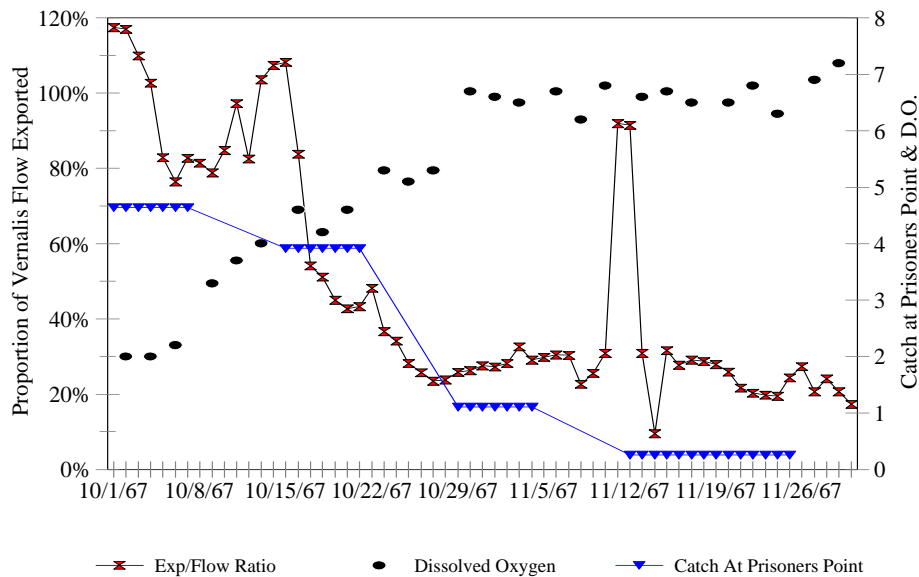


Figure 8 The catch rate of adult chinook salmon with a trammel net at Prisoners Point in the San Joaquin River relative to proportion of the flow in the San Joaquin River at Vernalis that was exported at the SWP and CVP Delta pumping facilities and DO levels (ppm) near Stockton in October and November 1967

There are three important results from Hallock and others (1970) regarding a straying analysis. First, adult salmon were migrating through the San Joaquin Delta near Prisoners Point primarily during October, the period when they are probably most susceptible to low flows and high exports. Second, the fish migrate slowly and do not arrive in the San Joaquin tributaries until about four weeks after they pass Prisoners Point, even when flows, exports, and dissolved oxygen concentrations near Stockton are suitable for migration. And third, migration rates of adult salmon are substantially higher when Vernalis flows exceed about 3,000 cfs and total exports are less than 100% of Vernalis flows. Although most of the tagged fish migrated into the Sacramento and Mokelumne rivers when Vernalis flows were less than about 2,000 cfs and total exports exceeded 150% of Vernalis flows, there is uncertainty as to whether these were San Joaquin fish that strayed or Sacramento River fish that were captured in the San Joaquin on their way to the Sacramento River. The US Fish and Wildlife Service reported that approximately 20% of the Sacramento River fall-run salmon returned to their natal streams by migrating through the lower San Joaquin, into the lower Mokelumne, and then through Threemile or Georgiana sloughs (Erkkila and others 1950). Evidence for this was based on the recapture of 44 adult salmon previously marked at the Coleman National Fish Hatchery as juveniles by the Paladini Fish Company in Pittsburg; nine of the recaptured fish were caught in gill nets drifted in the San Joaquin River below the mouth of the Mokelumne.

Recoveries of Coded-wire Tagged San Joaquin Chinook Salmon

This analysis is based on the number of recoveries of coded-wire tagged (CWT) juvenile chinook salmon in Central Valley streams that were originally reared at the Merced River Fish Facility and the Tuolumne Rearing Facility and released in the San Joaquin basin at Dos Reis Road and all upstream sites. The fish were recovered one to three years after their release when they returned to spawn. If these fish returned to one of the San Joaquin tributaries, they were judged to have successfully "homed." However, if they returned to the Sacramento River basin or one of the eastside streams, which include the Cosumnes, Mokelumne, and Calaveras rivers, they were judged to have strayed. The CWT recovery data were provided by Ralph Carpenter and Robert Kano, Inland Fisheries Division, California Department of Fish and Game (DFG), Sacramento (summarized in Table 1). Updated escapement estimates and the number of fish measured and sexed were obtained from the DFG's annual reports on chinook salmon spawner stocks in California's Central Valley from 1983 through 1989 (Reavis 1986; Kano and Reavis 1996, 1997, 1998; Kano and others 1996). The DFG identifies the 1995 and 1996 CWT recovery data and the escapement estimates from 1990 to 1996 as preliminary (Robert Kano, personal communication, see "Notes").

The accuracy of this analysis is limited because looking for a San Joaquin stray is like looking for a needle in a haystack. The number of spawners in the San Joaquin basin ranges between one and 10% of the numbers in the Sacramento and eastside basins. This means that even if half of the San Joaquin fish stray, the strays would constitute less than 5% of the populations in the Sacramento and eastside basins. Finding the strays is made more difficult because none of the fall-run fish spawning in the mainstem Sacramento River were examined for CWTs through fall 1995. Furthermore, surveys for tagged adults were not conducted every year in the Stanislaus and Merced rivers in the San Joaquin basin, or in the Yuba, American, or Mokelumne rivers in the Sacramento River basin. Overall, the percent of total spawners that was evaluated for tags ranged between 9% and 33% in the San Joaquin tributaries and between 6% and 22% in the Sacramento River basin and eastside rivers.

To compute the total number of salmon with CWTs in each river by survey year, the number of CWT recoveries was divided by the number of fish examined for tags and then multiplied by the escapement estimate. A comparison of the recovery data between the river surveys in the American, Feather, and Merced rivers and the recovery data at the hatcheries in those rivers suggests there are no accurate data to determine the number of fish examined during the escapement surveys. The hatchery data are assumed to be the most accurate, since all fish collected at the hatcheries were fresh and extensively handled, implying that there was a thorough inspection for adipose clips. When

the percentage of fish handled during the river escapement surveys was calculated with the assumption that all fish in the carcass counts, those marked and chopped, were examined for adipose clips (and therefore CWTs), the percentage of fish with tags was much lower for the river surveys than those handled at the hatcheries (Table 2).

Table 1 The total number of coded-wire-tags (CWT) recovered by the Department of Fish and Game from adult San Joaquin hatchery reared fish during carcass surveys and at hatcheries in the Sacramento River basin, Eastside tributaries, and the San Joaquin tributaries, and the estimated number of strays and returns and the percent that strayed from 1979 to 1996 ^a

| <i>Year</i> | <i>Total Recoveries</i> | <i>Estimated Number of Strays</i> | <i>Estimated Number of Returns</i> | <i>Percent Strays</i> |
|-------------|-------------------------|-----------------------------------|------------------------------------|-----------------------|
| 1979 | 10 | 7 | 85 | 7.6% |
| 1980 | 26 | 8 | 106 | 7.4% |
| 1981 | 32 | 0 | 361 | 0.0% |
| 1982 | 14 | 4 | 153 | 2.2% |
| 1983 | 300 | 0 | 3,129 | 0.0% |
| 1984 | 180 | 32 | 2,419 | 1.3% |
| 1985 | 138 | 101 | 1,570 | 6.1% |
| 1986 | 149 | 27 | 1,519 | 1.7% |
| 1987 | 245 | 680 | 3,298 | 17.1% |
| 1988 | 232 | 239 | 1,951 | 10.9% |
| 1989 | 120 | 58 | 432 | 11.8% |
| 1990 | 62 | 2 | 137 | 1.7% |
| 1991 | 16 | 6 | 66 | 7.9% |
| 1992 | 74 | 2 | 269 | 0.6% |
| 1993 | 157 | 5 | 269 | 1.9% |
| 1994 | 135 | 10 | 495 | 1.9% |
| 1995 | 237 | 0 | — | 0.0% |
| 1996 | 784 | 114 | 2,657 | 4.1% |

^a Rivers and hatcheries surveyed for CWTs in the Sacramento Basin include Clear Creek, Coleman National Fish Hatchery, Battle Creek, Mill Creek, Red Bluff Diversion Dam, Tehama-Colusa Fish Facility, Feather River Fish Hatchery, Feather River, Yuba River, Nimbus Fish Hatchery, and American River. The Mokelumne River and the Mokelumne River Fish Installation were surveyed in the Eastside tributaries. The Tuolumne River, Stanislaus River, Merced River, Merced River Fish Facility, Los Banos Wildlife Area were surveyed in the San Joaquin basin.

Table 2 A comparison of the percentage of San Joaquin basin adult chinook salmon recovered with coded-wire-tags to the percentages observed at the hatcheries in the Merced, American, and Feather rivers^a

| Merced River | | | | | | | | |
|---|--------|--------|-------|--------|-------|-------|--------|---------|
| River Escapement | | | | | | | | |
| Survey Years | 1983 | 1984 | 1985 | 1986 | 1987 | 1993 | 1994 | 1996 |
| Number of Tags Recovered | 5 | 49 | 14 | 13 | 0 | 22 | 38 | 263 |
| Total Carcass Count | 1634 | 2200 | 2200 | 781 | 426 | 532 | 1019 | 1220 |
| Number Measured & Sexed | 1124 | 448 | 535 | 291 | 138 | | | |
| Number of Fresh Fish | | | | | | 294 | 324 | 147 |
| Number of Fresh Fish & Decayed Adults | | | | | | 517 | 888 | 826 |
| Number of Fresh, Decayed Adults & 50% of Decayed Grilse | | | | | | 525 | 954 | 1023 |
| Escapement | 16453 | 27640 | 14841 | 6789 | 3168 | 1995 | 4635 | 4599 |
| Merced River Fish Facility | | | | | | | | |
| Number of Tags Recovered | 291 | 146 | 103 | 120 | 26 | 37 | 74 | 291 |
| Number Examined | 1795 | 2109 | 1211 | 650 | 958 | 409 | 943 | 1141 |
| Percentage of Fish Recovered with Tags | | | | | | | | |
| Based on the Hatchery | 16.21% | 6.92% | 8.51% | 18.46% | 2.71% | 9.05% | 7.85% | 25.50% |
| Based on Total Carcass Counts | 0.31% | 2.23% | 0.64% | 1.66% | 0.00% | 4.14% | 3.73% | 21.56% |
| Based on Number Measured & Sexed | 0.44% | 10.94% | 2.62% | 4.47% | 0.00% | | | |
| Based on Fresh Fish Counts | | | | | | 7.48% | 11.73% | 178.91% |
| Based on Fresh & Decayed Adult Counts | | | | | | 4.26% | 4.28% | 31.84% |
| Based on Fresh, all Decayed Adults, & 50% of Decayed Grilse | | | | | | 4.19% | 3.99% | 25.71% |

^a Recovery data for escapement surveys are not presented when no tags were recovered.

Table 2 A comparison of the percentage of San Joaquin basin adult chinook salmon recovered with coded-wire-tags to the percentages observed at the hatcheries in the Merced, American, and Feather rivers^a (Continued)

| American River | | | | | |
|--|-------|-------|-------|-------|-------|
| River Escapement Survey Years | 1984 | 1985 | 1987 | 1988 | 1989 |
| Number of Tags Recovered | 1 | 1 | 3 | 0 | 0 |
| Total Carcass Count | 10027 | 4875 | 9451 | 3944 | 5550 |
| Number Measured & Sexed | 4875 | 857 | 649 | 908 | 1070 |
| Escapement | 27447 | 56120 | 39885 | 24889 | 19183 |
| Nimbus Fish Hatchery | | | | | |
| Number of Tags Recovered | 3 | 14 | 13 | 6 | 2 |
| Number Examined | 12249 | 9093 | 6258 | 8625 | 9741 |
| Percentage of Fish Recovered with Tags | | | | | |
| Based on the Hatchery | 0.02% | 0.15% | 0.21% | 0.07% | 0.02% |
| Based on Total Carcass Counts | 0.01% | 0.02% | 0.03% | 0.00% | 0.00% |
| Based on Number Measured & Sexed | 0.02% | 0.12% | 0.46% | 0.00% | 0.00% |
| Feather River | | | | | |
| River Escapement Survey Years | 1984 | 1987 | 1988 | 1989 | |
| Number of Tags Recovered | 4 | 5 | 13 | 4 | |
| Total Carcass Count | 14603 | 21714 | 24099 | 9677 | |
| Number Measured & Sexed | 3268 | 3566 | 4066 | 3719 | |
| Escapement | 41769 | 67738 | 42556 | 40541 | |
| Feather River Hatchery | | | | | |
| Number of Tags Recovered | 4 | 75 | 23 | 0 | |
| Number Examined | 9288 | 10108 | 6480 | 7578 | |
| Percentage of Fish Recovered with Tags | | | | | |
| Based on the Hatchery | 0.04% | 0.74% | 0.35% | 0.00% | |
| Based on Total Carcass Counts | 0.03% | 0.02% | 0.05% | 0.04% | |
| Based on Number Measured & Sexed | 0.12% | 0.14% | 0.32% | 0.11% | |
| ^a Recovery data for escapement surveys are not presented when no tags were recovered. | | | | | |

Therefore, it is highly unlikely that all of the fish in the carcass counts were closely examined for adipose clips. This is partly true for the San Joaquin tributaries as some of the chopped fish, particularly the grilse, have been too decayed to detect an adipose fin clip and few if any of their heads were taken for CWT evaluation (Jennifer Bull and George Neillands, personal communication, see "Notes"). The problem also appears to have occurred during the escapement surveys in the American and Feather rivers. Even though only fresh fish (clear eyed) were usually marked or chopped in these rivers according to DFG annual reports 1983 through 1989, the percentage of fish with CWTs was also usually much higher at the hatchery than for the river based on the total carcass count (Table 2). On the other hand, when the number of fish measured and sexed during the escapement surveys (DFG 1988-1997) were used to compute the percentage of fish with tags, there was better agreement between the hatchery estimates and the river estimates (Table 2). Therefore, the hatchery data were used to compute the expansion factor for both the hatchery and the corresponding river in most cases. However, in 1989 no CWT recoveries were made at the Feather River Hatchery, whereas four tags were recovered during the Feather River escapement surveys (Table 2). This was very unusual in that usually many more CWT fish were recovered at the hatchery than during the escapement surveys. It was assumed that the Feather River hatchery data were incorrect and the expansion factors for both the river and hatchery were based on the escapement survey for 1989. Whenever total CWT recoveries were estimated for the Feather River in 1989 and for the rivers without a hatchery (primarily the Stanislaus, Tuolumne, and Yuba rivers), the expansion factors was computed using the number of fish measured and sexed, which was available for the 1983 to 1989 surveys. For the 1990 to 1996 surveys, the expansion factor for the Stanislaus and Tuolumne rivers was computed as the number of fresh fish and decayed adults in the carcass counts; decayed grilse were usually not examined for CWTs (George Neillands, personal communication, see "Notes"). The number of fresh fish and decayed adults counted during the escapement surveys in the Merced River provided estimates of "Percentage of Fish Recovered with Tags" that were slightly more similar to the hatchery estimates than estimates computed with the total carcass counts (Table 2).

Since 1984, the DFG has used a trap at Los Banos to collect fish that try to enter the westside agricultural drainage system. DFG Region 4 assumes that approximately half the fish that enter the westside drainage system are recovered at the Los Banos trap (DFG 1988-1997). Therefore, the recoveries for the Los Banos trap were doubled in number to compute the total number of salmon with CWTs entering the westside system.

The total number of CWT strays was computed by summing the estimated total number of salmon with CWTs for each of the Sacramento and eastside rivers and hatcheries surveyed. Rivers and hatcheries surveyed in the Sacra-

mento and eastside basin include Clear Creek, Battle Creek, Mill Creek, Feather River, Yuba River, American River, Mokelumne River, Coleman National Fish Hatchery, Tehama-Colusa Fish Facility, Feather River Hatchery, Nimbus Fish Hatchery, and the Mokelumne River Fish Installation.

The total number of CWT returns was computed by summing the estimated total number of salmon with CWTs for each the San Joaquin tributaries, the Merced River Fish Facility, and the Los Banos trap. No data on CWT recoveries are available for the Stanislaus River for the 1982, 1983, and 1986 surveys. Only the estimates for 1983 were used in the analysis of straying rates, because no strays were recovered in the Sacramento or eastside basins.

The percentage of CWT Merced hatchery fish that strayed was computed using the following equation:

$$\text{Percent Strays} = (\text{Total CWT Strays}) / (\text{Total CWT Returns} + \text{Total CWT Strays})$$

The effects of Vernalis flow and total Delta exports on the estimated Percent Strays was evaluated for four periods. The period from 15 September to 28 October was tested to evaluate whether flow and export conditions affected the homing ability of adult salmon in Suisun Bay that would be present in September and those at Prisoners Point that would be present in October. The period from 1 to 20 October was tested based on the assumption that Hallock's catch data reflected the time when most adult San Joaquin salmon migrated through the Delta. The period from 15 to 21 October was tested to evaluate the ability of short-term pulse flows in mid-October to affect homing behavior. The period from 9 to 15 October was tested to evaluate the peak time of migration based on Hallock's catch data.

The relationship between the estimate of Percent Strays and the ratio of Vernalis flow to total Delta exports for the four periods described above was evaluated for outliers. The estimate for the 1980 survey was relatively high and the estimate for 1981 was relatively low compared to the relationship of the other surveys to flows and exports. Since the number of tags recovered for the 1980 and 1981 surveys was 26 and 32 tags respectively (Table 1), no estimate with less than 33 recoveries was used in the analysis. This eliminated the surveys from 1979 to 1982 and 1991.

Results

The relationship between the estimated Percent Strays and the average ratio of SWP and CVP Export rates to Vernalis flows are shown for various periods in Figures 9 through 12. There are too few data to determine whether the relationship between the estimated Percent Strays and the export to flow ratios was linear, so regression analyses were not conducted. For example, if the

1989 estimate is assumed to be inaccurate, then the Percent Strays estimate appears to increase exponentially relative to the minimum export to flow ratio for both the 1 to 20 October period (Figure 9) and the 15 to 21 October period (Figure 10). However, if the 1987 estimate is assumed to be inaccurate, then Percent Strays appears to have a linear relationship with the minimum export to flow ratios for both periods. Rather than trying to determine the exact nature of the relationship based on the existing data, the uncertainty regarding the true number of fish examined for tags should be resolved first.

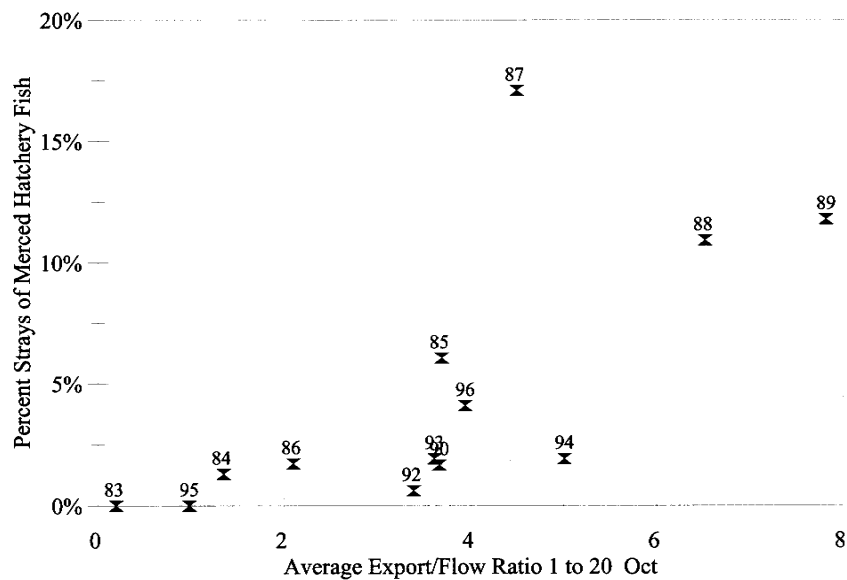


Figure 9 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish, and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average ratio of the export rate at the CVP and SWP pumping facilities in the Delta to the flow rate in the San Joaquin River at Vernalis during 1 to 20 October from 1983 through 1996

A casual inspection of Figures 9 through 14 suggests the estimates of Percent Strays are accurate enough to reach several conclusions in spite of the above uncertainties. First, this analysis indicates that straying rates increase as the percentage of San Joaquin flow exported by the CVP and SWP pumping facilities increases, and the critical period is between 1 and 21 October. Furthermore, pulse flows from the San Joaquin tributaries or a reduction of Delta exports resulting in no more than a 300% export rate of San Joaquin flows at Vernalis for 8 to 12 days in mid-October is sufficient to keep straying rates below 3%. In October 1990, there were eight days when the export rate was less than 300% of Vernalis flows and the estimated straying rate was about 2%. Since 1991, a 300% export rate or lower occurred for at least 10 days in

mid October. During most years evaluated when straying rates were less than 3%, San Joaquin River flows at Vernalis were at least 4,000 cfs. However in 1992, straying rates were estimated to be less than 1% when Vernalis flows averaged less than 700 cfs between 1 and 20 October, but Delta exports declined to less than 50% of Vernalis flows for four days and less than 100% of Vernalis flows for eight days. Conversely, straying rates were high, ranging between 11% and 17%, from 1987 to 1989 when between 400% and 700% of San Joaquin flows were exported and Vernalis flows ranged between 1,000 and 2,000 cfs.

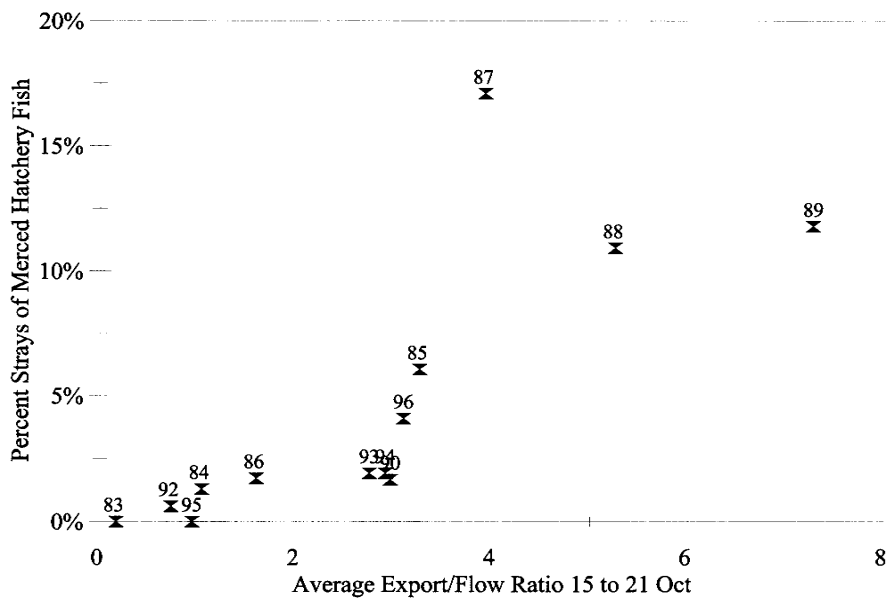


Figure 10 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish, and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average ratio of the export rate at the CVP and SWP pumping facilities in the Delta to the flow rate in the San Joaquin River at Vernalis during 15 to 21 October from 1983 through 1996

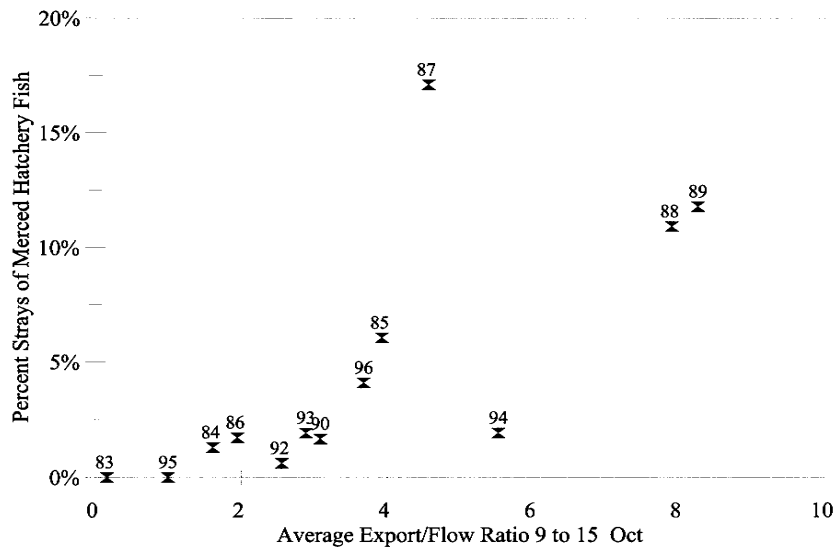


Figure 11 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish, and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average ratio of the export rate at the CVP and SWP pumping facilities in the Delta to the flow rate in the San Joaquin River at Vernalis during 9 to 15 October from 1983 through 1996

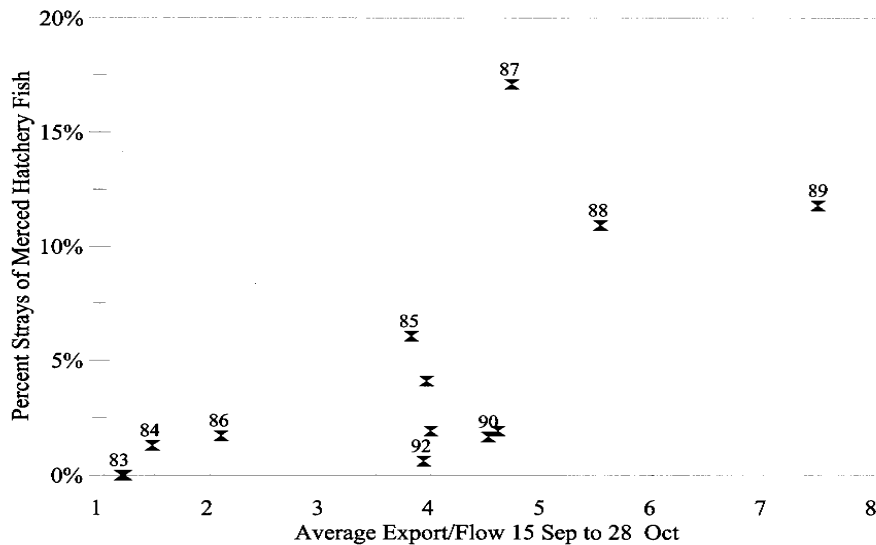


Figure 12 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish, and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average ratio of the export rate at the CVP and SWP pumping facilities in the Delta to the flow rate in the San Joaquin River at Vernalis during 15 September to 28 October from 1983 through 1996

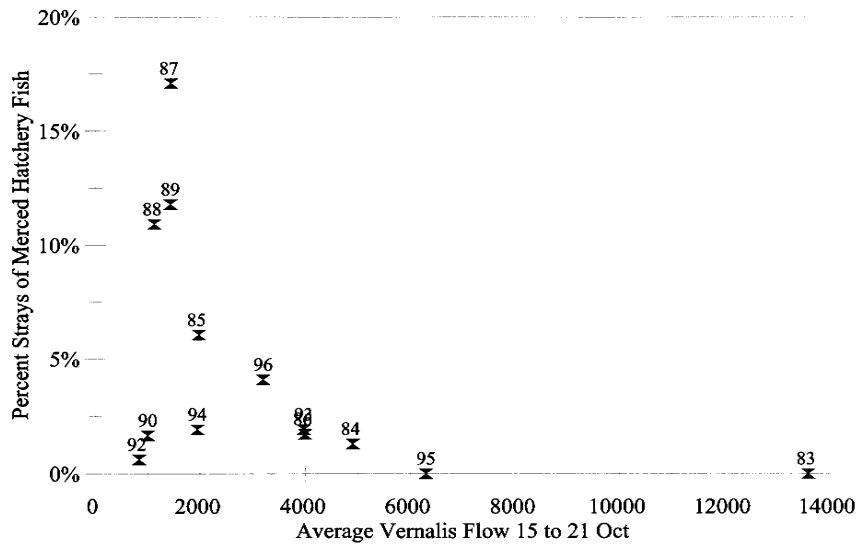


Figure 13 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average flow rate in the San Joaquin River at Vernalis during 15 to 21 October from 1983 through 1996

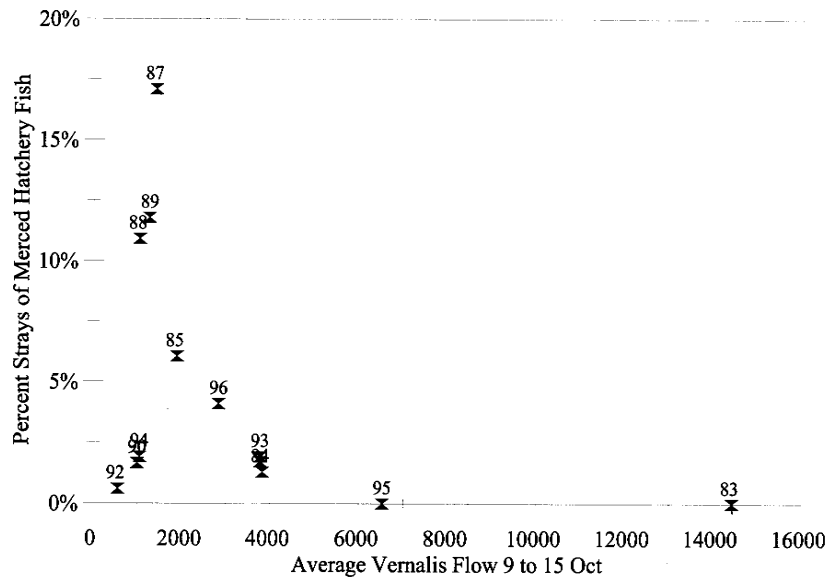


Figure 14 Estimated percent of adult CWT chinook salmon that were reared at the Merced River Hatchery, released in the San Joaquin basin as juvenile fish, and subsequently strayed to the Sacramento River and eastside tributary basins to spawn relative to the average flow rate in the San Joaquin River at Vernalis during 9 to 15 October from 1983 through 1996

Conclusions

The two-part investigation provided conflicting results. Reevaluation of the data collected by Hallock and others (1970) suggested that adult salmon that reared in the San Joaquin tributaries strayed when exports at the CVP and SWP pumping facilities exceeded about 100% of flow in the San Joaquin River at Vernalis and Vernalis flows were less than 2,000 cfs during the first three weeks of October. However, there is uncertainty about the origin of their study fish and data were collected in only four years.

The evaluation of the recovery of coded-wire-tagged fish suggests a maximum of about 20% of adult San Joaquin salmon strayed when Delta exports exceeded about 300% of Vernalis flows for a ten-day period in mid-October. Although the accuracy of the estimated number of strays is questionable, the estimates correlate strongly with the ratio of Delta exports to flows at Vernalis and with Vernalis flows.

Considering the results of these investigations, it is reasonable to assume that when more than 300% of Vernalis flow is exported over a ten-day period in mid-October that adult San Joaquin chinook salmon stray to the Sacramento and eastside basins. However due to the limitations of these analyses, further tests should be made by collecting the data needed to accurately evaluate the recoveries of coded-wire-tagged adults during future carcass surveys. These new data should include the results of annual surveys for adults with coded-wire tags in all major tributaries and the number of fish examined for the tags accurately recorded for each river surveyed. These data, along with accurate escapement estimates, records on the releases of tagged juvenile fish, and records on recovered adult fish with tags, will provide the information needed to accurately estimate the percentage of fish that stray.

Acknowledgements

This study was funded by the Stockton East Water District. I thank Robert Kano, Jennifer Bull, and George Neillands for their assistance.

References

- Bams RA. 1976. Survival and propensity for homing as affected by presence or absence of locally adapted paternal genes in two transplanted populations of pink salmon. *J Fish Res Board Can* 33:2716-25.
- Brannon EL, Quinn TP. 1990. Field test of the pheromone hypothesis for homing by Pacific salmon. *J Chem Ecol* 16 (2):603-9.

- [DFG] California Department of Fish and Game. 1988–1997. Annual Escapement Reports, San Joaquin River Chinook Salmon Enhancement Project [annual reports for fiscal years 1987–1996]. Sport Fish Restoration Act, Project F51-R-6, Project nr. 38, Jobs 1 – 7. Fresno (CA): California Department of Fish and Game, Region 4.
- Cooper JC, Scholz AT, Horrall RM, Hasler AD, Madison DM. 1976. Experimental confirmation of the olfactory hypothesis with homing, artificially imprinted coho salmon. *J Fish Res Board Can* 33:703–10.
- Craigie EH. 1926. A preliminary experiment upon the relation of the olfactory sense to the migration of the sockeye salmon (*Oncorhynchus nerka*, Walbaum). *Trans Roy Soc Can* 20:215–24.
- Dittman AH, Quinn TP, Dickhoff WW, Larsen DA. 1994. Interactions between novel water, thyroxine and olfactory imprinting in underyearling coho salmon. *Aquac Fish Manage* 25(Suppl 2):157–69.
- Dittman AH, Quinn TP, Nevitt GA. 1996. Timing of imprinting to natural and artificial odors by coho salmon. *Can J Fish Aquat Sci* 53:434–42.
- Donaldson LR, Allen GH. 1957. Return of silver salmon to point of release. *Trans Am Fish Soc* 87:13–22.
- Erkkila LF, Moffett JW, Cope OB, Smith BR, Nielson RS. 1950. Sacramento-San Joaquin Delta fishery resources: effects of Tracy Pumping Plant and Delta Cross Channel. US Fish and Wildlife Service special scientific report: Fisheries Nr. 56.
- Groves AB, Collins GB, Trefethen PS. 1968. Roles of olfaction and vision in choice of spawning site by homing adult chinook salmon. *J Fish Res Board Can* 25: 867–76.
- Hallock RJ, Elwell RF, Fry DH Jr. 1970. Migrations of adult king salmon *Oncorhynchus tshawytscha* in the San Joaquin Delta; as demonstrated by the use of sonic tags. California Department of Fish and Game. Fish Bulletin 151.
- Harden Jones FR. 1968. Fish migration. London (UK): Arnold. 325 p.
- Johnsen PB, Hasler AD. 1980. The use of chemical cues in the upstream migration of coho salmon. *J Fish Biol* 17:67–83.
- Kano R, Reavis R. 1996. Annual report. Chinook salmon spawning stocks in California's Central Valley, 1985. California Department of Fish and Game Anadromous Fisheries Branch administrative report nr. 96–04.
- Kano R, Reavis R. 1997. Annual report. Chinook salmon spawning stocks in California's Central Valley, 1986, 1987, 1988. California Department of Fish and Game Anadromous Fisheries Branch administrative report nrs. 97–02, 97–04, 97–10.

- Kano R, Reavis R. 1998. Annual report. Chinook salmon spawning stocks in California's Central Valley, 1989. California Department of Fish and Game Anadromous Fisheries Branch administrative report nr. 98-02.
- Kano R, Reavis R, Fisher F. 1996. Annual Report. Chinook salmon spawning stocks in California's Central Valley, 1984. California Department of Fish and Game Anadromous Fisheries Branch administrative report nr. 96-03.
- McIsaac DO, Quinn TP. 1988. Evidence for a hereditary component in homing behavior of chinook salmon. *Can J Fish Aquat Sci* 45:2201-5.
- Quinn TP. 1990. Current controversies in the study of salmon homing. *Ethol Ecol Evol* 2:49-63.
- Quinn TP, Brannon EL, Dittman AH. 1989. Spatial aspects of imprinting and homing in coho salmon. *Fish Bull* 87:769-74.
- Quinn TP, Fresh K. 1984. Homing and straying in chinook salmon from Cowlitz River Hatchery, Washington. *Can J Fish Aquat Sci* 41:1078-82.
- Reavis R. 1986. Annual report. Chinook salmon spawning stocks in California's Central Valley, 1983. California Department of Fish and Game Anadromous Fisheries Branch administrative report nr. 86-01.
- Unwin MJ, Quinn TP. 1993. Homing and straying patterns of chinook salmon from a New Zealand hatchery: spatial distribution of strays and effects of release date. *Can J Fish Aquat Sci* 50:1168-75.
- Wisby WJ, Hasler AD. 1954. Effect of olfactory occlusion on migrating silver salmon. *J Fish Res Board Can* 11(4):472-8.

Notes

- Jennifer Bull. California Department of Fish and Game fishery biologist, Fresno, California. Personal communication with the author on 27 July 1998.
- Robert Kano. California Department of Fish and Game fishery biologist, Sacramento, California. Personal communication with the author on 15 September 1997.
- George Neillands. California Department of Fish and Game fishery biologist, Fresno, California. Personal communication with the author on 16 July 1998.

Survival of Chinook Salmon Smolts in the Sacramento-San Joaquin Delta and Pacific Ocean

Peter F. Baker and J. Emil Morhardt

Abstract

This paper summarizes current knowledge about the effects of river flow and water export on the survival of San Joaquin River Basin chinook salmon smolts migrating through the Sacramento-San Joaquin Delta. As will become clear, there are serious deficiencies in our understanding of the needs of smolts as they pass through this region, but there is a general agreement that mortality can be high and can probably be reduced by management actions. The potential for success of the various alternatives remains speculative; something needs to be done, but it remains unclear what will work best. For example, smolt survival is usually better at very high (flood) flows than at very low flows, but there is little solid information about the potential for improved survival in the range that might be managed regularly. Researchers have not really begun the search for optimal flows for smolt survival; analyses to date offer, at best, only the qualitative guidance that "higher" flows are "better" for salmon, without any indication of just how much better survival can be or should be. Similarly, although there is reason to believe that strategically placed barriers should improve smolt survival, by keeping smolts well away from the Delta export pumps; however, experiments to date have not been able to demonstrate or refute the effectiveness of such barriers directly.

San Joaquin Chinook Salmon Life History

Only one chinook salmon run, the San Joaquin fall run, is generally recognized in the San Joaquin basin. This run forms spawning populations in the Stanislaus, Tuolumne, and Merced rivers (hereafter called simply "the tributaries"). These populations are distinguished from other Sacramento runs not just by geography, but also in many details of life-history. In particular, the timing of the runs to the San Joaquin tributaries is quite distinct from that of the Sacramento system fall runs.

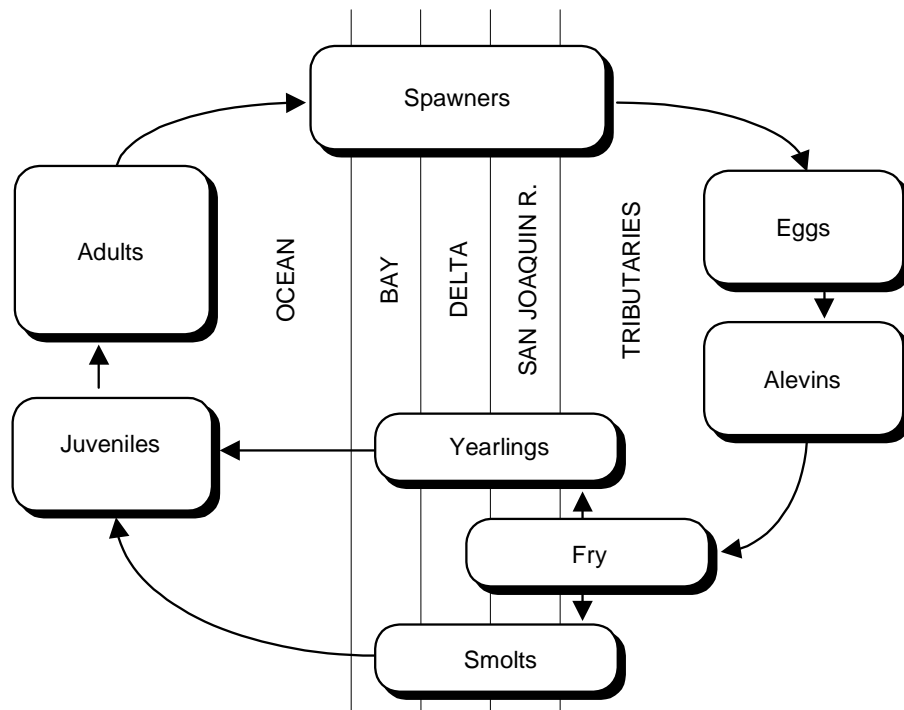


Figure 1 Schematic life history of San Joaquin fall-run chinook salmon. Salmon are vulnerable to export effects during upstream passage through the Delta as spawners, during emigration as smolts or yearlings, and as fry rearing in the Delta.

The life-history pattern of San Joaquin River chinook salmon is shown schematically in Figure 1. Adult chinook salmon typically migrate into the Stanislaus, Tuolumne, and Merced rivers as two-, three-, and four-year-olds. The age composition of the run varies considerably from year to year, but overall about half the migrants are three-year-olds, the remainder divided fairly evenly between two- and four-year-olds. Two-year-olds are disproportionately male, and are often reported separately as jacks, although the percentage of two-year-olds which are female is much higher for the San Joaquin runs than for other chinook salmon stocks, and such females contribute significantly to production in some years. The upstream migrants are collectively called the year's escapement.

The spawning run typically extends from October through December, with the bulk of the run appearing in the tributaries in November. Spawners are occasionally seen in September and are frequently reported in small numbers in January. They begin to construct nests, called redds, and spawn as soon as they arrive in the spawning reaches of the tributaries. Females defend their redds for seven to ten days after spawning. All adults die after spawning.

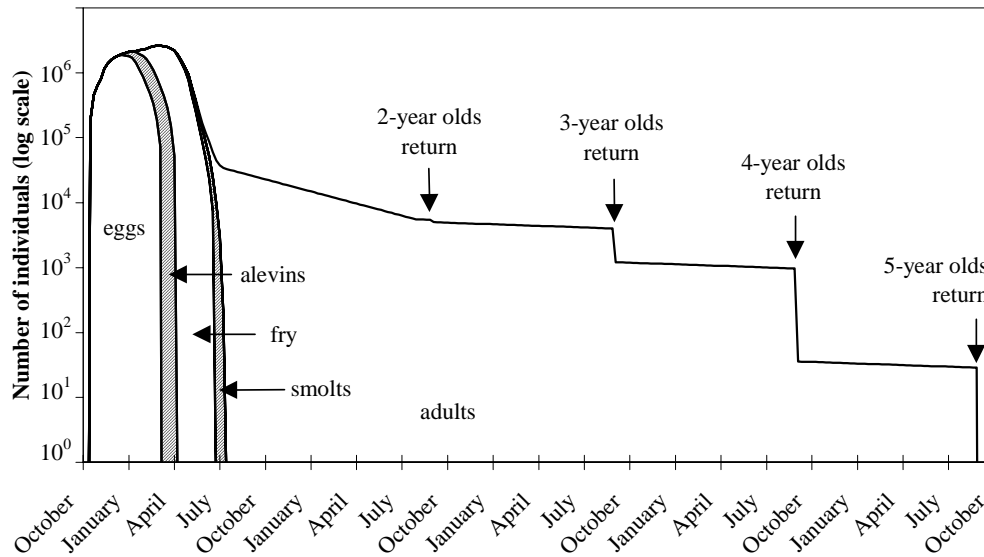


Figure 2 Representative numbers of individuals occurring in different life stages of a typical San Joaquin Basin cohort of chinook salmon. Estimates are derived from average numbers estimated by the EACH dynamic simulation population model.

The development of an idealized cohort over its lifetime is shown in Figure 2. The young fish emerge from the redds as fry from late December through April, with most emerging in February. Some fry soon migrate downstream into the San Joaquin River and the Delta, or are involuntarily displaced from the tributaries by high flows; whether such fry survive to contribute significantly to the total production is not known.

Most fry remain in the tributaries until spring, when they undergo smoltification, a set of physiological changes preparing them for ocean life, and begin their seaward migration. The smolt emigration peaks in April and May, but can extend from late February through June. Some fry do not join the spring emigration, but instead remain in the tributaries over the summer, emigrating in October and November as yearlings. Conditions in the tributaries for summer rearing have been highly variable until recently, however, and is not clear how important these fish have been to total San Joaquin Basin production.

Emigrating smolts experience considerable mortality in the lower reaches of the tributaries, the San Joaquin River, the Delta and San Francisco Bay, and during the first year of ocean life. Smolt mortality in the San Joaquin Delta, in particular, is known to be quite high in most years, and has become a principal focus of efforts to enhance San Joaquin salmon populations: this paper deals primarily with this issue.

Figure 2 illustrates the relative numbers of a typical cohort over the course of its life cycle based on average results from the EACH dynamic population simulation model (EA 1991). A few million eggs are produced in an average year. By the time the developing smolts reach the ocean, their number is reduced by two orders of magnitude. Comparatively minor improvements to survival in these early life stages can greatly improve the numbers of returning adults.

Sources of Information About Smolt Survival

Because of their complex life history, chinook salmon fall under multiple regulatory jurisdictions over their lifetimes. They are studied by many agencies; although there are many exceptions and much interagency coordination, the general tendency is for the California Department of Fish and Game (DFG) to study chinook salmon in the upstream tributaries, the U.S. Fish and Wildlife Service (USFWS) in the Delta, and the National Marine Fisheries Service (NMFS) in the ocean. The DFG's Region 4 annual reports are an important source of information about all stages of San Joaquin Basin salmon from spawning escapement to smolts in the San Joaquin River. The annual reports of the USFWS' Sacramento-San Joaquin Estuary Fishery Resource Office are a principal source of information about smolt survival in the Delta.

Since 1970, research activity by the State and Federal governments into environmental matters in the Delta has been consolidated under the Interagency Ecological Program (IEP). The IEP is a cooperative effort of the DFG, USFWS, NMFS, California Department of Water Resources, State Water Resources Control Board, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. Geological Survey, and U.S. Environmental Protection Agency. Activities under the IEP are reported in the quarterly *IEP Newsletter*. Bulk data generated by IEP studies are published electronically and can be accessed at the IEP web site (<http://www.iep.water.ca.gov>).

Although these are the primary "official" sources of data on San Joaquin salmon, many other entities have conducted studies or published analyses relevant to the needs of salmon in the Delta. Most such material has been presented at the Bay-Delta Hearings, and is part of the Administrative Record for the 1995 Water Quality Control Plan (SWRCB 1995a, 1995b). See also Brandes and McLain (this volume) for additional analyses and another view of survival of Central Valley juvenile salmon moving through the Delta.

Coded-wire-tag Releases Release and Recapture Studies

The principal source of information about smolt survival in the Delta is the recovery of coded-wire-tagged salmon. Coded-wire tags (CWTs) are short

lengths of wire, encoded with a group serial number, which are inserted into the heads of the salmon. These tags are not visible externally, so tagged fish also have their adipose fins clipped for recognition. Normally, fish bearing the same tag number are released at the same time and place, although in the past, tags left over from one experiment were occasionally used in another. Adipose fins do not regenerate, so tagged fish can be identified visually throughout their lives. To read the tag number, however, the fish must be killed.

In principle, all tag recoveries are reported to the Pacific States Marine Fisheries Commission (PSMFC), which maintains the Regional Mark Information System database (RMIS). In practice, the conversion from older, local archives is not complete. Information about all CWT releases, and all information about ocean recoveries, is accessible through RMIS; however, inland recovery data from California are most easily obtained through the DFG or the USFWS, depending on the nature of recovery.

CWT experiments are of two sorts. Most commonly, two or more groups are released at approximately the same time, and treatment effects are estimated by comparing the numbers recovered at downstream locations. It is convenient to refer to these as “paired release” experiments, although more than two groups may be involved. The virtue of this approach is that if the releases are arranged so that both groups reach the recovery locations at approximately the same time, estimates of relative survival between groups can be calculated using only qualitative assumptions about the sampling procedures used. Sometimes it is necessary to estimate absolute, instead of relative, survival, in which case additional information is needed, such as the probability of capture. Such estimates are often referred to as “survival indices” to alert readers to the extra level of uncertainty. The CWT experiments most relevant to San Joaquin salmon issues can be grouped as follows.

Upstream Survival Experiments. In a long-standing series of experiments, CWT groups are released in the Merced, Tuolumne, and Stanislaus rivers to investigate in-river migration and survival. These are always arranged as paired releases; one group is released “upstream” (usually near the passage-blocking dam), and another group is released “downstream” (usually near the mouth) in the same river a few days later. These releases are often further coordinated with releases at Mossdale or Dos Reis, to provide paired-release data for survival in the San Joaquin River between the mouths of the tributaries and the Delta.

Old River-San Joaquin River Survival Experiments. In another long-standing series of experiments, CWT groups are released in the vicinity of the Old River-San Joaquin River split. These are usually arranged as paired releases, groups being released simultaneously in two of the following three locations: Mossdale on the San Joaquin River (upstream of the split), Dos Reis on the San Joaquin

River (downstream of the split), and Stewart Road on Old River (downstream of the split). These releases are often further coordinated with releases at Jersey Point.

Lower San Joaquin River Survival Experiments. In 1991, two sequences of CWT releases were made at locations along the San Joaquin River between the head of Old River and Jersey Point: groups were released at Dos Reis (River Mile 50), Buckley Cove (RM39), Empire Tract (RM29), Lower Mokelumne (RM19), and Jersey Point (RM12) on April 15, 16, 17, 18, and 19, respectively, and again at Buckley Cove, Lower Mokelumne, and Jersey Point on May 6, 9, and 13, respectively.

Interior South Delta Survival Experiments. In many years CWT groups are released in Old River at Palm Tract. These are usually coordinated with releases at Stewart Road on Old River or at Mossdale on the San Joaquin River.

Trawl Surveys

Since 1978, as part of IEP, the USFWS has monitored the relative abundance of chinook salmon smolts emigrating from the Central Valley with mid-water trawl surveys at Chipps Island. The sampling effort varies over course of the season, but during the peak of the emigration season is typically at its maximum level of ten 20-minute trawls per day, seven days per week. Smolts with adipose fin clips are killed and their CWTs are read. The number of smolts captured is expanded to account for the amount of time spent sampling and the ratio of the net width to channel width to form an estimate of absolute abundance. For CWT-bearing smolts, the expanded recovery for each tag group is divided by the number of smolts originally released and reported as a smolt survival index (SSI).

The Chipps Island trawls are of special importance for investigating questions of Delta smolt survival, because this trawl location can be loosely regarded as marking the transition from delta to bay environments, and because data have been gathered quite consistently at this location for two decades. In the spring of 1997, as part of the Vernalis Adaptive Management Plan, a new USFWS trawl survey location was added at Jersey Point on the San Joaquin River, to supplement the Chipps Island data with data more specific to San Joaquin salmon populations.

Since 1989, DFG has conducted similar monitoring in the San Joaquin River near Mossdale Landing County Park, just upstream of the head of Old River. Ten 10-minute trawls are conducted during a five-hour "index" period each day, typically for 5 days each week during the peak of the emigration season. The number of smolts captured is expanded by an efficiency index obtained by experiments in which smolts marked with subcutaneously-injected paint

are released a short distance upstream of the trawl location. Sampling at this location is expected to become more consistent and intensive in future years.

Smolts Captured at the Delta Water Export Pumping Stations

Both the federal government's Central Valley Project (CVP) and California's State Water Project (SWP) export facilities in the South Delta include systems for the salvage of entrained fish: the Tracy Fish Collection Facility at the CVP's Tracy Pumping Plant and the John E. Skinner Fish Protection Facilities at the SWP's Harvey O. Banks Pumping Plant. In both cases, fish entrained at the facility are diverted by screens into a separate system of bypasses and holding tanks, from which they are loaded onto trucks for transport and release at one of two locations at Sherman Island. The salvage facilities are operated by USBR (Tracy) and by DWR and DFG (Skinner).

The salvage release locations are upstream from Chipps Island. Salvaged smolts are therefore vulnerable to recovery in the Chipps Island trawls, creating difficulties in interpreting Chipps Island trawl data: one doesn't know the route of the tagged smolts. Did they arrive through export salvage operations or on their own through Old and Middle rivers?

At both facilities, samples are taken at regular intervals by diverting the entire fish salvage flow into a separate holding tank. All salmonids in each sample are counted and measured, and used to estimate total salvage numbers. Salmon with clipped adipose fin are killed and their tags are read.

In addition to this regular sampling, the entire bypass system is flushed from time to time to remove predators that have taken up residence. A complete census is taken of the fish present, and all tagged smolts are killed and their tags are read.

Ocean Recoveries

Chinook salmon from the San Joaquin Basin are captured as adults in the commercial and sport fisheries. Detailed information about ocean recoveries in general, and CWT recoveries in particular, is collected by state, provincial, and federal agencies of the United States and Canada, and maintained by the PSMFC in the RMIS database.

Adult Escapement Estimates

From the size of the escapement it is possible to draw inferences about the survival of the adult salmon as smolts. In the San Joaquin Basin, all escapement estimates are based on carcass surveys, or returns to the Merced River Fish Facility, except for a few years in the early 1940s when counting weirs were used.

Management and Smolt Survival

Although it is generally recognized that considerable smolt mortality occurs between the mouths of the San Joaquin tributaries and the Delta, this mortality is not usually addressed directly. It is usually assumed that flow requirements upstream (for the benefit of fry and smolts in the tributaries), and downstream (for the benefit of smolts in the Delta), would equally benefit smolts in the San Joaquin River itself.

Smolt survival in the San Joaquin Delta is known to be poor, and there are many factors that could plausibly be manipulated to the benefit of survival. Foremost among these are the “usual suspects” in inland fisheries problems: flows, diversions, and water quality.

Flow and Export

As described above, the needs of smolts in the Delta have been studied by releasing large numbers of smolts marked with coded-wire tags upstream of the Delta and recovering them downstream of the Delta (near Chipps Island, in the ocean fisheries, or as returning adults). Researchers relate the observed recoveries to variables like flow and export in an attempt to determine empirical relationships that could be used to guide policy decisions.

This black-box approach, although it ignores the underlying mechanisms causing observed changes in survival, has merit. After all, the ultimate goal is to enhance salmon populations through management. If it could be shown that certain management actions would enhance survival, it would not be necessary to know why they did, or how survival depends on factors outside management control.

Unfortunately, this approach has not been entirely effective in the Sacramento-San Joaquin Delta. Although relationships between Delta smolt survival, flows, and exports have been the subject of investigation for many years, there is surprisingly little agreement on the value of management actions deriving from these relationships.

There are at least three reasons why these experiments have been so unsatisfactory:

- The data sets are small. Only a few points are added by each year's experiments.
- Recapture numbers are generally small, and expansion to survival indices is highly uncertain.

- Many potentially confounding factors cannot be satisfactorily controlled or taken into account.

The last reason is probably the most fundamental. The South Delta is a complex environment for smolts from the black-box point of view, some factors are simply distractions which contribute a great deal of noise. Increasingly, researchers have been compelled to study the mechanisms by which flow and export affect smolt survival in an effort to divide the problem into more digestible pieces. Two major steps have been taken in this direction.

The first step has been to separate the dual role of export on smolt survival. Export affects smolts directly, by entraining fish at the facilities, and indirectly, by altering Delta flow patterns. The direct entrainment effects can be studied through mortality experiments, screen efficiency experiments, fish salvage records, and so on. The effects of export on Delta flow patterns are naturally treated in combination with those of inflow, with the help of hydrodynamic modeling.

The second step has been to divide in-Delta flow effects on smolt survival into two parts: first, the effects of these flows on the routes taken by smolts through the Delta, and second, survival along individual routes. This step is motivated by the fact that smolt survival often varies greatly from one part of the Delta to another. The clearest expression of this comes from a series of six experiments conducted by USFWS between 1986 and 1990 (Figure 3). In each of these experiments, two groups of smolts were released on the same date in the Lower San Joaquin River and in Old River. Both release sites are a short distance downstream of the Old River-lower San Joaquin River split, but the two groups would be expected to take different routes through the Delta. The lower San Joaquin River group survived better than the Old River group in all six experiments – a result which is already significant, with no further statistical assumptions, at the 98% confidence level. Overall, smolts released in lower San Joaquin River were more than twice as likely to reach the recovery site at Chipps Island than were smolts released in Old River.

Current efforts to understand the scope for improving smolt survival through flow and export management are thus organized around the following questions:

- How do San Joaquin River flow and CVP-SWP export affect in-Delta flows?
- How do in-Delta flows affect smolt migration patterns?
- How do in-Delta flows affect smolt survival along particular migration routes?

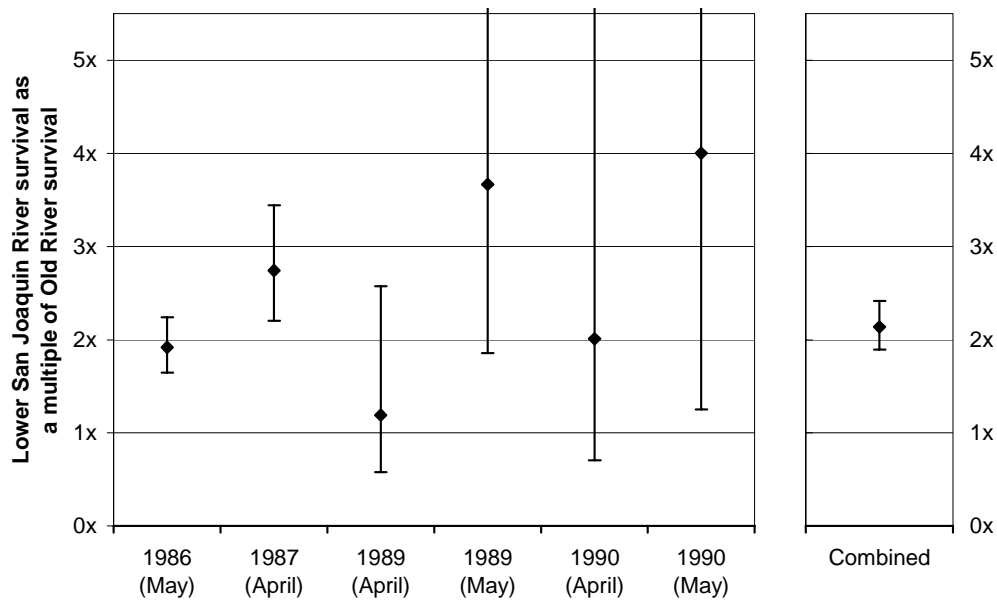


Figure 3 Survival of smolts released in lower San Joaquin River at Dos Reis, as a multiple of the survival of smolts released in upper Old River at Stewart Road, based on recoveries in trawls at Chipps Island and in the ocean fisheries. A value of 1x represents equal survival for both release. The survival ratio for all experiments combined was 2.14. The confidence intervals (95%) are calculated assuming that capture for each group at each location is a Poisson process and should be regarded as conservative.

San Joaquin River Flow, CVP and SWP Exports, and In-Delta Flows

In principle, the relationships between San Joaquin River flow, CVP-SWP export, and in-Delta flows are completely knowable, with the help of hydrodynamic models. There are several of such models in current use and more under development. Although there are important differences between these models, it may be safely said that the hydrodynamics of the Delta are understood far more thoroughly than are the effects of these hydrodynamics on Delta biota.

Two basic facts about Delta hydrodynamics important to emigrating smolts are (1) tidal flows are much larger than the tidally-averaged, or "net" flows, and (2) Old River is a principal channel through the Delta, typically receiving well over half the total flow of the San Joaquin River even in the absence of export.

It would be difficult to exaggerate the difference in magnitude between net and tidal flows. From water year (WY) 1940 through WY 1991, the average flow at Vernalis was 4,550 cfs, and the highest annual average flow over this period was 21,281 cfs (WY 1983). In the San Joaquin River near Columbia Cut and the mouth of Middle River, typical summer flows swing from roughly 50,000 cfs westward to 50,000 cfs eastward, and back again, each day (DWR 1993). At the confluence of the San Joaquin and Sacramento rivers, the typical daily excursion in each direction exceeds 300,000 cfs.

In-Delta Flows, Smolt Travel Time, and Smolt Migration Patterns

There is little theory available on the mechanisms by which smolts find their way through the estuary, or about how these mechanisms are affected by flow. Much of what is currently known about emigration mechanisms is negative. For example, the most straightforward model, that the movement of smolts mirrors the movement of water, has been shown to be incorrect. Smolts and water travel through the Delta at very different rates, and end up at very different places.

San Joaquin smolts pass through the Delta in a median time of 11 days, some arriving at Chipps Island as early as five days after release at the point where the San Joaquin River joins the Delta, and some taking as long as 26 days (Figure 4). This is considerably shorter than the transit time for neutrally-buoyant tracer particles, at least in hydraulic simulations. Figure 5 shows an example comparing the speed of smolt passage and the speed of tracer particles for a release made on April 4, 1987, in which 80% of the smolts were estimated to have been recovered after two weeks, but only 0.55% of the tracer particles were recovered after two months. (The estimated survival for this smolt group was atypically high, but the transit time was not. Typical survival estimates for smolts are still much larger than 0.55%.)

Not only do the tracer particles which reach Chipps Island take a long time to get there, but most of them go somewhere else. That somewhere else is the CVP and SWP pumps, at least for the hydraulic simulations available to us. Figure 6 shows that for the April 27, 1987 simulation, 77% of the tracer particles ended up at the export pumps, while only 13% of the smolts arrived there.

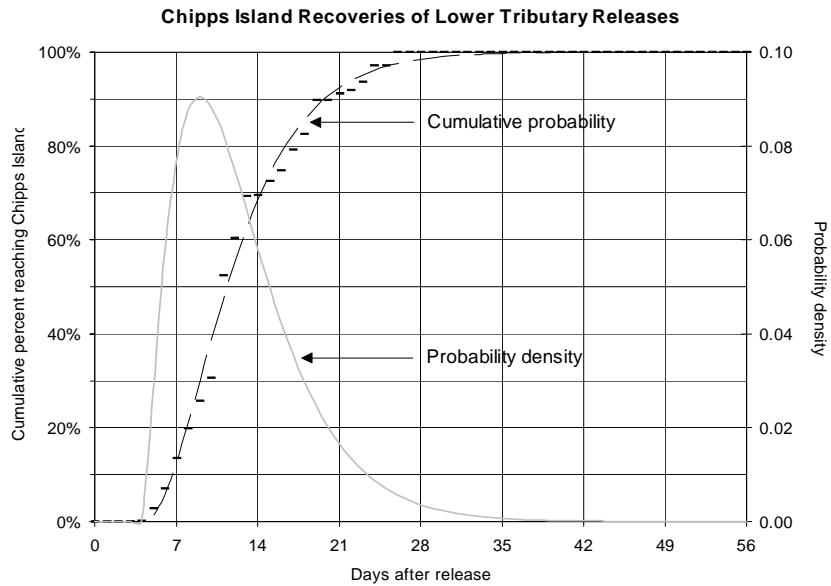


Figure 4 Empirical pattern of smolt recovery (cumulative) at Chips Island as a function of days after release in Merced (1989), Stanislaus (1986, 1988, 1989), and Tuolumne (1986, 1987, 1990) rivers. The dashed (---) line indicates smoothed recovery (cumulative); the gray line indicates probability density of reaching Chips Island based on smoothed recoveries. After release, the fastest smolts arrived at Chips Island in five days and the slowest in 26 days. Peak recoveries occurred on the tenth day after release, and half of the fish had arrived within 11 days.

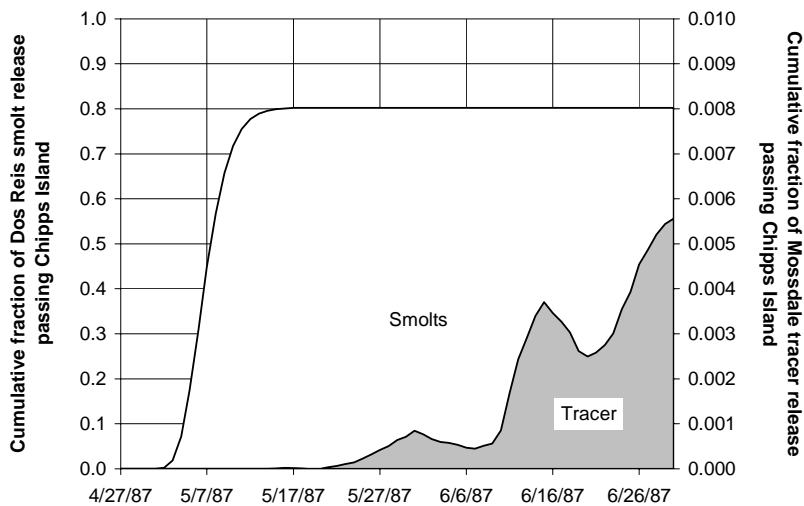
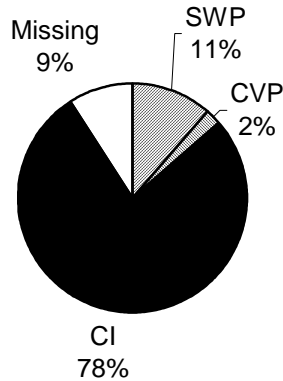


Figure 5 Comparisons of the movements of salmon smolts and passive particles released near the head of Old River on April 27, 1987. Cumulative recoveries at Chips Island of smolts released at Dos Reis, and simulated mass flux past Chips Island of tracer material released at Mossdale. The smolt recovery data have been fitted to an inverse gaussian distribution. Hydraulic simulations by Flow Science (1998).

Smolts released in Lower San Joaquin River at Dos Reis



Tracer released in San Joaquin River at Mossdale

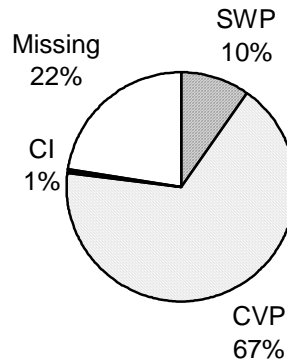


Figure 6 Comparisons of the final destinations of salmon smolts and passive particles released near the head of Old River on April 27, 1987. Estimated final disposition of tagged chinook salmon smolts released at Dos Reis and simulated disposition as of June 30, 1987 of tracer material released at Mossdale. For the smolts, the CVP and SWP values represent total entrainment, including estimates of screen inefficiency and mortality in Clifton Court Forebay, and the Chipps Island value represents successful emigration exclusive of release after salvage. Hydraulic simulations by Flow Science (1998).

Initially it seems intuitively reasonable that increased flows entering the Delta from the San Joaquin River at Vernalis would decrease travel times and speed passage, with concomitant benefits to survival. The data, however, show otherwise. Figure 7 (top) shows that Delta inflow has little if any effect on smolt travel time, probably because the large tidal flows swamp any passive effect of the incoming flows from the San Joaquin River, as suggested by the particle tracking results. On the other hand, Figure 7 (bottom) shows that the larger the smolts at the time of release, the shorter the travel time. This is in accordance with the striking difference between the passage time of smolts and passive particles: smolts actively swim toward the ocean, and the bigger they are the faster they do it.

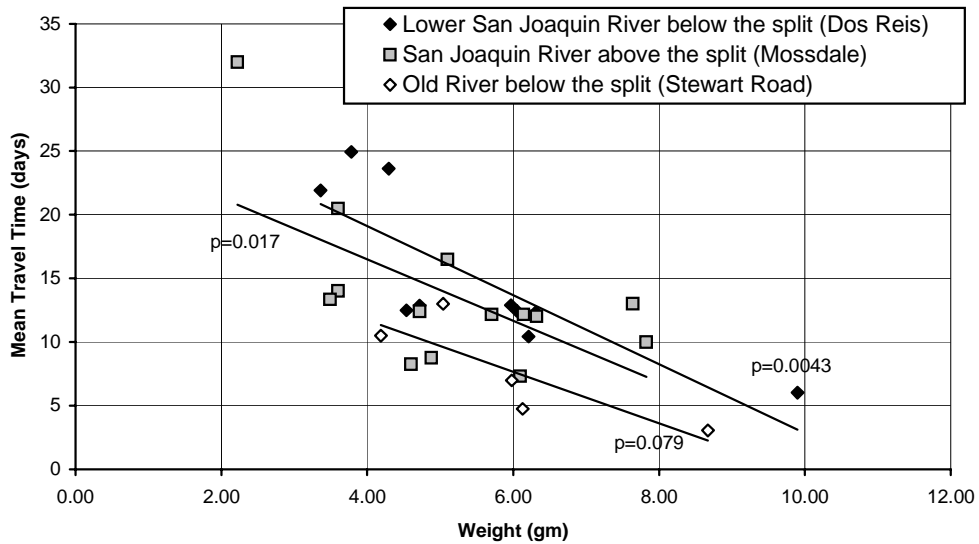
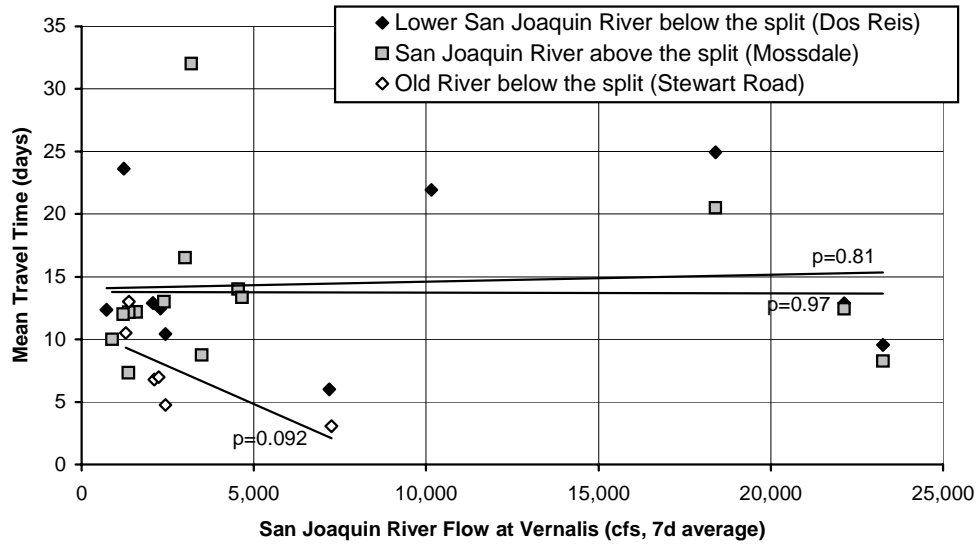


Figure 7 Mean smolt migration times from three locations near the Old River-San Joaquin River split to Chippis Island. The vertical ordering of the three trendlines in each plot agrees with the vertical ordering of the corresponding release locations in the legend. Top: Migration time and San Joaquin flow for the seven days following release. The regression for the Old River releases is significant only at the 90% confidence level, the other two are not significant at any acceptable confidence level. Bottom: Migration time and smolt weight at release. The regressions for both the San Joaquin and Lower San Joaquin releases are both highly significant (99% and 98% confidence levels, respectively). The regression for the Old River releases is only significant at the 90% level, but is still better than the corresponding regression with flow.

Choice of Routes Through the Delta

When arriving at the Delta from the San Joaquin River, smolts have a choice of routes, the initial decision of which is whether to remain in the larger channel, Old River, at the point that the San Joaquin River diverges toward the north. This decision is critical to their survival, because the Old River channel soon branches into two meandering through channels (Old and Middle rivers), a number of major canals (Grant Line, Fabian and Bell, Victoria), and various dead-ends (Paradise Cut, Tom Paine Slough). The through channels and canals all deliver smolts to or near the intake structures for the CVP and SWP pumping plants.

Under conditions of no export pumping, about 60% of the water arriving via the San Joaquin River goes down the Old River channel; as pumping increases, that proportion can increase to 100% (Figure 8). If smolts simply traveled at a fixed speed relative to the water they were in, one would expect 60% or more of them to go to the pumps as well. In fact, in the few experiments that have been done, the results show an even higher percentage of the smolts go down Old River than would be expected if they simply went with the flow. Figure 9 shows the results from a series of daily trawls in the San Joaquin River and in Old River below the flow split. The results are expressed as the number of naturally migrating smolts captured per 10,000 m³ of water sampled. If the smolts were simply following the flow, their concentrations in the two rivers would be identical. In fact, most of the daily data points occur well above the line of equal concentration, showing a higher concentration of smolts in Old River.

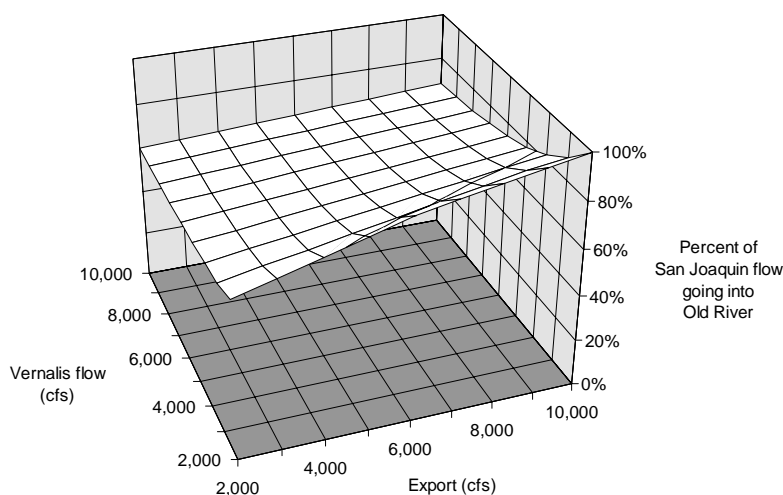


Figure 8 Percentage of net flow (calculated from 1986 DWR net flow equations) in the San Joaquin River at Vernalis flowing into Old River. At least 59% of the flow goes into Old River at any Vernalis flow, but as much as 100% can flow into Old River if Delta pumping is high.

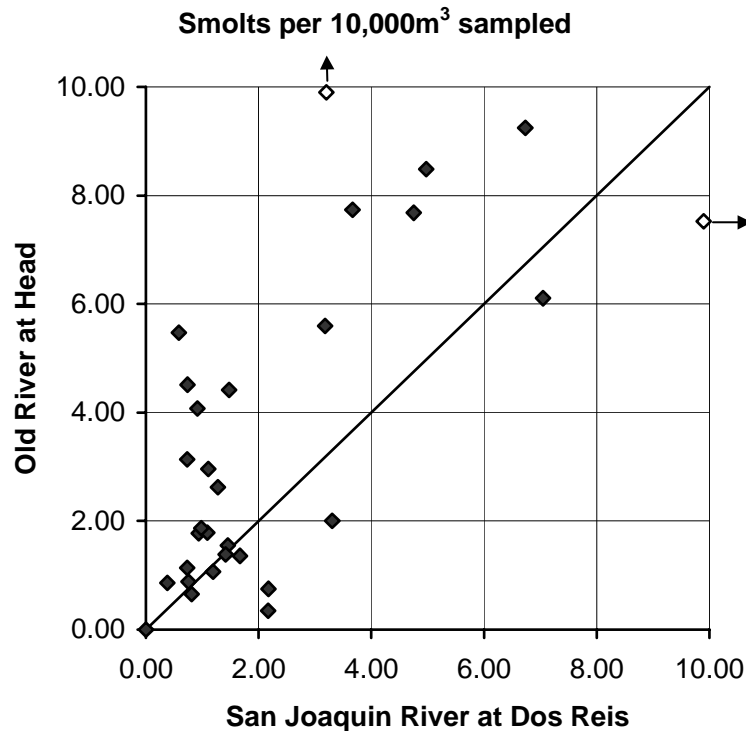


Figure 9 Daily smolt densities from 1996 real-time monitoring program from April 1 to May 6. These are unmarked natural smolts. If the proportion of smolts in each channel exactly followed flow, the data would all lie on the diagonal line. The data tend to lie well above the line, however, suggesting a preference on the part of the smolts for the Old River channel. The two open diamonds were well off-scale at 12.5 for the upper one and 18.7 for the one on the left axis, so we left them off to better visualize the majority of the data.

In-Delta Flows and Smolt Survival

Most of the USFWS CWT experiments in recent years have attacked the problem of relating survival along a given migration route to Delta hydrodynamics. In these experiments, two basic migration routes are recognized: down Lower San Joaquin River (past Stockton), or down Old and Middle rivers (past the export pumps). Delta hydrodynamics are represented by calculated net flows in Lower San Joaquin River at Stockton, and in Old River between its head and the split with Middle River, respectively.

This work has so far been inconclusive. There is a significant ($P = 0.049$) correlation between survival in Lower San Joaquin River and San Joaquin flow at Stockton. This relationship is no better (or worse) than that with San Joaquin flow at Vernalis, and thus sheds little light on what the underlying mecha-

nisms for such a relationship could be. There is no empirical correlation at all between survival in Lower San Joaquin River and the rate of CVP-SWP export.

Results so far on survival in Old River have been even more unsatisfactory. Taken at face value, multiple regression of survival vs. flow in Old River and CVP-SWP export leads to the conclusion that increased export would improve smolt survival along this route (presumably an artifact of the strong contribution of export to Old River flow). As with the Lower San Joaquin River, the problem is that the degree of scatter, and lack of good controls, makes interpretation difficult.

Beginning in 1997, major changes have been made to the design of South Delta CWT experiments. These changes are expected to result in higher recapture numbers (leading to more precise estimates of survival), better control of flow and export conditions during individual experiments, and some degree of statistical design in the combinations of flow and export to be tested. It is too soon to tell whether these improvements will lead to a clearer understanding of the effects of flow and export on survival, but results so far are encouraging.

Vernalis Flows and Smolt Survival

Figure 10 shows the relationship between the USFWS smolt survival index for CWT tagged fish and the flows in the San Joaquin River at Vernalis, just before the flow split between the lower San Joaquin River and Old River. Shown on the figure is a simple linear regression and the 95% confidence intervals. The data points are grouped in the regions of moderately low flow and quite high flow, with no data at all between 11,000 cfs and 18,000 cfs. The flows over 18,000 represent periods when the tributaries are spilling from the dams, and are essentially at flood stage; such conditions are probably very important to fish, but cannot be provided on demand by reservoir operators. When only the data below 10,000 cfs are considered, there appears to be a negative relationship between flow and smolt survival.

There are two ways to think about these data. One school believes that there is, in fact, a linear positive relationship between flow and smolt survival and that, on average, one could expect to get a survival improvement through the Delta corresponding to the slope of the regression line in Figure 10. The other school suspects that different mechanisms are at work at flood flows than low or moderate ones, and there is little reason to believe that altering flows within the lower range will have much effect on smolt survival through the Delta. Data from the middle range of flows will help, but the data are very scattered and factors other than flow are obviously influential.

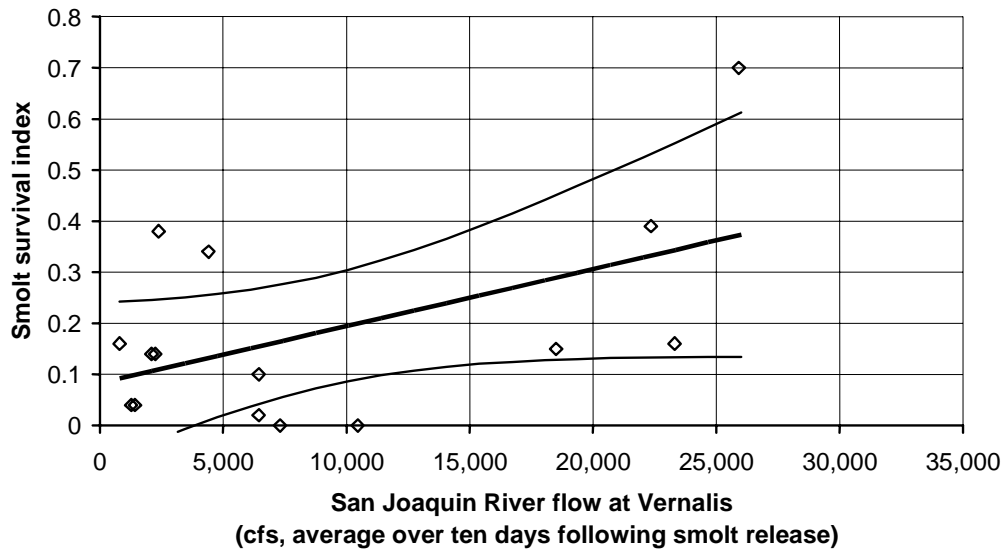


Figure 10 USFWS smolt survival index for tagged smolts released in the lower San Joaquin River at Dos Reis and average flow in the San Joaquin River at Vernalis over the 10 days following tag release. Fitted regression line and envelope of 95% confidence region for fitted line are shown.

Vernalis Flows and Escapement

Another way to look at the effects of flow at Vernalis is to examine the escapement as a function of flows when the escapees were smolts. Figure 11 shows such a result, based on the simplifying assumptions that all adults returned 2.5 years after their emigration as smolts and that in every year there were the same number of smolts. The results are similar to those for the smolt survival relationship with Vernalis flow, but with considerably more data and consequently, with narrower confidence limits. As with the smolt data, there is a clear relationship when high flows are included in the analysis, but at flows below 10,000 cfs there is very little correlation between flows at Vernalis and escapement, and there is a very large amount of scatter in the data. The scatter is undoubtedly partly attributable to failure of the two assumptions, but efforts to correct for these assumptions have not been particularly successful, so there are likely to be other issues as well.

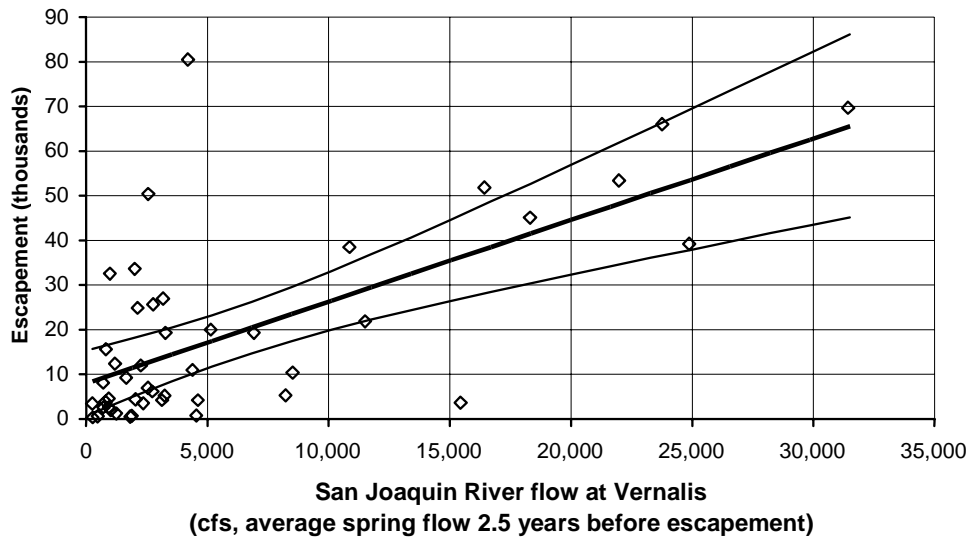


Figure 11 Total escapement to San Joaquin tributaries, 1951 through 1996, and spring flow in the San Joaquin River at Vernalis 2.5 years earlier. Fitted regression line and envelope of 95% confidence region for fitted line are shown.

Conclusions

Smolt survival through the Delta may be influenced to some extent by the magnitude of flows from the San Joaquin River, but this relationship has not been well quantified yet, especially in the range of flows for which such quantification would be most useful. Salvage records show clearly that export-related smolt mortality is a major problem, but no relationship between export rate and smolt mortality, suitable for setting day-to-day operating levels, has been found. Survival measured in the Delta using paired releases of tagged smolts shows a twofold better survival for individuals that travel past Stockton via San Joaquin River rather than past the export facilities via Old River. Since more than 60% of the smolts usually go down Old River, any measure that decreased this percentage would be expected to benefit smolts, however such a benefit has yet to be demonstrated empirically.

In general, current methods used to explore smolt survival in the Delta have not succeeded in clarifying basic technical and biological issues. Some of these methods are contributing useful information, but very slowly. New kinds of studies are needed, focussed on fundamental questions of salmon biology and survival methods, and designed with more concern for issues of statistical power and refutability.

References

- Brandes P, McLain J. 2001. Juvenile chinook salmon abundance, distribution, and survival in the Sacramento-San Joaquin Estuary. In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 2. Sacramento (CA): California Department of Fish and Game.
- [DWR] California Department of Water Resources. 1993. Sacramento San Joaquin Delta Atlas. Sacramento (CA): California Department of Water Resources. 121 p.
- [EA] EA Engineering, Science, and Technology, Inc. 1991. San Joaquin River system chinook salmon population model documentation and validation. Prepared for Turlock Irrigation District and Modesto Irrigation District, California. 80 p.
- [Flow Science] Flow Science, Inc. 1998. Determination of the sources of water arriving at Clifton Court Forebay and Bethel Island. Task 1 of Delta Flow Determination Project. Prepared for San Joaquin River Group, Modesto, California. 9 p.
- [SWRCB] State Water Resources Control Board. 1995a. Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. 95-1 WR. Sacramento (CA): State Water Resources Control Board. 45 p.
- [SWRCB] State Water Resources Control Board. 1995b. Environmental report. Appendix 1 to Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. 95-1 WR. Sacramento (CA): State Water Resources Control Board. 494 p.

Additional References

- [DFG] California Department of Fish and Game. 19- (Series). San Joaquin River chinook salmon enhancement project. Sport Fish Restoration Act. Annual Progress Reports. Fresno (CA): California Department of Fish and Game, Region 4.
- [IEP] Interagency Ecological Program for the Sacramento-San Joaquin Estuary. 19- (Series). IEP Newsletter. Sacramento (CA): California Department of Water Resources.
- [USFWS] US Fish and Wildlife Service. 19- (Series). Survival and productivity of juvenile chinook salmon in the Sacramento-San Joaquin Estuary. Annual Progress Reports. Stockton (CA): US Fish and Wildlife Service, Fisheries Assistance Office.

Ocean Salmon Fishery Management

L.B. Boydston

Abstract

California ocean salmon fisheries are managed by the Pacific Fishery Management Council (Council) under the federal Magnuson-Stevens Fishery Conservation and Management Act. This chapter describes the ocean fisheries impacting California Central Valley (CV) chinook stocks, the federal regulatory process that is followed in managing these ocean fisheries, and discusses alternative management measures for protecting valuable natural resources. The CV supports fall, late-fall, winter, and spring chinook runs. The Council has adopted a spawning escapement goal for the fall run, while a federal rebuilding plan is used to regulate the fisheries to protect the winter run, an endangered species. The winter run plan is also protective of CV spring run, a threatened species. Some potential alternative management strategies include (1) a revised escapement goal for the Sacramento fall run, (2) a separate escapement goal for the spring run, (3) an escapement goal for the San Joaquin fall run, and (4) a selective ocean fishery for marked hatchery fish. The CV salmon management program is lacking in two areas: (1) river return estimates for coded-wire-tagged fish releases and (2) inconsistent tagging of hatchery fish releases, precluding estimation of hatchery fish contributions. I conclude that a comprehensive fishery management program should be implemented for CV chinook salmon under the Central Valley Project Improvement Act and that the Klamath Fishery Management Council be used as a model for developing such a program.

Introduction

Central Valley (CV) chinook salmon (*Oncorhynchus tshawytscha*) are primarily harvested in ocean fisheries off California between Point Sur and Point Arena, but are taken in significant numbers as far north as Cape Falcon in northern Oregon (Figure 1). Ocean fishing for salmon (*Oncorhynchus* spp.) off the Washington, Oregon, and California coasts is managed by the Pacific Fishery Management Council (Council) under the Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). Increasing concern for the protection of CV chinook stocks has led fishery and inland habitat managers to question the efficacy of current management strategies for ocean and

river fisheries. This report describes (1) the ocean fisheries impacting CV chinook; (2) the process followed by the Council for managing CV chinook stocks; (3) alternative or complementary management measures aimed at providing additional protection for these valuable natural resources; and (4) recommendations for developing and implementing a comprehensive program for addressing fishery management concerns for CV chinook.

River fishery management, which comes under regulation of the Fish and Game Commission (Commission), is not discussed in this report. A Council "overfishing" review report provides a summary of CV sport fishery catch data through 1993 (PFMC 1994).

Fishery Resource

The Central Valley supports four runs of chinook salmon: fall, late-fall, winter, and spring, so named because of the time of year adults enter fresh water to spawn, which occurs within a few weeks or several months following river entry, depending on stock. CV chinook mature at ages 2 to 4, with a few individuals at age 5, except for winter-run chinook which mature at ages 2 to 3. Age 2 fish of all runs are primarily males (jacks).

The fall run is the more abundant and ubiquitous of the four runs, occurring in all suitable spawning areas. The other runs occur in the main stem or the various tributaries to the Sacramento River above the mouth of the American River. The winter run is listed as endangered under the State and federal Endangered Species Acts; the spring run as threatened under the two acts; and the fall and late-fall runs as candidates for listing under the federal act. All CV hatcheries (Coleman, Feather River, Nimbus, Mokelumne River, and Merced River) propagate fall chinook, while Feather River and Coleman also propagate spring and winter chinook, respectively. Hatchery production has a major effect on the number of fish available to ocean fisheries and that return to spawn each year to the hatcheries and natural spawning areas. Trucking of CV chinook salmon production from the State hatcheries for release below the Sacramento-San Joaquin Delta is done to bypass Delta water diversions. This practice increases hatchery fish survival but also increases straying of returning adults.



Figure 1 Map of coastal landmarks and Central Valley streams and hatchery locations

Ocean Fisheries

Salmon taken for commercial or recreational purposes may be taken only by hook and line (8210.1, Fish and Game Code and 27.80, Title 14, California Code of Regulations). Most salmon fishing is conducted by trolling a baited hook or lure behind a diesel or gasoline powered boat. In recent years, a baited hook fished from a drifting vessel (mooched) has become the most popular fishing method in the San Francisco Bay and Monterey Bay sport fisheries. Salmon are rarely harvested from shore although they are occasionally caught by sport fishing from the Princeton Pier, located just south of the Golden Gate.

Fishery Monitoring. The California Department of Fish and Game (DFG) aims to sample 20 percent of the salmon fishery landings to collect fishery management data by time, area, and fishery (and has done so since 1962). The heads from all ad-clipped salmon observed in the sampling are retained and the coded wire tag (CWT) contained in each head is extracted, decoded and the associated data are entered into the coastwide CWT data base maintained by the Pacific States Fisheries Commission. Fishery catch estimates are based on (1) State landings reports required from commercial and charterboat landings, and (2) random stratified sampling of the private boat fishery by the DFG. The actual sampling rates achieved in the respective fisheries (commercial, charterboat, and private boat) are used to develop the CWT expansion factors that produce estimates of CWT contributions, which are available by fishery, time, and area strata.

Commercial Fishery. The commercial fishery harvests about two-thirds of the chinook salmon taken off California. For example, commercial landings during 1995–1999 averaged 407,700 chinook compared to a sport catch of 200,000 fish (see PFMC 2000 for extensive data on California fisheries and spawning escapements).

Commercial fleet size (under limited entry) has dropped from nearly 6,000 vessels in 1982 to about 1,800 vessels in 1999. In 1999, 101 vessels landed 50 percent of the fish compared to 438 vessels in 1982 (PFMC 2000).

Commercial fishing in recent years has taken place primarily south of Point Arena because of conservation and allocation requirements for Klamath River fall chinook salmon. Commercial fisheries operate as far south as Point Conception but most landings occur in Monterey, Half Moon, and San Francisco bays. The commercial season takes place from May through September and the fishery has a 26-inch minimum size limit, although 27 inches has been used at times in recent years to protect winter chinook. Most chinook are landed from May through July.

Commercial fishing north of Point Arena has generally been limited to the month of September when Klamath chinook abundance is low.

Sport Fishery. The sport fishery has traditionally taken place between February and November and had a two fish per angler bag limit and 20-inch minimum size limit. In recent years, the season length has been reduced and higher size limits have been applied to fisheries south of Shelter Cove (Horse Mountain) to protect winter chinook. Beginning in 2000, the season opening south of Point Arena was delayed until April to protect CV spring chinook.

Chinook are taken in the sport fishery from Santa Barbara to the Oregon border, but most are landed in San Francisco and Monterey bays where most of the fishing effort originates. Charterboats take most of the fish south of Point Arena, while private boats or skiffs take most of the chinook harvested in the Fort Bragg, Eureka, and Crescent City areas. Coho fishing has been banned off California in recent years due to federal listing of Oregon and California coho stocks. This has led to salmon fishing closures north of Point Arena during most of July when coho are most abundant.

June, July, and August are the most important sport salmon fishing months off California. Since 1995, an average of 134 charterboats landed salmon in California. Annual salmon angler effort in those years (charterboat plus private) averaged 227,600 angler days. This effort produced a catch of 200,300 chinook for a catch per angler day of 0.88 chinook (PFMC 2000).

Ocean Fishery Management

The Council's Salmon Framework Plan (Plan) contains the management objectives that are followed in regulating the ocean fisheries. It specifies the area of jurisdiction, species, types of regulations, and procedures the Council must follow to make any changes. Amendment 14 to the Plan has been completed and is aimed at the meeting the requirements of the Magnuson-Steven Act as amended in 1997. It includes a recent escapement goal amendment for Oregon coho salmon and defines "Essential Fish Habitat" for salmon stocks that come under Council purview.

The Council has three advisory bodies that provide input on salmon amendment and regulatory issues. The Scientific and Statistical Committee (SSC) provides multi-disciplinary peer review of proposed fishery management actions. This includes review of stock assessments and assessment methodologies as well as review of biological, economic, and social impact analyses. The Salmon Technical Team (STT) provides the reports that summarize the previous fishing season, estimate ocean abundance for the coming season, and analyze the impacts of the Council's proposed and final management

recommendations and Plan amendments. The Salmon Advisory Subpanel (SAS) develops annual regulation options and comments on all salmon issues that come before the Council, including habitat issues (PFMC 1996).

Each year the Council recommends ocean fishing regulations aimed to meet Plan escapement goals and jeopardy opinions for federally listed species. California fisheries are managed, in part, to meet escapement, allocation, and rebuilding goals for Sacramento River fall chinook, Klamath River fall chinook, Oregon and California coastal natural spawning coho salmon, and Sacramento River spring and winter chinook. A description of CV chinook salmon goals and Council stock management procedures follows.

Biological and Allocation Goals

Sacramento River Fall Chinook. The escapement goals for this stock is to achieve a spawning escapement in all years of 122,000 to 180,000 adults. The goal is based on historical river escapement levels and includes both hatchery and naturally produced fish. It should be noted the goal was modified in 1984 to establish a goal range because of the effect of Red Bluff Diversion Dam on upriver returns (PFMC 1984).

A predictor model has been developed to project CV chinook adult abundance. The model uses an index of abundance for CV chinook salmon runs (Central Valley Index or CVI), which is the sum of ocean fishery landings south of Point Arena and the adult CV spawning escapement in the same year (Table 1). The ocean prediction is based on the relationship between the CVI and the previous year CV jack estimate (Figure 2). The CVI harvest rate represents the sum of ocean fishery catches divided by the CVI for the same year. Recent years' CVI harvest rates and the proportion of adult fall chinook returning to the Sacramento River are used to project the Sacramento River fall chinook Salmon escapement under the proposed or adopted ocean fishing regulations (PFMC 2000).

The Sacramento River escapement goal has been met in all years since 1970 not including 1972, 1983, and 1990–1992 when the escapement declined to between 85,300 and 121,000 fish (Figure 2, PFMC 2000).

Table 1 Indices of annual abundance and ocean fishery impacts on California Central Valley chinook in thousands of fish

| Year | Ocean chinook landings south of Point Arena | | | Hatchery and natural escapements of Central Valley adults | | | CVI abundance ^b | CVI harvest index (%) ^c |
|-------------------|---|-------|---------|---|--------------------|-------|----------------------------|------------------------------------|
| | Troll | Sport | Total | Fall | Other ^a | Total | | |
| 1970 | 226.8 | 111.1 | 337.9 | 190.5 | 55.6 ^d | 246.1 | 584.0 | 58 |
| 1971 | 150.7 | 166.3 | 317.0 | 190.6 | 62.0 | 252.6 | 569.6 | 56 |
| 1972 | 299.8 | 187.6 | 417.4 | 99.6 | 46.1 | 145.7 | 563.1 | 74 |
| 1973 | 422.5 | 180.9 | 603.4 | 227.1 | 27.1 | 254.2 | 857.6 | 70 |
| 1974 | 282.7 | 141.6 | 424.3 | 205.6 | 35.7 | 241.3 | 665.6 | 64 |
| 1975 | 234.4 | 92.7 | 327.1 | 159.2 | 47.6 | 206.8 | 533.9 | 61 |
| 1976 | 237.9 | 68.6 | 306.4 | 168.8 | 43.8 | 212.6 | 519.0 | 59 |
| 1977 | 263.8 | 76.6 | 340.4 | 148.7 | 42.8 | 191.5 | 531.9 | 64 |
| 1978 | 291.0 | 65.9 | 356.9 | 136.9 | 17.1 | 154.0 | 510.9 | 70 |
| 1979 | 234.1 | 108.5 | 342.6 | 167.9 | 11.3 | 179.2 | 521.8 | 66 |
| 1980 | 294.3 | 77.1 | 371.4 | 155.9 | 31.6 | 187.5 | 558.9 | 66 |
| 1981 | 289.9 | 73.8 | 363.7 | 189.3 | 18.8 | 208.1 | 571.8 | 64 |
| 1982 | 418.4 | 122.5 | 540.9 | 177.2 | 38.3 | 215.5 | 756.4 | 72 |
| 1983 | 178.2 | 53.0 | 231.2 | 121.0 | 12.8 | 133.8 | 365.0 | 63 |
| 1984 | 221.7 | 78.7 | 300.3 | 197.5 | 17.0 | 214.5 | 514.8 | 58 |
| 1985 | 212.3 | 121.8 | 334.1 | 308.9 | 18.1 | 327.0 | 661.1 | 51 |
| 1986 | 502.5 | 114.8 | 617.3 | 259.0 | 33.2 | 292.2 | 909.5 | 68 |
| 1987 | 446.8 | 152.8 | 599.7 | 188.0 | 25.5 | 213.5 | 813.2 | 74 |
| 1988 | 830.5 | 130.4 | 960.9 | 244.9 | 28.0 | 272.9 | 1,233.8 | 78 |
| 1989 | 363.8 | 130.9 | 494.7 | 149.6 | 17.9 | 167.5 | 662.2 | 75 |
| 1990 | 336.2 | 112.7 | 448.9 | 108.3 | 13.6 | 121.9 | 570.8 | 79 |
| 1991 | 254.6 | 62.1 | 316.7 | 112.3 | 15.3 | 127.6 | 444.3 | 71 |
| 1992 | 163.5 | 66.7 | 230.2 | 85.3 | 8.2 | 93.5 | 323.7 | 71 |
| 1993 | 259.7 | 99.3 | 359.0 | 131.5 | 10.4 | 141.9 | 500.9 | 72 |
| 1994 | 290.4 | 159.9 | 450.3 | 148.8 | 6.8 | 155.6 | 605.9 | 74 |
| 1995 | 670.6 | 354.6 | 1,025.2 | 272.0 | 16.2 | 288.2 | 1,313.4 | 78 |
| 1996 | 348.9 | 129.3 | 478.2 | 255.3 | 8.7 | 264.0 | 742.2 | 64 |
| 1997 | 482.5 | 208.4 | 690.9 | 350.8 | 17.4 | 368.2 | 1,059.1 | 65 |
| 1998 | 221.5 | 114.5 | 336.0 | 253.0 | 40.1 | 293.1 | 629.1 | 53 |
| 1999 ^e | 258.8 | 76.1 | 334.9 | 294.5 | 14.9 ^f | 309.4 | 644.3 | 52 |

^a Spring run of the current calendar year and late-fall and winter runs of the following calendar year.

^b Ocean landings + escapement.

^c Ocean harvest landed south of Point Arena as a percent of the CVI.

^d Percent of adults in 1970 spring run assumed the same as 1971 (72%, 5,500 total).

^e Preliminary.

^f Late-fall and winter contributions unknown—respective averages of 1995–1999 escapement used.

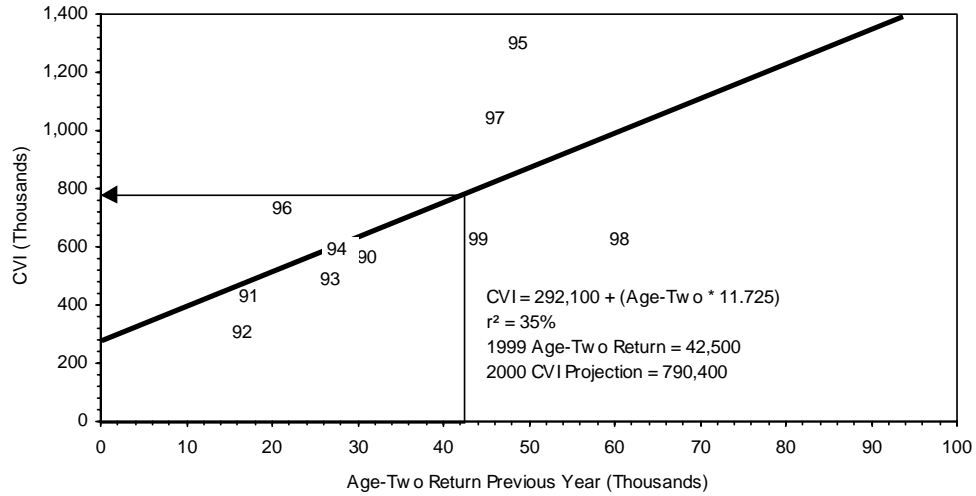


Figure 2 Linear regression of CVI on in-river age-two Central Valley chinook of the previous year, 1990–1999. Years shown are CVI year.

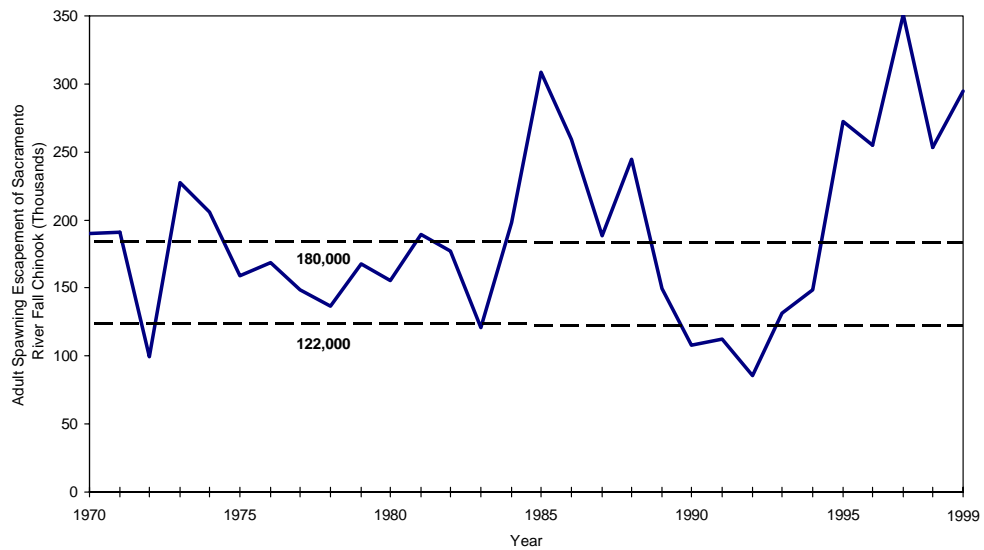


Figure 3 Spawning escapements of adult Sacramento River fall chinook, 1970–1999, and the goal range for the stock of 122,000 to 180,000 adult fish. Estimate for 1999 is preliminary.

Winter Chinook. The escapement goal for this stock is to achieve a 31 percent increase in escapement over the 1989–1993 mean rate. An ocean fishery model has been developed based on historical marked (fin-clipped) winter chinook data with which to compare proposed or actual ocean fishing regulations (DFG 1989). The model is stratified by the time and area and includes a length at age module to evaluate minimum size limits and the mortality associated with hook and release of undersized fish. It is noteworthy that the shift in recent years to mooching in the ocean sport fishery off central California has decreased the benefits associated with an increased minimum size limit (from 20 to 24 inches). This is because fish caught by mooching tend to swallow the hook, which is often fatal. Thus, in addition to an increased minimum size limit, time, and area closures have been required to meet the winter chinook harvest rate objective.

Spring Chinook. Spring chinook were listed as threatened under the State and federal acts in 1999. The NMFS recently issued a biological opinion regarding the effect of ocean fisheries on CV spring chinook. They concluded that recent action by the California Fish and Game Commission to delay the sport season opening south of Point Arena, in combination with the management measures in place to protect winter and spring chinook, should be sufficient to allow for stock rebuilding.

Administrative Process

Regulatory. The Council is advisory to the Secretary of Commerce (Secretary) who has the authority to implement federal salmon fishing regulations for ocean waters 3 to 200 miles offshore. The DFG Director has the authority under Section 7650 et seq. of the Fish and Game Code to conform State regulations affecting the commercial fishery in State waters (0 to 3 miles) to the Council's salmon fishery plan (or the actual federal regulations). The Commission retains regulatory authority over the sport fishery in State waters and must follow the State's Administrative Procedures Act in conforming State regulations to the PFMC plan. Each year the ocean salmon fishing regulations (federal and State) are adopted to be effective starting May 1.

Plan Amendment. The Salmon Plan contains the basic elements for regulating the ocean fisheries. The states generally have the lead with regard to recommending Plan amendments, and Council concurrence is required to proceed with any amendment proposals. The Council generally considers amendments at its September or November meetings, but can make an exception at its March, April, or June meetings. The amendment process requires the development of a document for public review, public hearings, final Council action, and publication (if approved) by the Secretary in the *Federal Register*. Extensive Council review is provided during the Plan development process, and the Secretary can reject the Plan or return it for additional development and public hear-

ings. A Plan amendment generally takes a year or longer to complete. For species listed under the federal ESA, federal restrictions supersede the Council's goals.

Alternative Management Strategies

In response to the concern over the status of chinook stocks in the CV and elsewhere, the need may arise to implement additional or revised management objectives for CV chinook salmon runs. Alternative harvest strategies may also need to be considered. A discussion of possible Plan amendment options and the procedure to follow in implementing such changes through the Council process is presented in the following sections.

Revise the Escapement Goal for Sacramento River Fall Chinook. Raising the gates at Red Bluff Diversion Dam during most of the adult fall salmon run is expected to increase natural salmon production in the upper river. It follows that the Council goal range may no longer be appropriate for the stock and should be set at no less than 180,000 adult fish. This proposal would take a Plan Amendment and require the development of an analysis showing how a revised ocean fishing strategy would produce optimum yield to the U.S. fishing industry, as compared to the current goal (National Standard 1). Such an amendment would take a year or longer to complete. Listing under the federal ESA would supersede the Council's management goal for the stock.

Establish an Escapement Goal for Sacramento River Spring-run Chinook. The Council has approved Salmon Plan Amendment 14 in which a provision is included to allow for additional management goals for stocks not listed in the Plan as part of a two-meeting regulatory process. Such an action would have a time constraint, and would require a Plan amendment to complete the process. CWT spawning escapement estimates may not be available for CV hatchery spring-run chinook because a program has not been in place to make such estimates. The paucity of data could complicate the development of a fishery harvest strategy for the stock because it would be difficult to show the relationship between fishing and spawning escapement under historic or recent fishing regulations. A thorough review of available spring run CWT data is needed to assess the adequacy of available data for developing a spring run fishery model. Consideration should also be given to continuing or implementing a spring chinook CWT program at Feather River Hatchery, and to estimating river returns of CWT spring chinook beginning as soon as possible.

Establish an Escapement Goal for San Joaquin Fall Chinook. The original Salmon Plan developed in 1977 had an escapement goal for this stock, but the goal was removed in 1984 because Delta water withdrawals were affecting the run. The San Joaquin run has not been proposed for separate listing under the federal ESA, but was included as part of the fall and late-fall CV complex in the recent review of California chinook populations (Myers and others 1998). A separate goal could be established for the run under the Council's Plan amendment process. Any such proposal would have to show how goal attainment would affect the ocean fisheries, particularly with regard to their ability to access other chinook stocks when the San Joaquin run is depressed due to water diversion conditions. Analysis of CWT data might show a different ocean distribution pattern for San Joaquin chinook, which could ameliorate any reduction in harvest opportunity for other chinook runs. The amendment process would take a year or longer to complete.

Conduct Selective Fisheries for CV Hatchery Stocks. The Council has approved regulations since 1998 that allow for an ocean fisheries off Washington and Oregon for ad-clipped coho salmon. The fishery is for hatchery fish that were marked in the previous year for the purpose of providing for an ocean selective fishery. Post season analysis showed that the majority of fish encountered in the fishery were, in fact, ad-clipped hatchery fish. The ad mark historically was used as a "flag" for CWT salmon, but an exception was made in the case of Oregon and Washington hatchery coho releases. A selective fishery for hatchery-origin CV chinook salmon could be implemented in California fisheries. Hooking mortality of released (unmarked) fish would be an important consideration. Recent DFG studies show that hook and release mortality of sublegal chinook caught by mooching in the sport fishery is about 24 percent. Hooking mortality of chinook caught by trolling is lower in the sport fishery and about 30 percent in the commercial fishery. Use of the ad mark in a selective fishery could adversely impact the CV CWT program. This is because the tag detection rate, using currently available hand-held detection equipment, is much lower than it is for coho, stemming from the much larger head size of chinook.

Final Remarks and Recommendations

California ocean fisheries are regulated under a Plan developed by the Council and approved by the Secretary pursuant to the Magnuson-Steven Act. The process provides for thorough discussion of Council and State management objectives along with extensive scientific stakeholder input. The Plan amendment process is flexible and requires that proposed Plan amendment proposals are consistent with the National Standards of the Magnuson-Steven Act. The amendment process may take a year or longer to complete, but can be done in less than a year if the change is agreeable to the affected interest groups.

The Council's escapement goal for Sacramento River fall chinook has been met in all but five years since 1970. The goal does not differentiate between hatchery and natural production. Attainment of the winter chinook escapement goal is evaluated based on the adopted regulation structure and is not linked to the actual escapement.

NMFS has expressed concern that natural production in the CV is depressed and that hatchery production is masking the situation. NMFS has also concluded that CV chinook are subjected to excess fishing mortality in the ocean fisheries (NMFS 1998).

In my view, the major problem with current CV salmon fishery management is two fold: (1) the lack of river return estimates for CWT releases and (2) the lack of a comprehensive CWT program to estimate fishery and spawning escapement returns for all hatchery releases. To remedy this situation, I recommend using the Klamath River salmon management program as a model for developing a counterpart CV program. In addition to a comprehensive hatchery CWT and river spawning escapement estimation program; government, tribal, and stakeholder input is provided through a basin management advisory council (Klamath Fishery Management Council, KFMC). The KFMC has a scientific team that evaluates and analyzes biological data and fishery management options (Klamath River Technical Advisory Team). The opportunity is at hand to develop a comprehensive CV fishery management program as a main element of the fishery program to be developed under the Central Valley Project Improvement Act.

Thanks, Nat Bingham

In closing, I would like to recognize and pay tribute to former Council member and friend of many years Nathaniel (Nat) S. Bingham. Nat and I had agreed to prepare this report, but he passed away before we could actually begin work on the manuscript. Had he been around to help write the report, more would have been written about the importance of habitat protection and restoration to the sustainability of CV salmon populations. Nat was an important contributor to the management of California salmon fisheries, and, in particular, to the protection and conservation of the State's rivers and streams upon which our salmon resources depend. Nat was the consummate statesman, but he will mostly be remembered as the tireless advocate for the fish. He was a driving force behind the creation of the Council's Habitat Steering Committee, and was active with the Committee right up to the end. California salmon are better off today in large part because of Nat Bingham's motivation and desire to do what was right for the fish.

References

- [DFG] California Department of Fish and Game. 1989. Winter chinook model. Sacramento (CA): California Department of Fish and Game, Ocean Salmon Project.
- Myers JM, Kope RG, Bryant GJ, Teel D, Liertheimer LJ, Wainwright TC, Grant WS, Waknitz FW, Neeley R, Lindley SF, Waples RS. 1998. Status review of chinook salmon from Washington, Idaho, Oregon, and California. US Department of Commerce. NOAA technical memorandum. NMFS-NWFSC-35. 443 p.
- [PFMC] Pacific Fishery Management Council. 1984. Framework plan for managing the ocean salmon fisheries off the coasts of Washington, Oregon, and California commencing in 1985. Portland (OR): Pacific Fishery Management Council.
- [PFMC] Pacific Fishery Management Council. 1994. Sacramento River Fall Chinook Review Team report. Portland (OR): Pacific Fishery Management Council.
- [PFMC] Pacific Fishery Management Council. 1996. A guide to the Pacific Fishery Management Council and Regional Fishery Management Process. Portland (OR): Pacific Fishery Management Council.
- [PFMC] Pacific Fishery Management Council. 2000. Review of 1999 ocean salmon fisheries. Portland (OR): Pacific Fishery Management Council.

Population Trends and Escapement Estimation of Mokelumne River Fall-run Chinook Salmon (*Oncorhynchus tshawytscha*)

Joseph J. Miyamoto and Roger D. Hartwell

Abstract

In 1990 the East Bay Municipal Utility District (EBMUD) began a program to monitor the fall-run chinook salmon (*Oncorhynchus tshawytscha*) populations in the lower Mokelumne River using video and trapping at Woodbridge Dam and weekly redd surveys.

Over the eight years of this monitoring program, the Mokelumne River fall-run chinook salmon escapement showed a trend of increased abundance of both hatchery and natural spawners. The 1997 estimated total spawning escapement (combined hatchery and natural run) was 10,175 compared to a spawning escapement of 497 in 1990 and the 57-year average escapement of 3,434 fish. The estimated natural spawning population fluctuated from a low of 369 in 1991 to a high of 3,892 fish ($1,739.3 \pm 1,384.9$) in 1996. The percentage of natural spawners ranged between 31% to 90% (52.3 ± 19.9) of the total spawning escapement during the 1991–1997 period.

Significant correlations were observed between the number of redds and total escapement ($R^2 = 0.941$, $P < 0.0001$) and the hatchery returns and total spawning escapement ($R^2 = 0.972$, $P < 0.001$). The later correlation was used to determine the accuracy of past spawning escapement estimates based upon a similar correlation using a narrower dataset.

These results suggest accurate total spawning escapement estimates can be obtained from hatchery returns and from redd counts. Escapement estimates calculated from redd counts and compared with known estimates were accurate in the mid-range while those calculated from hatchery returns were accurate throughout the range of run sizes.

Introduction

East Bay Municipal Utility District (EBMUD) began daily monitoring of the fall-run chinook salmon (*Oncorhynchus tshawytscha*) population in the lower Mokelumne River in 1990. The focus of the monitoring was to document the timing and magnitude of adult salmon upstream migration and the number and distribution of salmon redds on the upstream spawning grounds.

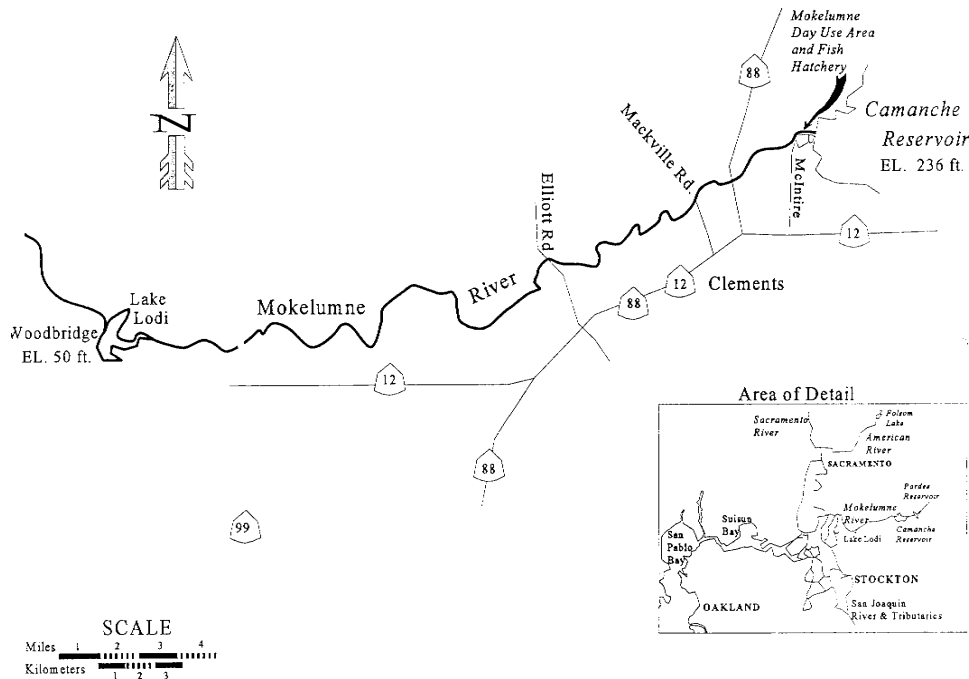


Figure 1 The Lower Mokelumne River between Camanche Dam and Woodbridge Dam, San Joaquin County, California

The Mokelumne River originates in the Sierra Nevada mountains at the Sierra Crest and flows through the Central Valley near the towns of Lockeford, Clements, and Lodi before entering the Delta forks of the Mokelumne just downstream of the Delta Cross Channel (Figure 1). The Mokelumne River watershed drains some 627 square miles. The average annual unimpaired runoff is 720,000 acre-feet with a range of 129,000 to 1.8 million acre-feet. The Mokelumne River watershed has a number of dams and reservoirs. In the upper watershed, Pacific Gas & Electric operates 19 dams, seven storage reservoirs, seven diversions, three regulating reservoirs and two forebays (FEIS 1993). Pardee Dam and Reservoir (river mile 39.6) is owned and operated by EBMUD to provide water for 1.2 million customers in Alameda and Contra Costa counties (EBMUD 1992). The reservoir also provides flood control stor-

age, maintenance of the Camanche Reservoir hypolimnion, and water-based recreational opportunities including both coldwater and warmwater fisheries. Camanche Dam and Reservoir, completed by EBMUD in 1964, provides storage for flood control operations, water to meet agricultural and senior water rights, instream flows for fish needs and a number of water-based recreational opportunities. Camanche Dam (river mile 29.6) represents the upstream limit for anadromous salmonid migration. Historically, salmon and steelhead used the habitat to within one-half mile below Pardee Dam where a natural barrier existed at the Arkansas Ferry Crossing, a distance of some eight and one-half miles above Camanche Dam (EBMUD 1992).

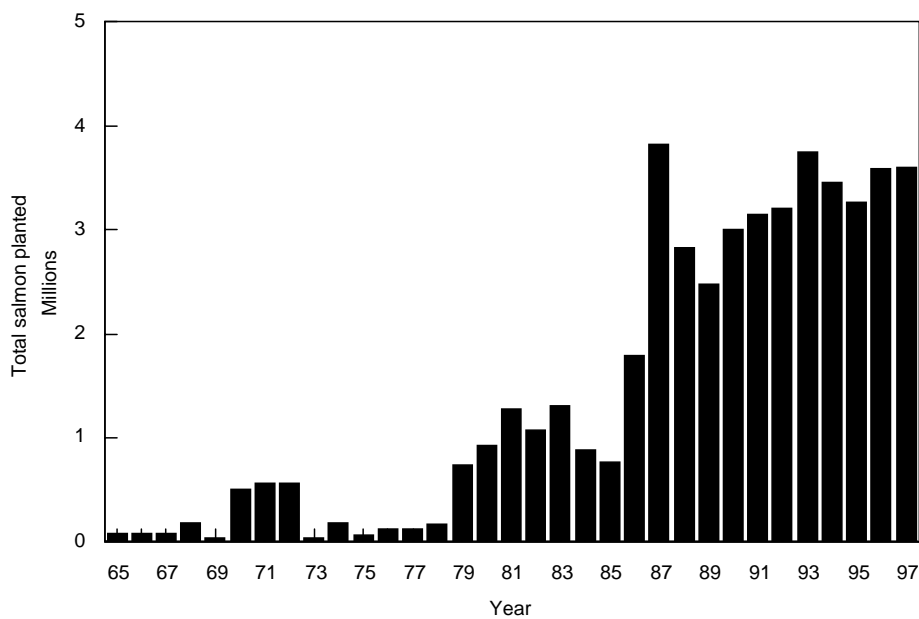


Figure 2 Mokelumne River Fish Hatchery production, 1965–1997. Source: Data from DFG reports. DFG corrections may have modified some previously reported yearly data.

To mitigate for lost habitat above Camanche Dam, the Mokelumne River Fish Hatchery was constructed in 1964 to produce both fall-run chinook salmon and steelhead trout (*Oncorhynchus mykiss*) (EBMUD 1992). Average production from the facility during the 1990s was 3.0 to 4.0 million fall-run chinook salmon smolts, 500,000 yearling chinook salmon, and 100,000 yearling steelhead (Figure 2). The source of most of the salmon broodstock was Feather River Hatchery fish. Two million salmon were raised to post-smolts each year for an ocean enhancement program. All of the enhancement salmon production was trucked around the Delta for release in San Pablo Bay (Figure 3). Salmon smolts that were Mokelumne origin fish were planted below Woodbridge Dam. In 1992 and 1993, yearling chinook salmon were planted in the

Mokelumne Day Use Area adjacent to the Mokelumne River Fish Hatchery just downstream of Camanche Dam (see Figure 1). After 1994, yearlings were released below Woodbridge Dam. During drought years, naturally produced juvenile salmon were collected at Woodbridge Dam and trucked around the Delta for release at Rio Vista or Carquinez (see Figure 1) (Bianchi and others 1992).

Woodbridge Dam spans the lower Mokelumne River near the City of Lodi and the town of Woodbridge (see Figure 2). Each year in March, flashboards are installed in the dam to create Lake Lodi and raise the water surface elevation to operate the Woodbridge Irrigation District diversion canal. Following the end of the irrigation season in late October or early November, the flashboards are removed to empty Lake Lodi. Fish passage past the dam under either mode of operation is provided by a pool-and-weir system that includes high-stage and low-stage fish ladders. The fish ladders provide a unique opportunity to obtain complete counts of fall-run chinook salmon passing Woodbridge Dam under nearly all flow and operating conditions.

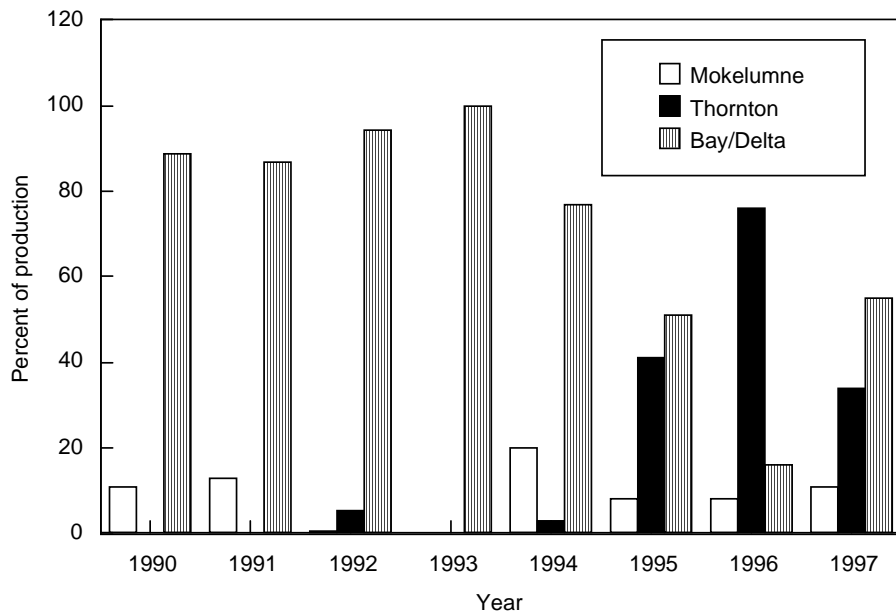


Figure 3 Release locations of Mokelumne River Fish Hatchery chinook salmon production 1990–1997. Production includes smolts, post-smolts, and yearlings. Source: Data from DFG annual reports.

Objectives

Daily video and trap monitoring at Woodbridge Dam provided a new, more reliable method to obtain salmon spawning escapement in the lower Moke-lumne River. One of the objectives of this study was to compare results from this monitoring program to historical escapement estimators. These historical estimators are based on linear regression of hatchery return and estimated annual spawning escapement derived from carcass surveys.

Another objective of this study was to determine if alternate methods could be used to estimate spawning escapement based on the 1990–1997 dataset. The statistical relationships between the number of redds and total spawning escapement, and hatchery returns and total spawning escapement were examined for this purpose.

Methods

Escapement Estimation

From 1940 to 1990, the California Department of Fish and Game (DFG) estimated and/or counted the numbers of chinook salmon migrating upstream to spawn in the lower Mokelumne River. Several methods have been used to estimate spawning escapement (Table 1). These methods included carcass surveys of spawning grounds as well as projections of the natural run using linear regression equations based on the relationship between numbers of hatchery and natural spawners. Direct counting methods included observations of the number of salmon ascending the fish ladders at Woodbridge Dam (Fry 1961).

Table 1 Mokelumne River stock estimates

| <i>Period of sampling</i> | <i>Sampling method</i> |
|---------------------------|----------------------------|
| 1940 – 1942, 1945 | Visual count at Woodbridge |
| 1943, 1944, 1946, 1947 | No estimate |
| 1948 – 1971 | Visual count at Woodbridge |
| 1972 – 1981 | Carcass survey |
| 1982, 1983 | Regression |
| 1984 – 1990 | Carcass survey |
| 1990 – 1997 | Video and trap monitoring |

In 1990, a video and trap monitoring system was installed by EBMUD in both the upper and lower ladders of Woodbridge Dam. An overhead video camera was mounted in the high-stage fish ladder, and a waterproof enclosure housing a camera mounted for a side view was installed in the low-stage fish ladder. Both video cameras shot footage against a 1.2 m² plywood backboard covered with a white plastic sheet and marked with black grid lines spaced five centimeters apart. Four 150-watt flood lamps mounted above the water surface illuminated the backboard. Video camera recording was conducted 24 hours per day, seven days per week, throughout the fall upstream migration. The tapes were reviewed and count data were recorded. The start date of the video monitoring varied between 1 September and 26 October and the ending date each year was 31 December, except for 1997 when high flows ended operations on 10 December.

The sex ratios and age composition of the salmon spawning escapement at Woodbridge Dam were determined by reviewing the videotapes from the underwater camera in the low-stage fishway and collecting data from trapped fish. Sex ratios and age composition of hatchery fish were obtained from DFG Mokelumne River Fish Hatchery personnel.

Upstream migrant traps were installed each year between 1990 and 1997 and operated in the Woodbridge low-stage fishway in pool 8a (Figure 4). The traps were checked two to four times per day, depending on the number of fish captured. The two primary trap checks were one-half hour before sunrise and one-half hour after sunset. The traps were operated intermittently to verify results from the video monitoring program or when highly turbid conditions precluded the use of video cameras.

For a complete description of the video equipment, setup of the video monitoring stations, trap equipment and operations protocol see Bianchi and others (1992) and Marine and Vogel (1996).

Physical and environmental data collected included river flow, river temperatures from Campbell recorders at each gauging station and from a Ryan RTM 2000 thermograph in pool 6a of the Woodbridge low stage fishway (see Figure 4), National Weather Service data on barometric pressure from Stockton and local watershed precipitation from Camanche Dam, and water transparency measured by Secchi disk from pool 9a or from the left abutment of Woodbridge Dam (Marine and Vogel 1996).

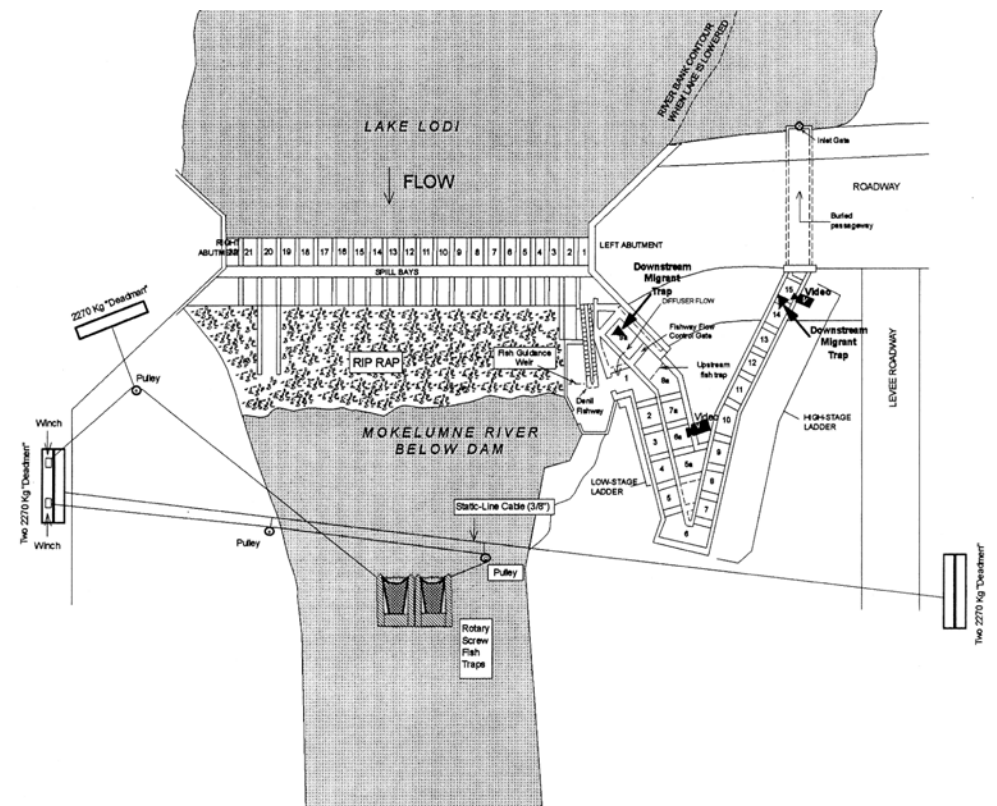


Figure 4 Plan view of Woodbridge Dam showing video monitoring sites and location of upstream migrant fish trap

The percentage composition of grilse and adult salmon in the run was based on a length criterion. A fork length of 61 cm was used to separate grilse from adults. Marine (1997) found this length to be conservative criterion for Moke-lumne coded wire tagged hatchery fish recovered in Central Valley streams and hatcheries during 1992–1995. Using this criterion, Marine (1997) found that 20% of the two-year-old fish were greater than 61 cm and 5% of the three-year-old fish were less than 61 cm. The Mokelumne River Fish Hatchery used the 61-cm criterion, except in 1993 when a large number of grilse (57%) returned to the hatchery and the criterion was increased to 65 cm (Marine and Vogel 1994).

Salmon Redd Abundance Analysis

Salmon redd surveys were conducted weekly in the lower Mokelumne River from 1990 to 1997 (Hagar 1991; Hartwell 1996; Setka 1997). The surveys typically began in early to late October and ended the first week in January, except in 1996 when flood flows ended the surveys on 3 December. For recording the

distribution of salmon redds, the lower Mokelumne River was divided into three reaches (Reach A: Camanche Dam to Highway 88, Reach B: Highway 88 to Mackville Road, and Reach C: Mackville Road to Elliott Road.) (Figure 5). The surveys involved teams of three biologists canoeing or boating and wading down the river in search of redds. Each redd was marked with a fluorescent colored brick and assigned a unique number. During the surveys, data were also collected on redd characteristics including the redd size, water depth, velocity, habitat characteristics, degree of redd superimposition, and usage of prior gravel enhancement sites. The different levels of redd superimposition were based upon the degree of overlap between adjacent estimated redd egg pockets and tail-spills (Hartwell 1996). Habitat types were characterized according to a modified Bisson system (Bisson and others 1981) and included glide, riffle, riffle-glide complex, side-channel glide, and side-channel riffle.

Physical and environmental data collected included water temperature, dissolved oxygen, and stream flow. Water temperatures were collected using hand held thermometers and Campbell data loggers at EBMUD gauging stations (see Figure 5). Total Camanche Dam and powerhouse releases were combined to determine streamflow in the spawning reaches (Hartwell 1996; Setka 1997).

To evaluate alternate methods for determining spawning escapements, linear regression equations were computed for the hatchery return and total escapement past Woodbridge Dam, hatchery return and natural spawning escapement, and total number of redds and total escapement.

The escapement at Woodbridge Dam includes both hatchery and naturally spawning fish. The natural spawning escapement estimate was derived by subtracting the hatchery fish return from the total escapement.

Results

Escapement Estimation

During the first year of the video and trap operations in 1990, the counts at Woodbridge Dam were compared with the DFG escapement estimate based upon the carcass survey. The results showed that substantially more salmon passed Woodbridge Dam than estimated by DFG using carcass survey data (497 actual count compared to 64 from carcass survey estimator) (Bianchi and others 1992). Because the accuracy of the carcass surveys was influenced negatively by environmental conditions such as streamflow and turbidity, DFG discontinued the carcass surveys on the lower Mokelumne River in favor of the more reliable daily video and trap monitoring.

Lower Mokelumne River

Spawning Reaches & Gauging Stations

Contributions to the Biology of Central Valley Salmonids

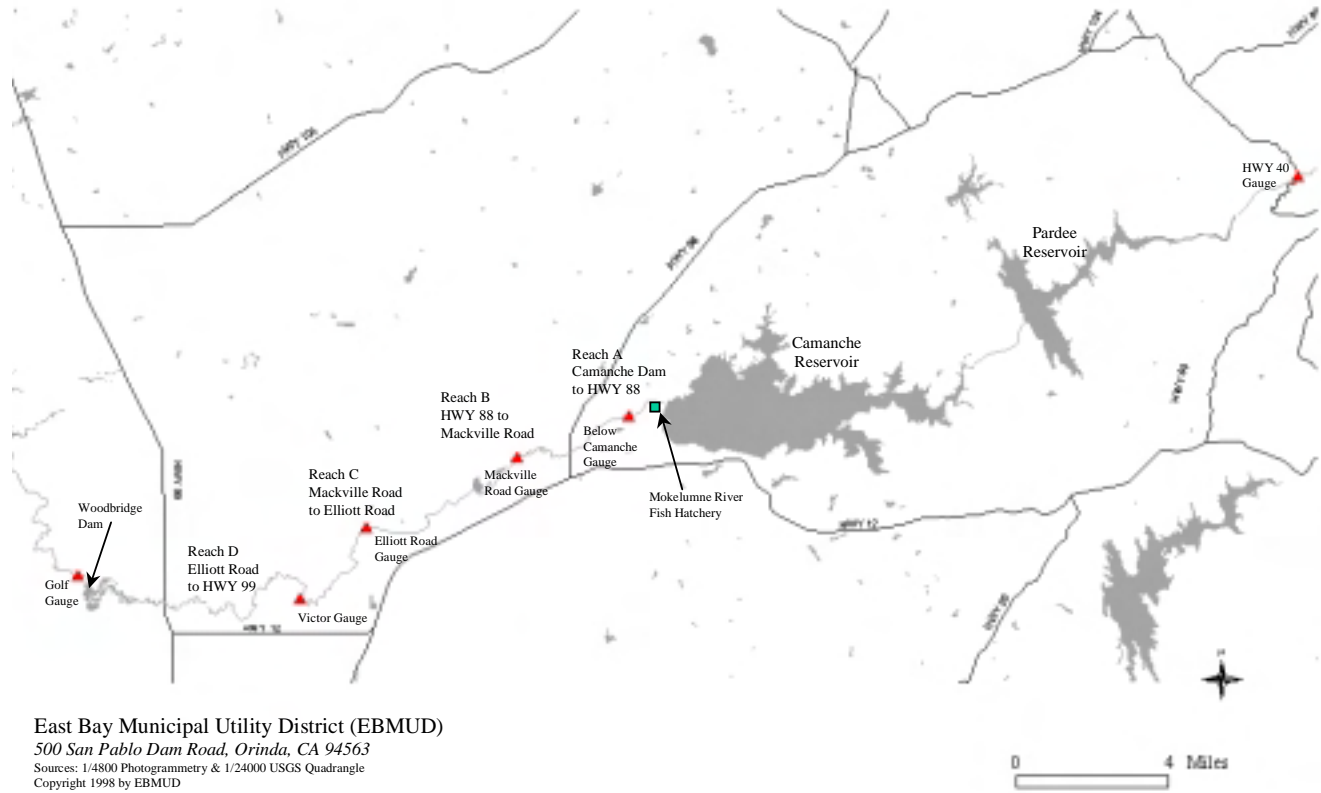


Figure 5 Location of US Geological Survey and EBMUD gauging stations

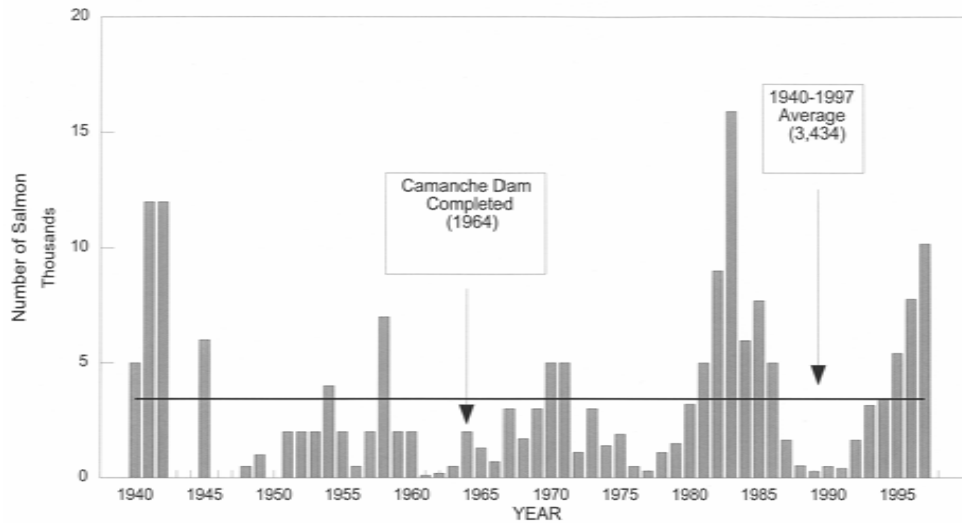


Figure 6 Lower Mokelumne River fall-run chinook salmon escapement, 1940–1997. Source: Data are from DFG, Biosystems, and NRS, Inc. Monitoring of salmon escapement in 1996 was discontinued early (on December 10, 1996) due to high flows. No data were collected in 1943, 1944, 1946, 1947, and 1950. Calculated from the average of the salmon escapement values from 1940 to 1997, excluding 1943, 1944, 1946, 1947, and 1950.

The estimated annual spawning escapement of fall-run chinook salmon over the 57-year period of record is shown in Figure 6. Estimates of spawning escapement during this period have varied from 100 fish in 1961 to 15,900 fish in 1983 (average = 3,434). The 1983 count was based upon an estimate projected from the regression between the hatchery returns and total escapement (Meinz 1983). This regression was based on hatchery return numbers ranging from 17 to 1,386 (average = 463). Over the course of the daily video and trap monitoring (1990 to 1997), the counts of fall-run chinook salmon have ranged between 410 and 10,175 fish (average = 4,062) (Marine 1997). So, the average spawning escapement estimated from 1940 to 1989 was 3,434 fish and average escapement counted by video trap and monitoring from 1990 to 1997 was 4,062.

During the daily video and trap monitoring at Woodbridge Dam (1990 to 1997), the percentage of total spawners ranged between 31% and 90%, with an average of 52.3% (Figure 7).

Adult salmon migrating into the lower Mokelumne River are primarily two- and three-year-old fish. The percentage of grilse in the spawning run has been highly variable, ranging between 7% and 57% over the eight-year monitoring period with an average of 26.8% (Figure 8) (Marine 1997).

The sex ratio of adult salmon counted at Woodbridge Dam over the 1990–1997 period varied between 46% and 57% female with an average of 50.4%. For the Mokelumne River Fish Hatchery, the sex ratio of adult fish varied between 33% and 53% females with an average of 44.9%.

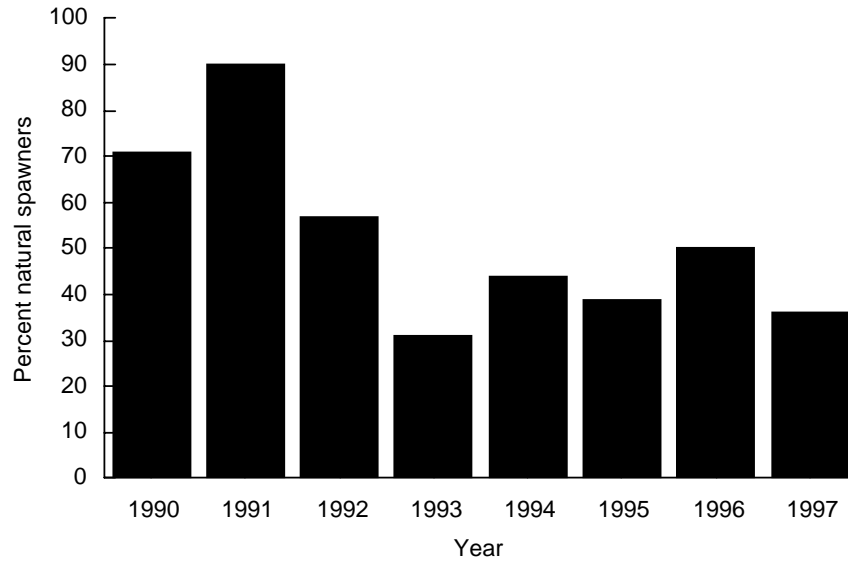


Figure 7 Percent of fall-run chinook salmon spawning naturally in the lower Mokelumne River. Source: Data from Biosystems and NRS, Inc. taken at WID.

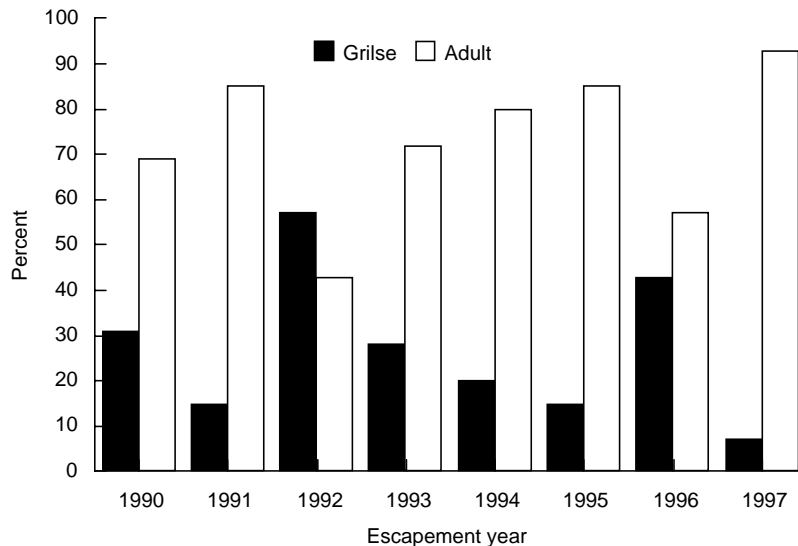


Figure 8 Percent of fall-run chinook salmon passing Woodbridge Dam that are grilse, 1990–1997

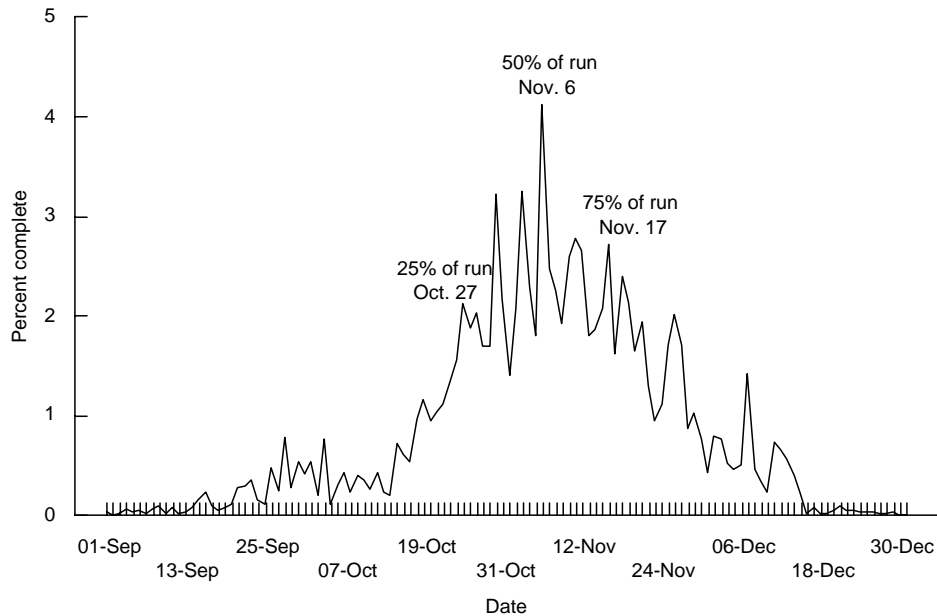


Figure 9 Daily average percent of fall-run chinook salmon escapement in the lower Mokelumne River, 1990–1997

The duration of the salmon run has expanded with increases in salmon spawning escapement from 1990 to 1997. Video and trap monitoring at Woodbridge Dam initially began in October, but was started in early September beginning in 1995 as spawning escapement increased. Except for 1996, when high flood flows ended monitoring on 3 December, the video and trap monitoring ended on 31 December of each year (Bianchi and others 1992; Marine and Vogel 1996; Marine 1997). The mean dates for the 10%, 50%, and 90% completion of the average upstream migration run timing were 27 October, 6 November, and 17 November, respectively. The average daily percentage of adult salmon migration past Woodbridge Dam from 1990 to 1997 show a peak in late October to mid-November (Figure 9).

Salmon Redd Abundance Analysis

Redd surveys show that chinook salmon use all three reaches from Camanche Dam to Elliott Road for spawning (Figure 10). The years with the greatest percentage of redds constructed in Reach A occurred during the highest spawning escapements (Hartwell 1996; Setka 1997).

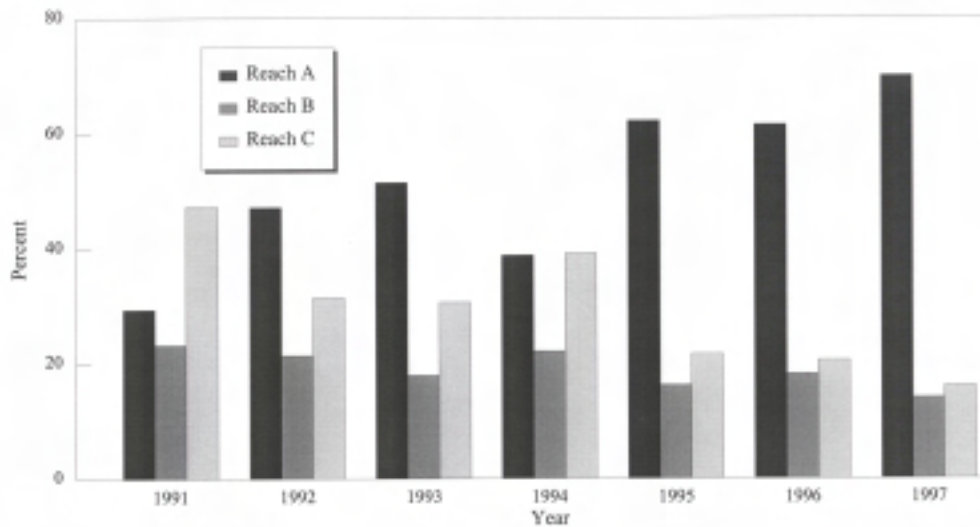


Figure 10 Lower Mokelumne River fall-run chinook salmon redd construction by reach, 1991–1997

The salmon redds in the lower Mokelumne River during the monitoring period increased from 71 redds in 1990 to 1,316 in 1997. The 1996 estimate of 1,284 redds is a projection based on the average percentage of redds completed on 3 December (the last date of the partial redd survey), from 1991–1995 (Setka 1997). The peak redd construction activity occurred from early November to mid-December.

The amount of redd superimposition increased with increased spawning escapement and ranged between 3% and 17%. There was a dramatic increase in redd superimposition from 3% in 1993 to 14% in 1994 (Hartwell 1996). Natural spawning escapement between these years increased from 993 to 1,503 fish (Figure 11). Between 1991 and 1997 no distinct relationship was evident between redd superimposition and other factors such as flow, temperature, or number of in-river females (Hartwell 1996; Setka 1997).

The relationship between the number of redds constructed and total escapement by linear regression ($R^2 = 0.941$, $P < 0.0001$) is shown in Figure 12. The database used to generate the linear regressions includes a range of salmon redds from 71 to 1,316 and total spawning escapements based upon video and trap counts of 410 to 10,175 salmon. The ratio of female spawners to redds during the study period ranged between 0.9:1 to a high of 2.3:1. The highest ratios were obtained at both lowest and highest spawning escapements during the study period (Figure 13).

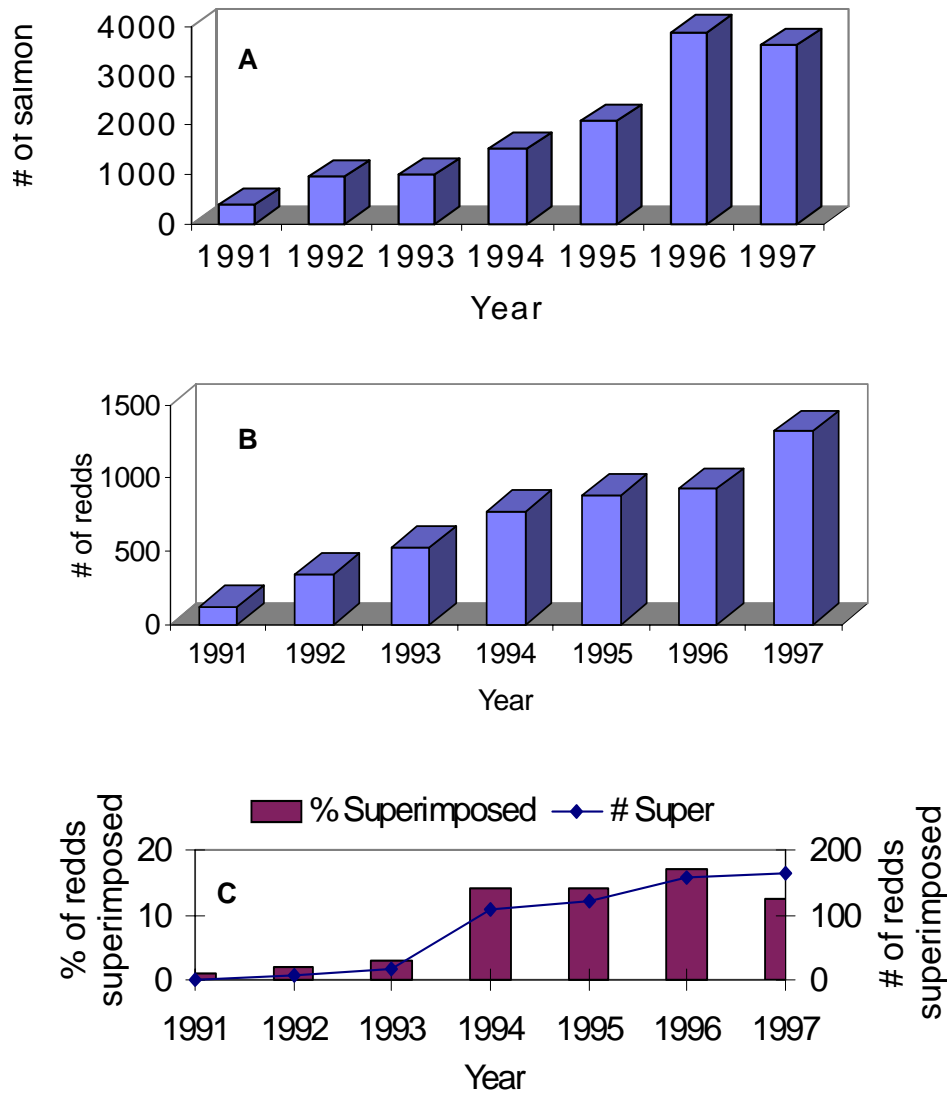


Figure 11 Comparison of salmon redd superimposition with spawning escapement, 1991–1997: (A) number of in-river spawners in Mokelumne River; (B) number of redds constructed per year in Mokelumne River; (C) percent and number of superimposed redds in Mokelumne River.

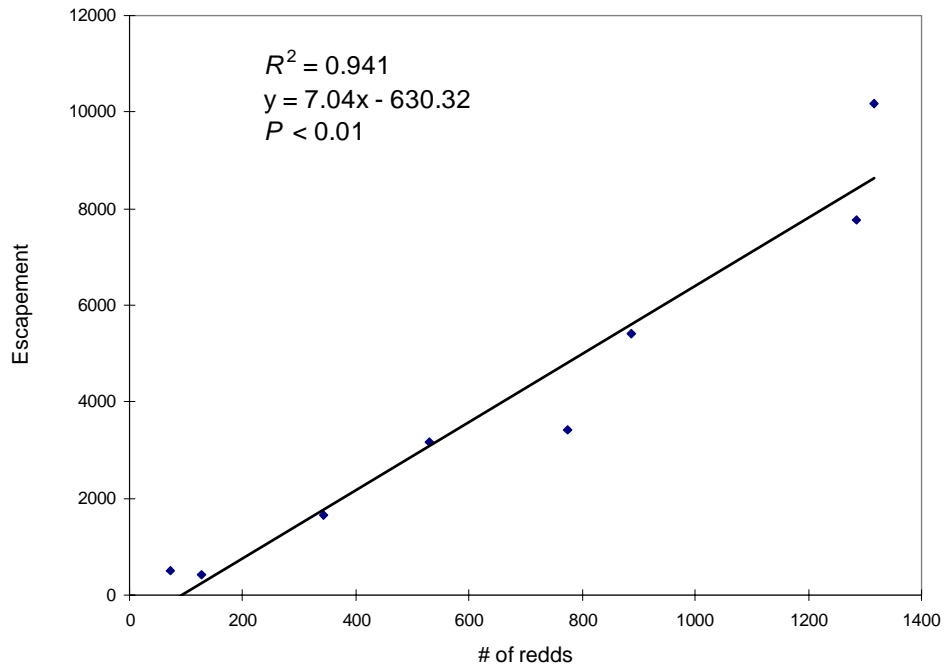


Figure 12 Linear regression of Mokelumne River total escapement compared with number of redds constructed, 1990–1997

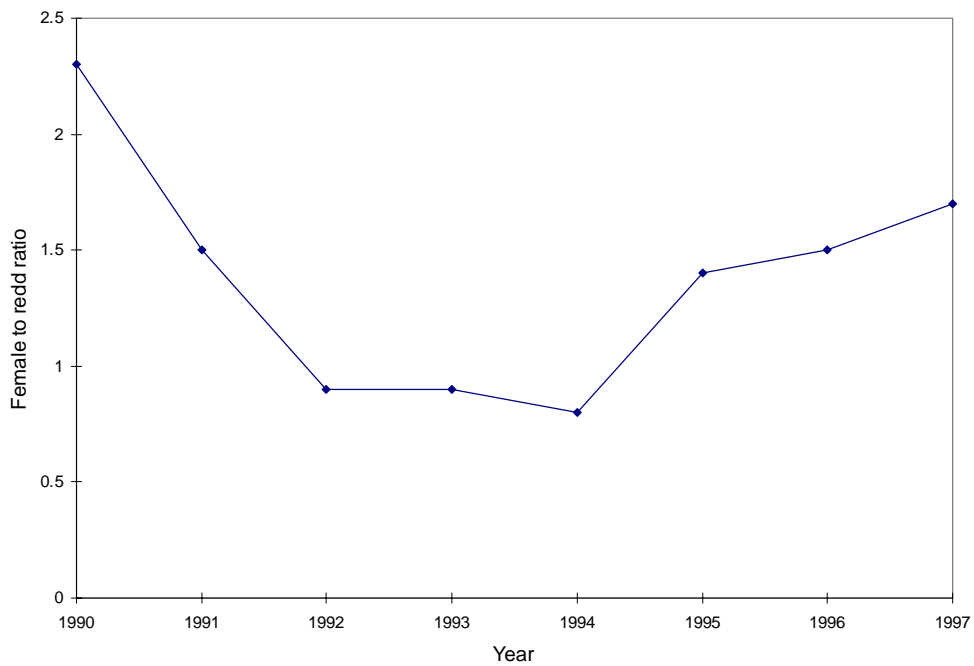


Figure 13 Female to redd ratio, 1990–1997

Discussion

Escapement Estimates

From 1972 to 1990 (with the exception of 1982 and 1983), DFG estimated the total salmon spawning escapement in the lower Mokelumne River from carcass survey recovery data. The recovery rates of marked carcasses were used to calculate the total number of spawners. The recovery rates ranged between 0% and 25%. In one-half of their surveys, DFG used the recovery rate for carcasses in the lower Mokelumne River. In 1976 and 1979, a rate of 20% was used when no carcasses were recovered. The 20% rate was based upon the average historic recovery rate for Sacramento River systems (DFG 1978). In 1990, DFG and EBMUD biologists conducted five carcass surveys between Camanche Dam and the Mackville Road Bridge (Reaches A and B). During the surveys, three carcasses were found including one grilse. The two adult carcasses were tagged and released and only one tagged carcass was recovered in subsequent surveys, resulting in a 50% recovery rate. Based upon this recovery rate, the 1990 spawning escapement estimate including 64 hatchery fish was 70 salmon (Fjelstad 1991). The daily count at Woodbridge Dam in 1990 totaled 497 fish.

One limitation of the 1990 carcass survey was that the survey was only conducted from Camanche Dam to Mackville Road. The shortened survey reach in 1990 may have contributed to the low spawning escapement estimate. Subsequent redd surveys conducted by EBMUD have shown that as many as 47% of the salmon redds are constructed below Mackville Road during low escapement years (Hartwell 1993). If as for 1976 and 1979, a Sacramento River system 20% recovery rate is used, the resulting escapement estimate of 94 salmon would still fall short of the total number counted at Woodbridge Dam.

During 1982 and 1983, Camanche flood control releases in excess of 2,000 cfs made it impossible to conduct carcass surveys (DFG 1986). The spawning escapement during these years was estimated using a statistical relationship between the number of salmon entering the Mokelumne River Fish Hatchery and the spawning escapement estimate from carcass survey data. A linear regression was established using data from the 1972 to 1981 runs (1977 was excluded because the ladder to the fish hatchery was closed). The 1982 and 1983 estimates were generated by extrapolating the hatchery returns to the regression line to obtain an estimate of total escapement (Meinz 1983; Figure 14). This methodology resulted in two of the highest spawning escapement estimates for the lower Mokelumne River (9,000 fish for 1982 and 15,866 for 1983). The hatchery returns for these years of 2,677 and 4,573 fish respectively were outside the range of the 1972 to 1981 database. In addition, the spawning stock estimates from carcass surveys used to generate the linear relationship may have been low because of the use of incomplete surveys in some of the years during the base period.

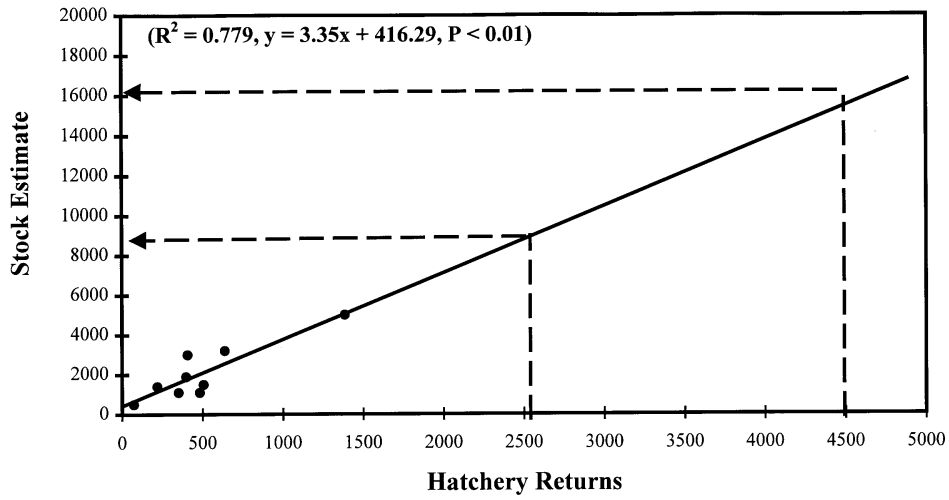


Figure 14 Mokelumne River stock estimates compared with hatchery returns, 1972–1981. 1997 data are omitted because no hatchery returns were reported.

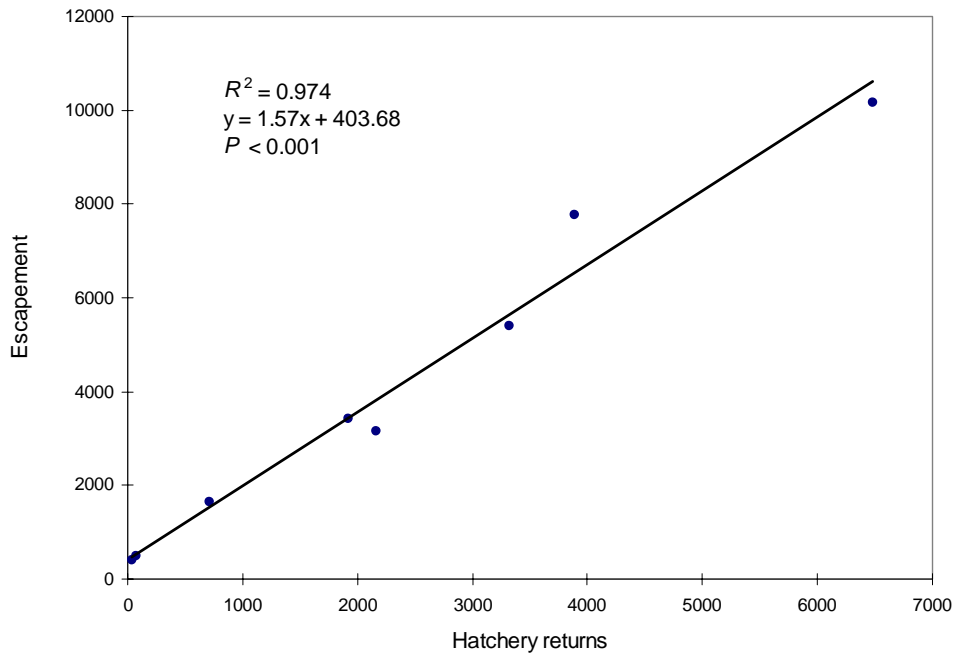


Figure 15 Linear regression of Mokelumne River escapement compared with hatchery returns, 1990–1997

Using the salmon spawning escapement data collected in the 1990–1997 monitoring program, a highly significant positive linear regression is obtained ($R^2 = 0.972$, $P < 0.001$) for the relationship between the number of salmon entering the Mokelumne River Fish Hatchery and the total spawning escapement (Figure 15). The Mokelumne River Fish Hatchery fish returns during this period ranged from 41 to 6,408 (DFG 1998). Using this relationship produces a spawning escapement estimate for 1982 of 4,590 and for 1983 of 7,548 (Table 2).

Table 2 1982 and 1983 spawning

| <i>Year</i> | <i>Hatchery return</i> | <i>DFG regression estimate</i> | <i>1991–1997 regression equation estimate</i> |
|-------------|------------------------|--------------------------------|---|
| 1982 | 2,677 | 9,000 | 4,590 |
| 1983 | 4,573 | 15,866 | 7,548 |

Salmon Redd Abundance Analysis

Fjelstad (1991) suggested that observations of the number of salmon redds could be used to generate a broad estimate of run size. Using the data collected in this monitoring program, the highly significant statistical relationship that was found between the number of redds and total escapement (see Figure 12) confirms this suggestion. This relationship regresses one empirical number on another, and because these values represent both the entire population and all salmon spawning in the river, includes spawning grilse in the estimation. Predictions of total escapement based on this relationship produces reasonable estimates at escapements in the 1,000 to 8,000 range. Multiple redds constructed by a single female, multiple superimpositions, and multiple female redds are all factors that may reduce the accuracy of these predictions. Linear regressions using redd counts and hatchery returns both provide reasonable estimates of the spawning escapements for the lower Mokelumne River (Table 3). The linear regression using hatchery returns provides the better estimate at both high and low levels of spawning escapement within the range of the database. Whether this relationship holds up in the future may depend upon the response of the natural population to habitat improvements or changes in the operation of future fish hatchery programs such as stocking levels, release locations or source of broodstock.

Table 3 Mokelumne River fall-run chinook salmon escapement, 1990–1997

| <i>Year</i> | <i>Number of redds</i> | <i>Hatchery returns</i> | <i>Natural spawners</i> | <i>Escapement (WID)</i> | <i>Predicted escapement^a</i> | <i>Predicted escapement^b</i> |
|-------------|------------------------|-------------------------|-------------------------|-------------------------|---|---|
| 1990–1991 | 71 | 68 | 429 | 497 | –131 | 511 |
| 1991–1992 | 127 | 41 | 369 | 410 | 264 | 468 |
| 1992–1993 | 343 | 711 | 934 | 1,645 | 1,784 | 1,523 |
| 1993–1994 | 530 | 2,164 | 993 | 3,157 | 3,100 | 3,810 |
| 1994–1995 | 774 | 1,918 | 1,503 | 3,421 | 4,817 | 3,422 |
| 1995–1996 | 888 | 3,323 | 2,094 | 5,417 | 5,620 | 5,634 |
| 1996–1997 | 1,284 ^c | 3,883 | 3,892 | 7,775 | 8,407 | 6,516 |
| 1997–1998 | 1,316 | 6,485 | 3,624 | 10,175 | 8,633 | 10,612 |

^a Based on redds.

^b Based on hatchery returns.

^c 929 redds were observed through the first week of December 1996 when redd surveys were discontinued due to high flows. The value of 1,284 ($\pm 8.1\%$) is an estimate based on total 1992–1995 end-of-run average added to the observed number.

Acknowledgements

We thank the following people: Keith Marine for providing the size-at-age analysis to the Mokelumne River Technical Advisory Committee; EBMUD biologists Joe Merz and Jim Smith for their review of the draft; redd survey team leader Jose Setka, Bert Mulchaey, Christine Tam and the balance of the EBMUD Fisheries and Wildlife staff for accurate data and long hours in the field; the Natural Resource Scientists staff for producing reliable video and trap counts; and Jim Dunne, Bert Mulchey, and Christine Tam for data management and graphics production.

References

- Bianchi EW, Walsh W, Marzuola C. 1992. Task reports of fisheries studies on the Mokelumne River, 1990–1992. Appendix A of the Lower Mokelumne River Management Plan. Report to EBMUD, Oakland, California. Tiburon (CA): BioSystems Analysis, Inc.
- Bisson P, Nielson J, Palmason R, Grove L. 1981. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low stream flows. In: Armantrout N, editor. Symposium on acquisition and utilization of aquatic habitat inventory information. Portland (OR): American Fisheries Society. p 62–73.

- [DFG] California Department of Fish and Game. 1979. King chinook salmon spawning stocks in California's Central Valley, 1977. Anadromous Fisheries Branch Administrative Report nr. 79-11.
- [EBMUD] East Bay Municipal Utility District. 1992. Lower Mokelumne River management plan. Tiburon (CA): BioSystems Analysis, Inc.
- [FEIS] FERC Final Environmental Impact Statement. 1993. Proposed modifications to the lower Mokelumne River project, California. FERC Project Nr. 2916-004. Washington, D.C.
- Fjelstad M. 1991. Mokelumne River chinook salmon escapement, 1990 [memorandum]. Rancho Cordova (CA): California Department of Fish and Game.
- Fry DH. 1961. King salmon spawning stocks of the California Central Valley, 1940-1959. *California Fish and Game* 47(1):55-71
- Hagar JM. 1991. Upstream migration and spawning of fall-run chinook salmon in the Mokelumne River, 1990. Orinda (CA): East Bay Municipal Utility District. 21 p.
- Hartwell, R. 1993. Upstream migration and spawning of fall-run chinook salmon in the Mokelumne River, 1992. Orinda (CA): East Bay Municipal Utility District. 28 p.
- Hartwell R. 1996. Upstream migration and spawning of fall-run chinook salmon in the Mokelumne River, 1995. Orinda (CA): East Bay Municipal Utility District. 52 p.
- Marine KR, Vogel DA. 1994. Mokelumne River chinook salmon and steelhead monitoring program, 1993-1994. A report to the East Bay Municipal Utility District, Oakland, California. Red Bluff (CA): Vogel Environmental Services. 42 p.
- Marine KR, Vogel DA. 1996. Mokelumne River chinook salmon and steelhead monitoring program, 1994-1995. A report to the East Bay Municipal Utility District, Oakland, California. Red Bluff (CA): Vogel Environmental Services. 42 p.
- Marine KR. 1997. Minutes of the Mokelumne River Technical Advisory Committee. Sacramento, California.
- Meinz M. 1983. The 1982 Mokelumne River king salmon stock survey [memorandum dated 21 January 1983]. Available from Mokelumne File, California Department of Fish and Game, Region 2, Rancho Cordova, California.
- Setka J. 1997. Upstream migration and spawning of fall-run chinook salmon in the Mokelumne River, 1996. Orinda (CA): East Bay Municipal Utility District. 55 p.

Studies of Spawning Habitat for Fall-Run Chinook Salmon in the Stanislaus River Between Goodwin Dam and Riverbank from 1994 to 1997

Carl Mesick

Abstract

The spawning habitat of fall-run chinook salmon (*Oncorhynchus tshawytscha*) was studied in the Stanislaus River between Goodwin Dam and Riverbank between 1994 and 1997 to evaluate whether habitat quality was potentially limiting the population and whether two restoration projects improved spawning conditions. Redd surveys in 1994 and 1995 indicated that spawning was concentrated in the riffles located in the 12-mile reach between Goodwin Dam and Orange Blossom Bridge. Most of the spawning (73%) occurred upstream of the riffles' crests where the streambed gradient was positive (for example, the tail of a pool). Sample areas were divided into the upper, middle, and lower portions of riffles to determine why the salmon used the upper areas.

Substrate samples collected from the upper six inches of the streambed indicated that predicted survival probabilities for chinook salmon eggs using Tappel and Bjornn's (1983) laboratory study averaged 75.6% in the reach above the Orange Blossom Bridge, 58.6% in the lower spawning reach between the bridge and town of Riverbank, and 95.4% at two restoration sites near the U.S. Army Corps of Engineers' Horseshoe Road park where gravel was added in 1994. Predicted egg survival probabilities averaged 73.2% upstream of riffle crests and 62.1% downstream of riffle crests at four natural riffles with pronounced crests.

Intragravel dissolved oxygen (DO) concentrations were relatively constant at 32 piezometer sites in the 12 study riffles during five surveys conducted at 10-day intervals in November and December 1995. The DO levels declined markedly in early February 1996 at nine sites shortly after runoff from four major storms increased base flows from 300 cfs to as much as 800 cfs for several days after each storm. Prior to the storms in November and December, intragravel DO concentrations were less than 5 ppm at six piezometer sites (19%) and less than 8 ppm at eleven sites (34%). Immediately after the fifth major storm in early February, intragravel DO concentrations were less than 5 ppm

at 11 piezometer sites and less than 8 ppm at 16 sites (50%). Many of the sites where DO concentrations were low were associated with intragravel water temperatures that were between 1° and 6° F higher than surface temperatures. The elevated temperatures suggest the inflow of oxygen-poor groundwater. A high rate of groundwater inflow into the Stanislaus River's riffles would explain the unexpectedly positive vertical hydraulic gradients upstream of the riffle crests measured at most of the piezometer sites in fall 1996.

A regression model of the average intragravel DO concentrations in November and December 1995 had an adj- R^2 of 0.80 with significant ($P \leq 0.05$) variables that include an index of groundwater inflow, abundance of Asian clams (*Corbicula fluminea*), percent fines <2 mm, and mean column water velocity. A model for the February 1996 DO concentrations had an adj- R^2 of 0.68 with significant variables that include the groundwater index and the percent fines <2 mm. Although streambed gradient indexes were not selected for the regression models, DO concentrations that were greater than 80% saturation in February 1996 usually occurred where the gradient was positive 2% or higher.

Not all restoration sites in the Stanislaus River where clean gravel was added were used by spawning salmon. Two riffles constructed with imported gravel from the Merced River were used by very few fish for three years even though intragravel DO levels were near saturation and spawning occurred in the immediate vicinity. After high flows deposited a large berm of native rock at the crest of one of these riffles in spring 1997, a relatively high number of salmon began spawning in the new substrate in fall 1997. In Goodwin Canyon, where gravel was lacking, many salmon quickly spawned in newly added gravel from the Stanislaus' floodplain placed in late summer 1997.

Introduction

Two studies, one conducted in summer 1993 by the California Department of Water Resources (DWR 1994) and the other conducted in fall 1994 by Carl Mesick Consultants, Thomas R. Payne & Associates, and Aquatic Systems Research (CMC and others 1996), suggest that a majority of the spawning habitat in the Stanislaus River between Goodwin Dam and Riverbank is unsuitable for fall-run chinook salmon (*Oncorhynchus tshawytscha*). These studies reported that chinook salmon primarily spawn in the upper 30-ft sections of riffles where the streambed usually had an upward slope. The explanation for this pattern was not obvious as there were suitable water depths and velocities and an abundance of gravel in the unused, lower riffle areas.

The DWR (1994) study of 22 riffles between Goodwin Dam and Riverbank indicated that 45% of the substrate samples collected from the upper 30-ft section of the study riffles had high levels of fines (silt and sand). DWR did not sample the middle and lower sections of the riffles, but it is likely that the spawning activity concentrated in the upper sections would remove fines and make the upper sections relatively “clean” compared to the middle and lower riffle sections. If true, the percentage of riffle habitat with excessive amounts of fines would have exceeded 45%.

This report describes three years of spawning surveys from fall 1995 to fall 1997 that evaluated two questions:

1. Is habitat in the Stanislaus River’s primary spawning reach unsuitable for spawning?
2. Did a riffle restoration project implemented in summer 1994 and a gravel augmentation project implemented in summer 1997 improve spawning conditions for salmon?

The first question was investigated by measuring the percentage of fines and monitoring intragravel dissolved oxygen (DO) concentrations and temperatures with piezometers buried in artificial and natural redds in the upper 30 feet, middle 30 feet, and lower portions of natural riffles between Goodwin Dam and Riverbank in fall 1995 and fall 1996. Measurements of vertical hydraulic gradient (an index of upwelling and downwelling of flow into the substrate), intragravel nitrate concentration, percentage of fines in the substrate, weight of Asian clams (*Corbicula fluminea*), streambed gradient, and the depth and velocity of the surface flow were also made to evaluate the cause of low intragravel DO concentrations.

Two restoration projects were also evaluated. The first involved two riffles that were reconstructed at the Horseshoe Recreation Area (river miles 50.4 and 50.9) by DWR in September 1994. At these sites, the streambed was excavated to a depth of 1.5 feet and then refilled with washed gravel from 0.5 to 4 inches in diameter to provide a uniform streambed (-0.2% to -0.5% gradient). The imported gravel was river-rock obtained from the Blasingame Quarry near the Merced River. Rock weirs were constructed at the upstream and downstream boundaries of each site to retain the imported gravel during high flows. The two riffles near the Horseshoe Recreation Area were surveyed for spawner use from 1994 through 1997 and intragravel conditions were monitored in fall 1995.

The second restoration project involved adding 2,000 tons of gravel to four locations in the Goodwin Canyon (near river mile 58) in summer 1997. There was almost no gravel in these areas before this project. The project was

designed to create bars of introduced gravel that would be gradually transported to downstream spawning areas by high flows. At two locations, the gravel bars were placed in pools just upstream from the pool's tail at a depth of about ten feet. At the other two locations, the gravel bars were placed across the width of the river in shallow, moderately swift water. The imported gravel was river rock from 0.35 to 5 inches in diameter that was obtained from a quarry near the Stanislaus River. Shortly after the rock was placed, flows were increased to 1,200 cfs for ten days to help distribute the gravel and attract adult salmon to the river. Spawner use at these sites was surveyed in fall 1997.

This report presents a summary of the surveys conducted in the Stanislaus River from 1994 to 1997. The complete data sets and analyses for the fall 1994 and fall 1995 surveys are presented in CMC and others (1996) and for the fall 1996 survey in CMC (1997).

Methods

Surveys were conducted in the primary spawning reach of the Stanislaus River at approximately ten-day intervals in fall 1995 and 1996 to monitor spawner use and measure intragravel conditions at natural riffles and the restoration riffles at the Horseshoe Recreation Area. In 1995, six surveys were conducted between 2 November and 22 December while salmon were spawning and a seventh survey was conducted between 2 and 7 February 1996 after the fry had begun to emerge from the gravel. In 1996, three surveys were conducted between 31 October and 19 November. Flood control releases were begun on 21 November that made it impossible to continue the 1996 study. In 1997, spawner use was surveyed at the restoration sites and 12 natural riffles on 29 October and 3 December. Two of the riffles surveyed (R27 and R78) had a substantial amount of newly deposited gravel across the crest of the riffle as a result of the spring 1997 high flows (5,000 cfs with a maximum of 8,000 cfs compared to 300 to 400 cfs base flows).

Study Area

The spawning reach for fall-run chinook salmon in the Stanislaus River is about 25.5 miles long and extends from Goodwin Dam, which is impassible for salmon, downstream to the town of Riverbank (Figure 1). In a 4.2-mile, high-gradient canyon between Goodwin Dam and the Knights Ferry, U.S. Army Corps of Engineers (ACOE) Recreation Area, there are only four short natural riffles near the Two-Mile Bar Recreation Area at river mile 56.9 and several very small areas that have sufficient gravel for spawning. The largest natural riffle, which is identified as TM1, is the tail of a relatively wide pool that is just upstream of where the river divides into two channels. The double-

channel riffle that begins at the pool's tail is high gradient, has no gravel, and was unused by salmon for spawning in 1994, 1995, and 1996. Two other riffles, which are identified as TM2 and TM3, are just downstream of TM1 and are relatively short, each about 30 feet long. The fourth natural riffle, which is about 150 yards upstream of TM1, was very armored and received few spawners.

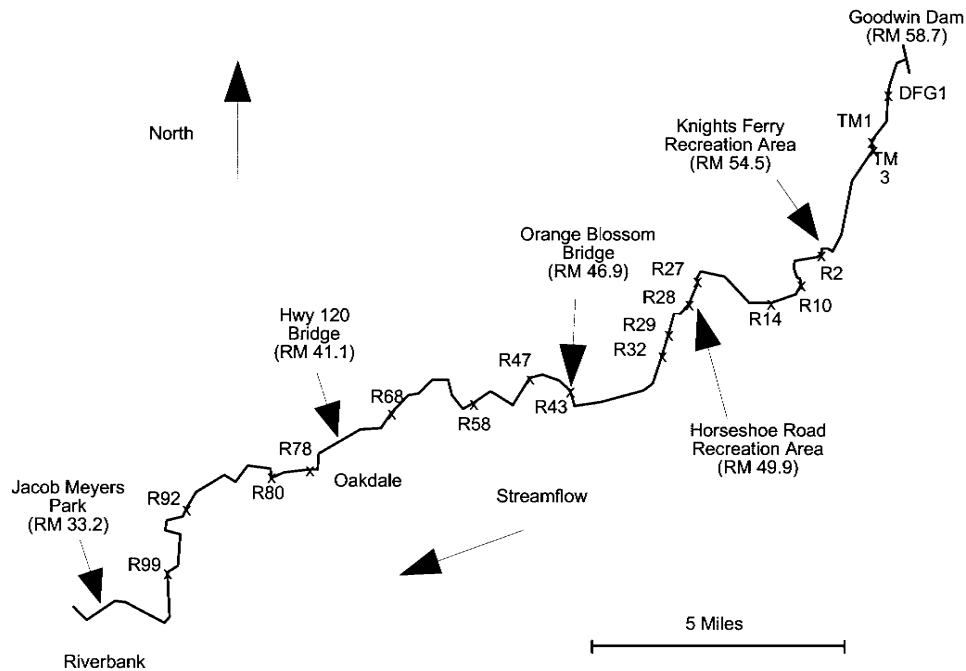


Figure 1 Location of riffles where spawning habitat for fall-run chinook salmon was studied in the Stanislaus River between Goodwin Dam and the town of Riverbank

During October 1995, 106 riffles between the ACOE Knights Ferry Recreation Area and Jacob Meyers Park in Riverbank were identified with a numbered 3-inch orange square that was nailed to either a tree or woody debris near the upstream boundary of each riffle. The riffle immediately upstream of the bridge at the ACOE Knights Ferry Recreation Area was identified as "R1." The other riffles were sequentially numbered in a downstream direction from there. During the fall 1995 surveys, salmon were observed at an additional 26 riffles and four small accumulations of gravel that were not numbered with orange squares. These areas were identified by adding a letter to the upstream riffle's number. For example, an unmarked spawning area downstream of Riffle R2 was called Riffle R2A.

Redd Distribution Within Riffles and the Spawning Reach, Fall 1995

Redds, "test-digs," and the number of live and dead adult salmon were counted at each of the 135 riffles between Goodwin Dam and Riverbank during the 1995 November and December surveys. Redds were identified as a disturbance in the substrate, approximately four feet wide by eight feet long, with a shallow pit or depression near the middle of the disturbed area and a tail spill. Test-digs were assumed to be unfinished redds that lacked eggs, because they lacked a pit and tail spill. Redds and test-digs were most conspicuous when first constructed because (1) the depth of the pit and the height of the tail spill were gradually reduced by the "smoothing action" of streamflow and (2) redd construction temporarily reduced the amount of algae and silt on the substrate's surface. Since some, but not all, of the redds became indiscernible during the study, it was necessary to distinguish new redds from previous redds. New redds were identified by comparing their appearance to old redds in the same riffle, the location within the riffle, and whether adult salmon were observed near the new redds. The total number of redds at each riffle was estimated as the cumulative total of new redds observed during each survey.

Redd counts for each riffle were subdivided into a maximum of three sections with the two uppermost sections being about 30 feet long each. For example, a 30-ft riffle had only an upper section, whereas a 120-ft riffle was subdivided into an upper 30-ft section, a middle 30-ft section, and a lower 60-ft section. The boundaries between riffle subsections were not measured or marked but visually estimated for each survey.

Surveys were conducted on foot and by canoe. The Two Mile Bar Recreation Area was accessed by road and observations were first made from the streambank and then by walking through the riffles. The reach between the Knights Ferry Recreation Area and Jacob Meyers Park in Riverbank was surveyed with two canoes, one on each side of the river. Visibility in the water column was usually about eight feet and so most of the streambed and all redds were easily observed in riffles, which ranged in depth between one and 3 feet. Streamflows releases at Goodwin Dam were consistent at about 305 cubic feet per second (cfs) during the 1995 surveys and 400 cfs during the 1996 and 1997 surveys.

Intensively Studied Riffles

Spawning habitat and redd distribution was intensively studied at 12 riffles in fall 1995 and at seven riffles in fall 1996 (Figure 1). The fall 1995 study riffles (TM1, R2, R10, R27, R28, R32, R43, R47, R68, R80, R92, and R99), were selected at approximately two-mile intervals between Goodwin Dam and Jacob Meyers Park in Riverbank. They were selected because they were highly used for spawning during fall 1994, a condition that was necessary to evaluate the relationship between redd distribution and the quality of incubation habitat. Riffles TM3, R10, R14, R29, R43, R58, and R78 were selected for the fall 1996 study because each had an upper section with an upward slope or positive streambed gradient, a relatively flat middle section, and a bottom section with a negative streambed gradient. These selection criteria made it possible to evaluate the effect of streambed gradient on the downwelling of surface water and intragravel conditions. Riffle R10 was studied during both fall 1995 and fall 1996. Different sections of Riffle R43 were studied in 1995 and 1996; a small concrete weir separated the lower section which was studied in 1995 from the upper section studied in 1996.

Intragravel Water Quality

Intragravel water samples were collected from piezometers buried 12 inches deep in the substrate. Piezometers were installed between 2 and 4 November in 1995 and between 25 and 27 October in 1996. One piezometer was installed at each of the top, middle, and lower sections of each riffle, except at Riffle R10 where two were installed in each section in fall 1996.

Typical piezometers were 0.25-inch diameter copper tubes, each with eight 0.04-inch diameter holes at one end and a flexible tube at the other end that extended above the substrate surface (Figure 2). Redd construction was extensive at Riffle TM1 in October 1995, and so a different design, called a pipe-piezometer, was used which did not require streambed excavation. Pipe-piezometers consisted of 0.33-inch outside diameter hollow aluminum shafts that were driven straight down into the substrate so that eight 0.04-inch holes in the shafts were approximately 12 inches deep in the substrate and the top of the shaft extended about ten inches above the substrate. A 3-foot-long plastic tube was clamped to the upper end of the shaft for sample collection. Each pipe-piezometer was attached to a 4-foot-long, 0.5-inch diameter reinforcing bar with hose clamps to facilitate driving the shaft into the substrate. The pipe-piezometers at Riffle TM1 were left in place throughout the study, although they fell after the 20 December 1995 survey and had to be reinstalled on 3 February 1996. A pipe-piezometer was used at the top piezometer site in Riffle R2 because the buried piezometer was quickly vandalized. This pipe-piezometer was reinstalled during each survey.

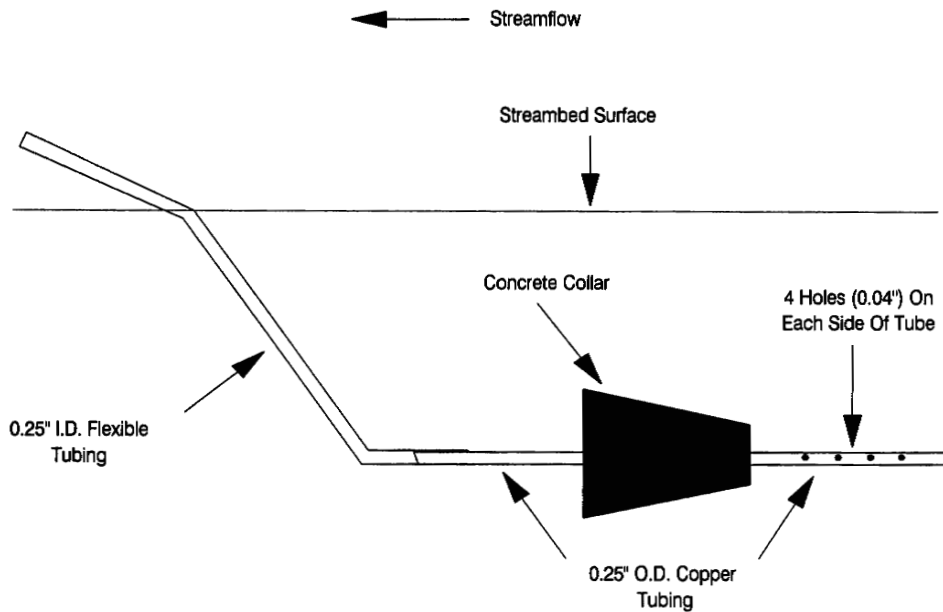


Figure 2 Typical piezometer used to collect intragravel water quality samples. The concrete collar was the shape and size of an eight-ounce Dixie cup. The copper tubing was about 11 inches long and the flexible tubing was about three feet long.

Piezometer sites were selected in areas where water depths ranged between 1.1 and 2.4 ft and mean column water velocities ranged between 1.6 and 4.2 ft/s, which were within the range used by spawning salmon. The typical piezometers (Figure 2) were installed to simulate sampling an egg pocket in a natural salmon redd. Pits were dug approximately 12 inches deep by 12 inches wide at the bottom with a hand-held hoe. The excavated substrate was piled downstream of the pit to simulate the tail spill formed in a natural redd. After the piezometer was placed in the pit, sediment was pulled into the pit in thin layers from the upstream areas using the hoe. The blade of the hoe was then fanned over each layer of gravel in the pit to flush most of the fines onto the tail spill. When completed, the piezometer was located at the upstream end of the tail spill which was raised several inches above the undisturbed streambed. An egg pocket would be expected to occur in this location in a natural redd. Immediately upstream of the tail spill, there was a two- to four-inch deep depression in the substrate that simulated the pit of a small, but natural-looking, redd. However, natural sediment transport filled the depression, and the tail spill was flushed away at most of the piezometer sites after approximately seven days. This smoothing of the streambed also occurred at natural redds.

Pipe-piezometers were also installed in the vicinity of the egg pockets of 21 completed salmon redds at study riffles R10, R14, and R43 on 11 and 12 November 1996. All of these redds had been observed on the previous survey when most had already been completed. These pipe-piezometers were driven approximately 12 inches into the upstream end of the tail spill of a completed redd. This was done by placing a 5/8-inch bolt into the upper end of the piezometer, inserting it into the bottom of a 4-foot-long, 0.5-inch ID steel pipe, placing a 3-foot-long, 0.25-inch diameter rod on top of the lag bolt, and then driving the pipe, rod, and piezometer into the redd. The pipe and rod were then removed and a plastic tube was fitted to the upper end of the piezometer, which extended about two inches above the substrate's surface to permit periodic collection of water samples. To avoid collecting surface water that may have been introduced into the redd during installation, the first measurements and samples were not collected until approximately five minutes after the pipe-piezometers had been installed. To minimize disturbance to the eggs, the pipe-piezometers were not removed between surveys.

Intragravel measurements of DO concentration, water temperature, and vertical hydraulic gradient were made at each piezometer in the artificial redds at approximately ten-day intervals. During the fall 1995 study, five measurements were made between 11 November and 22 December 1995 and a sixth measurement was made between 2 and 7 January 1996. During the fall 1996 study, three measurements were made between 31 October and 19 November 1996.

Two sets of measurements were taken from the redd-type piezometers between 11 and 19 November 1996. During 1997, measurements were made only at Riffles R27 and R78 on 3 December.

Intragravel water samples were collected to measure DO concentration and temperature using a 50-ml polypropylene, disposable syringe (Henke-Sass Wolf GmbH, Germany) fitted with a six-inch-long, 1/8-inch inside diameter polypropylene tube and a tapered connector that provided an airtight seal between the piezometer's tubing and the syringe's tubing. Samples were collected by first slowly withdrawing and discarding 50 ml of water, the approximate volume of water in the piezometer's tubing. Then a 70-ml sample was slowly withdrawn for a DO analysis using a LaMotte test kit, model EDO/AG-30. The LaMotte test kit uses the azide modification of the Winkler Method and a LaMotte Direct Reading Titrator for the final titration. The LaMotte Kit measures DO concentrations in 0.1 parts per million (ppm) increments. Kit reagents were replaced for each survey. During the fall 1995 and fall 1997 studies, samples were analyzed at the study riffles within five minutes of collection. During the fall 1996 study, the DO samples were fixed immediately after collection, placed in an ice chest, and analyzed at room temperature within ten hours.

After collecting the DO sample, a 100-ml sample was slowly collected and injected into a plastic sample bottle, which had been rinsed with surface water, for an immediate measurement of intragravel water temperature. Water temperature was measured with a Yellow Springs Instrument (YSI) model 55 meter in 1995 and with a mercury thermometer in both 1995 and 1996. A sample of surface water was also collected in the same 100-ml plastic bottle for a temperature measurement. The date and time that each water sample was collected were recorded for comparison with the thermograph recordings.

Nitrate concentration was determined for intragravel and surface water sampled during the 11–12 December 1995, 20–22 December 1995, and the 19 November 1996 surveys. During 1995, AquaCheck Nitrate/Nitrite test strips were used, which measure nitrate concentrations between zero and 50 mg/liter. The test strips were dipped into the samples collected for the LaMotte DO tests immediately prior to adding any of the LaMotte reagents. During 1996, one intragravel water sample was collected from one piezometer at each riffle for analysis of nitrate concentration. One surface sample was collected at Riffle R29 for nitrate analysis. These samples were immediately placed in an ice chest and analyzed by FGL Environmental in Stockton approximately 24 hours later.

The ratio of the differential head to the depth of the piezometer below the sediment-water interface (Lee and Cherry 1978; Dahm and Valett 1996) is known as the vertical hydraulic gradient (VHG). Negative VHG measurements indicate the downwelling of surface flow and positive values indicate the upwelling of intragravel flow. VHG was measured at each piezometer in fall 1996 and fall 1997. The differential head was measured with a manometer, which consisted of an 8-ft-long, 1/8-inch inside diameter, clear tube with one end attached to the piezometer's tubing and the other held near the substrate surface (Lee and Cherry 1978; Dahm and Valett 1996). A silicone pipet bulb with emptying and filling valves was attached to the middle of the tubing with a T-connector to facilitate filling the manometer with water. Measurements were made by partially filling the manometer's tubing with water and then holding the middle of the tube above the water's surface to form a loop with two vertical tubes and an air bubble, approximately 16 inches long at the top of the loop. After the water levels in both sides of the manometer's tubes stabilized, the differential head was read as the difference in height (centimeters) between the water levels in the two tubes. Negative measurements occurred when the water level in the side of the tube connected to the piezometer was lower than the level in the side of the tube submerged in surface water. VHG was computed as the differential head divided by 30 cm, the depth of the piezometers below the substrate's surface.

Streambed Elevation, Water Velocity, and Water Depth at Piezometers and Redds

Redds were identified by placing a numbered, three-ounce lead sinker with red flagging into the pit. The sinkers were replaced whenever redd construction buried or displaced the original sinker. The locations of redds and piezometers were mapped at each riffle using permanent headstakes (for example, 18-inch sections of reinforcing rods or nails partially driven into trees) on both sides of the river. The location of redds and water quality samples were determined by first running a tape measure from the redd or sample to the closest permanent transect at a perpendicular angle. The distance in feet from the right streambank along the permanent transect to the perpendicular line was recorded as the station. Then the distance in feet from the permanent transect to the redd or piezometer and the direction (upstream or downstream) from the permanent transect were recorded.

Water depth and mean column velocity were measured at the undisturbed substrate surface immediately adjacent to all piezometer sites, including those at redds, during 300-cfs releases in 1995 and 400-cfs releases in 1996. Mean column velocities were measured with a Marsh McBirney electronic flow meter and a top-set wading rod.

In fall 1995, a single longitudinal transect was used to measure the streambed elevation along the entire length of each study riffle. The transect was established by installing a three-foot piece of reinforcing bar about ten feet upstream of the riffle and then running a tape through the site to approximately ten feet downstream of the riffle. Relative streambed elevations were measured along the transect with an automatic level and a fiberglass stadia rod at five-foot intervals in steep gradient ($>2\%$) sites or at ten-foot intervals in low gradient ($<2\%$) sites. The absence of large structures in the study riffles produced a relatively uniform contour of the streambed across the river and it was assumed that the transect represented the entire width of the river.

In fall 1996, streambed elevations were measured at each piezometer site and at distances of 5 ft, 10 ft, and 20 ft immediately upstream of the piezometer to determine the streambed gradient.

Substrate Size Distribution, Crushed Rock, and Asian Clams

During 2–7 February 1996 substrate samples were collected at each of the piezometer sites after the water quality sample had been collected. Samples were taken with a six-inch diameter modified McNeil sampler. The sampler was placed over the approximate location of the piezometer and worked into the substrate to a depth of about six inches. If the sampler could not be inserted to a depth of six inches, the sampler was moved about one foot. The substrate inside the sampler was scooped into a plastic bag for transport to the laboratory for analysis. The water inside the sampler was not collected, because the

sampler was too short to prevent a small amount of river water from entering at some sites, thereby resulting in the loss of some of the suspended sediments. Furthermore, it is likely that the total weight of the suspended sediments was small and would not have significantly affected the measured weight of fines <1 mm.

The samples were processed by first drying the samples, sorting the particles according to size, then determining the weight of each size class. The samples were dried by placing them in two-gallon metal buckets and occasionally stirring them as they were heated over a propane flame. After the sample had cooled, it was placed in the upper layer of a set of sieves of decreasing size. Sieve sizes used included 64 mm, 45 mm, 32 mm, 24 mm, 16 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Sieves between 16 and 64 mm were shaken by hand for one minute, after which the size of the particles in each sieve was checked. Smaller sieves were shaken for about five minutes. After the sorting had been completed and before the sieve's contents were weighed, Asian clam (*Corbicula fluminea*) shells were weighed, counted, and removed from each sieve. Sieve contents were weighed on a triple-beam balance to the nearest 0.1 grams. The percentage of broken rock, 8-mm or larger particles with sharp edges, was determined for most of the samples, particularly those from Riffles R27 and R28, which are the 1994 restoration sites.

Percent fines were evaluated as two size classes, one as substrate particles less than 1 mm to correspond to the results of Young and others (1991) and the other as particles less than 2 mm, which corresponds to many other studies (Chapman 1988). Both of these size classes were evaluated as a percentage of the entire sample and as a percentage of the sample that excluded particles larger than 24 mm to minimize weight bias as recommended by Tappel and Bjornn (1983). To account for potential bias that would result if smaller sample volumes consisted of surface substrates that typically have lower percentages of fines, total sample weight was included in the statistical analyses of percent fines.

The predicted survival probability for chinook salmon eggs was estimated using the results of Tappel and Bjornn's (1983) laboratory study based on the percentages of substrate particles less than 0.85 mm and particles less than 9.5 mm in samples that exclude particles larger than 51 mm (largest size tested by Tappel and Bjornn). The percentages of particles less than 0.85 mm and 9.5 mm for Stanislaus River samples that excluded particles larger than 51 mm were estimated from a plot of the cumulative percentage of particles that passed through specific sieves versus the sieve apertures on a log scale. The following equation from Tappel and Bjornn (1983) was then used to compute predicted egg survival for chinook salmon:

$$\text{Percent Survival} = 93.4 - 0.171S_{9.5}S_{0.85} + 3.87S_{0.85}$$

Statistical Analyses

Multiple regression analyses were conducted to evaluate the environmental factors that appeared to influence DO concentrations during the November–December 1995 surveys and the February 1996 survey. The mean DO concentrations in percent saturation were used for the November–December surveys, since those concentrations were relatively stable and showed no increasing or decreasing trends during that period. DO concentrations measured during the February survey were substantially lower at some of the piezometer sites and so those data were evaluated separately.

The environmental factors evaluated for both analyses included six indices of percent fines, three indices of gradient, weight of clam shells, water depth, mean column velocity, two indices of nitrate concentration, a turbidity index, and the difference in temperature between the intragravel sample and the surface sample during the 20–22 December survey which served as an index of groundwater inflow (Tables 1 and 2). The variables for nitrate concentration, turbidity, and the temperature difference are described in further detail in the “Results and Discussion.”

Transformations and tests were made on the assumptions of statistical analyses relating to normal distributions, linear relationships, and an absence of collinearity between independent variables (Sokal and Rohlf 1995). An arcsine transformation was made to variables consisting of percentages (which include DO concentrations, the absolute value of the gradient indexes, and substrate fines), to minimize bias resulting from the distribution of the variance being a function of the mean (Sokal and Rohlf 1995). “Wilk-Shapiro/rankit plots” were used to test the assumption of normality. Plots of standardized residuals versus fitted values of the independent variables were used to assess the assumptions of linearity and constant variances. A variance inflation factor was used to detect collinearity (Analytical Software 1994).

The regression analyses were affected by the absence of water depth and mean column velocity measurements at the piezometer sites at TM1 and the middle piezometer at Riffle R47. When the analyses included the depth and velocity variables, all variables from these sites were excluded from the analyses. To avoid this limitation, regression analyses were conducted with and without the depth and velocity variables.

Table 1 Habitat data from 32 piezometers at 12 riffles in the Stanislaus River, fall 1995

| Site | Intragravel DO percent saturation ^a | | Groundwater Inflow Index (°C) ^b | | Asian clam shells (g) ^c | Percent fines | | | | Sample Size (g) | Tappel and Bjornn Index ^d | | |
|----------|--|-------|--|------|------------------------------------|---------------|-------|-----------------|-------|-----------------|--------------------------------------|---------|--------------|
| | Nov-Dec | Feb | Dec | Feb | | Entire sample | | Excludes >24 mm | | | Percent substrate | | Egg Survival |
| | | | | | | <1 mm | <2 mm | <1 mm | <2 mm | | <0.85 mm | <9.5 mm | |
| TM1-TOP | 94.3 | 100.0 | 0.1 | 1.1 | 0.0 | 2.3 | 5.9 | 3.7 | 9.3 | 7327.6 | 2.1 | 37.6 | 88.0 |
| TM1-BOTR | 95.1 | 100.0 | 0.05 | 1.3 | 0.0 | 2.6 | 7.1 | 4.6 | 12.5 | 9567.5 | 2.4 | 36.8 | 87.6 |
| TM1-BOTL | 99.6 | 100.0 | 0.05 | 1.3 | 0.0 | 1.5 | 3.2 | 5.2 | 11.5 | 8195.6 | 1.5 | 15.3 | 95.3 |
| R2-TOP | 96.8 | 100.0 | 0.3 | 1.4 | 0.0 | 5.3 | 7.3 | 22.9 | 31.7 | 4485.6 | 6.3 | 19.0 | 97.3 |
| R2-BOT | 88.8 | 54.8 | 0.3 | 1.2 | 7.0 | 3.0 | 8.8 | 7.7 | 22.5 | 7685.3 | 3.3 | 28.8 | 89.9 |
| R10-TOP | 94.4 | 84.3 | 0.2 | 1.0 | 0.0 | 3.7 | 7.6 | 7.8 | 15.8 | 9453.3 | 4.1 | 41.7 | 80.0 |
| R10-MID | 61.8 | 32.4 | 1.1 | 3.0 | 0.0 | 8.3 | 12.8 | 15.8 | 24.4 | 9597.4 | 7.7 | 40.4 | 70.0 |
| R10-BOT | 64.7 | 36.0 | 0.8 | 1.0 | 0.0 | 13.4 | 24.9 | 21.5 | 40.0 | 8147.5 | 11.7 | 50.7 | 37.2 |
| R27-TOP | 98.8 | 100.0 | 0.3 | 0.0 | 0.0 | 0.4 | 0.4 | 0.9 | 0.9 | 5376.4 | 0.4 | 3.6 | 94.7 |
| R27-MID | 97.4 | 100.0 | 0.3 | 0.5 | 0.0 | 0.5 | 0.5 | 1.8 | 1.8 | 5342.0 | 0.6 | 2.3 | 95.5 |
| R27-BOT | 97.8 | 100.0 | 0.4 | 0.5 | 0.2 | 0.1 | 0.1 | 0.2 | 0.3 | 4836.4 | 0.1 | 3.5 | 93.7 |
| R28-TOP | 99.4 | 98.6 | 0.5 | 1.0 | 28.7 | 9.2 | 9.9 | 27.3 | 29.4 | 7133.6 | 8.7 | 13.8 | 100.0 |
| R28-MID | 98.1 | 97.7 | 0.3 | 1.0 | 0.3 | 0.4 | 0.4 | 0.9 | 1.0 | 6113.1 | 0.4 | 3.4 | 94.7 |
| R28-BOT | 98.7 | 94.1 | 0.2 | 0.5 | 8.9 | 9.3 | 13.1 | 17.0 | 23.8 | 7057.1 | 7.6 | 22.4 | 93.7 |
| R32-TOP | 93.4 | 87.0 | 0.6 | 1.0 | 10.5 | 7.1 | 16.4 | 14.2 | 32.9 | 13483.0 | 7.8 | 48.5 | 58.9 |
| R32-BOT | 89.6 | 82.0 | 0.6 | 1.0 | 3.6 | 10.5 | 19.9 | 18.6 | 35.2 | 8263.9 | 10.9 | 48.9 | 44.4 |
| R43-TOP | 92.6 | 16.2 | 0.9 | 2.2 | 2.6 | 2.8 | 9.8 | 4.4 | 15.6 | 8383.0 | 2.7 | 47.3 | 82.0 |
| R43-BOT | 96.0 | 82.4 | 0.4 | 0.9 | 0.0 | 3.2 | 8.9 | 5.9 | 16.2 | 8887.1 | 3.0 | 35.4 | 86.8 |
| R47-TOP | 78.7 | 66.0 | 0.7 | 1.1 | 6.2 | 8.1 | 20.9 | 12.6 | 32.7 | 9240.6 | 6.8 | 47.1 | 64.9 |
| R47-MID | 42.3 | 41.2 | 0.8 | 0.7 | 95.1 | 12.1 | 19.7 | 19.7 | 32.0 | 10067.0 | 9.5 | 41.7 | 62.4 |
| R47-BOT | 44.1 | 34.1 | 1.1 | 1.1 | 79.5 | 21.0 | 28.9 | 26.8 | 37.0 | 9439.9 | 17.0 | 53.0 | 5.1 |
| R68-TOP | 39.0 | 40.1 | 1.1 | 1.1 | 57.9 | 12.0 | 23.1 | 14.3 | 27.5 | 8219.5 | 9.4 | 47.8 | 52.9 |
| R68-MID | 90.0 | 76.0 | 0.3 | 1.1 | 1.7 | 10.2 | 20.0 | 15.8 | 31.0 | 9459.6 | 9.0 | 45.9 | 57.6 |
| R68-BOT | 92.9 | 95.0 | 0.1 | 1.1 | 3.5 | 7.7 | 14.7 | 12.1 | 23.1 | 7423.4 | 6.3 | 41.4 | 73.2 |
| R80-TOP | 94.6 | 66.7 | 0.1 | 1.4 | 5.3 | 4.0 | 8.8 | 8.1 | 18.0 | 7651.1 | 3.4 | 24.4 | 92.4 |
| R80-BOT | 62.9 | 28.5 | 1.0 | 0.9 | 0.3 | 6.3 | 12.8 | 12.1 | 24.6 | 9396.5 | 5.5 | 31.9 | 84.7 |
| R92-TOP | 20.1 | 18.4 | 0.5 | -0.2 | 147.0 | 20.8 | 33.4 | 27.4 | 43.9 | 7681.3 | 16.9 | 55.6 | 0.0 |
| R92-MID | 82.1 | 81.8 | 0.2 | 1.2 | 4.4 | 4.9 | 13.3 | 7.9 | 21.5 | 8620.7 | 4.0 | 39.2 | 82.1 |
| R92-BOT | 82.9 | 45.9 | 0.3 | 0.0 | 3.6 | 6.3 | 16.7 | 16.9 | 44.7 | 10394.0 | 9.2 | 52.2 | 46.9 |
| R99-TOP | 85.4 | 38.3 | 0.6 | 0.6 | 0.0 | 11.1 | 20.7 | 18.9 | 35.5 | 9551.9 | 10.9 | 45.4 | 51.0 |
| R99-MID | 94.5 | 86.2 | 0.4 | 0.3 | 1.8 | 4.0 | 8.8 | 8.7 | 19.3 | 9254.9 | 4.7 | 31.6 | 86.2 |
| R99-BOT | 53.1 | 27.7 | 0.8 | 0.1 | 2.8 | 8.0 | 18.2 | 11.9 | 26.9 | 8915.6 | 6.9 | 48.2 | 63.2 |

^a Mean levels for five November and December 1995 surveys, including one measurement for February 1996.

^b Computed as the difference in temperature between the intragravel sample and the surface sample during the 20–22 December 1995 survey.

^c From February 1996 substrate samples.

^d Source: Tappel and Bjornn 1983.

Table 2 Habitat data from 32 piezometer sites at 12 riffles in the Stanislaus River, fall 1995

| Site | Streambed gradient upstream of samples ^a | | | Mean column velocity (ft/s) ^b | Water depth (ft) ^b | Surface water turbidity (JTU) ^c | Intragravel nitrate concentration (ppm) ^d | | Channel width (ft) | Distance downstream of Goodwin Dam (mi) |
|----------|---|-------|-------|--|-------------------------------|--|--|------|--------------------|---|
| | 5 ft | 10 ft | 20 ft | | | | Sample | Diff | | |
| TM1-TOP | 7.0% | 3.6% | 4.1% | - | - | 3 | 1 | 0.5 | 99.0 | 1.5 |
| TM1-BOTR | 5.0% | 7.6% | 5.4% | - | - | 3 | 0.5 | 0 | 99.0 | 1.5 |
| TM1-BOTL | 5.0% | 7.6% | 5.4% | - | - | 3 | 0.5 | 0 | 99.0 | 1.5 |
| R2-TOP | 9.1% | 8.7% | 5.0% | 3.1 | 1.8 | 3 | 0.5 | 0 | 92.0 | 3.9 |
| R2-BOT | -5.8% | -5.2% | -2.7% | 2.7 | 1.3 | 3 | 0.5 | 0.25 | 92.0 | 3.9 |
| R10-TOP | 4.8% | 5.8% | 2.7% | 1.5 | 1.3 | 5 | 0.5 | 0 | 82.2 | 4.9 |
| R10-MID | -1.2% | -0.8% | -0.0% | 0.5 | 1.3 | 5 | 0.5 | 0 | 81.0 | 4.9 |
| R10-BOT | -1.4% | -3.3% | -5.4% | 1.3 | 1.1 | 5 | 0.5 | 0 | 80.0 | 4.9 |
| R27-TOP | 0.6% | 5.5% | 0.7% | 2.1 | 1.5 | 10 | 0.5 | 0 | 91.0 | 7.4 |
| R27-MID | 9.8% | 4.6% | 1.6% | 2.9 | 1.7 | 10 | 0.5 | 0 | 85.6 | 7.4 |
| R27-BOT | -3.2% | -1.6% | -0.7% | 1.4 | 1.6 | 10 | 0.5 | 0 | 75.0 | 7.4 |
| R28-TOP | 2.0% | 2.1% | 1.2% | 3.0 | 1.3 | 10 | 0.5 | 0 | 84.0 | 7.9 |
| R28-MID | -3.4% | -2.4% | -0.8% | 3.2 | 1.3 | 10 | 0.5 | 0 | 86.0 | 7.9 |
| R28-BOT | 14.8% | 8.3% | 6.0% | 2.4 | 1.0 | 10 | 0.5 | 0 | 88.0 | 7.9 |
| R32-TOP | 2.2% | 4.1% | 3.3% | 3.4 | 1.7 | 7 | 0.25 | 0.25 | 63.4 | 8.9 |
| R32-BOT | -4.2% | -2.2% | -2.3% | 3.9 | 1.2 | 7 | 0.25 | 0.25 | 65.6 | 8.9 |
| R43-TOP | 0.6% | 2.2% | 6.8% | 2.2 | 1.6 | 7 | 0.5 | 0 | 80.1 | 11.5 |
| R43-BOT | 1.0% | 1.2% | 1.0% | 2.0 | 1.0 | 7 | 1.0 | 0 | 80.1 | 11.5 |
| R47-TOP | 0.8% | -1.3% | -1.6% | 1.4 | 1.6 | 7 | 0.5 | 0 | 91.6 | 12.4 |
| R47-MID | 0.2% | 0.2% | -1.0% | - | - | 7 | 1.0 | 0.5 | 96.1 | 12.4 |
| R47-BOT | 0.3% | 0.3% | 0.2% | 1.1 | 1.7 | 7 | 1.0 | 0 | 90.0 | 12.4 |
| R68-TOP | 0.8% | -0.2% | 1.6% | 1.6 | 1.2 | 5 | 5.0 | 2.8 | 143.0 | 16.3 |
| R68-MID | -2.9% | -2.9% | -1.7% | 1.8 | 1.2 | 5 | 1.5 | 0 | 70.7 | 16.3 |
| R68-BOT | -0.6% | -0.6% | 1.5% | 1.7 | 1.9 | 5 | 0 | 0.3 | 62.5 | 16.3 |
| R80-TOP | 0.8% | 1.3% | 1.9% | 2.5 | 1.4 | 10 | 2.0 | 0.5 | 64.0 | 19.1 |
| R80-BOT | -3.6% | -1.5% | -0.4% | 2.5 | 1.3 | 10 | 1.5 | 0 | 64.0 | 19.1 |
| R92-TOP | -1.9% | -0.5% | 0.4% | 0.7 | 1.5 | 5 | 1.0 | 0 | 152.0 | 21.2 |
| R92-MID | -1.2% | -1.2% | -0.5% | 0.9 | 1.6 | 5 | 1.5 | 0.25 | 113.0 | 21.2 |
| R92-BOT | 3.4% | 3.4% | 1.5% | 3.1 | 1.4 | 5 | 1.0 | 0 | 109.0 | 21.2 |
| R99-TOP | 0.6% | 0.0% | 0.1% | 1.5 | 1.6 | 5 | 1.0 | 0 | 81.2 | 23.1 |
| R99-MID | 1.6% | 1.6% | 2.5% | 2.5 | 1.5 | 5 | 1.0 | 0 | 86.5 | 23.1 |
| R99-BOT | 0.0% | 0.0% | 0.2% | 1.3 | 1.5 | 5 | 2.0 | 0.8 | 82.2 | 23.1 |

^a Measured 2–7 February 1996.

^b Measured 2–4 November 1995.

^c Measured 11 and 20 December 1995.

^d Intragravel nitrate concentration and the difference between the intragravel sample and the surface sample. Collected 11–12 December 1995.

Habitat variables were selected for the final regression models by evaluating Pearson correlation coefficients (r), adjusted multiple coefficients of determination ($\text{adj-}R^2$) and Mallows' C_p statistic for all possible combinations of variables, and stepwise regression procedures using Statistix 4.1 software (Analytical Software 1994). The relative importance of the variables was evaluated with the t -statistic (Bring 1994).

Results and Discussion

The California Department of Fish and Game's preliminary estimate of chinook salmon escapement (grilse and adults) to the Stanislaus River was 1,079 for fall 1994, 611 for fall 1995, and 168 for fall 1996 (G. Neillands, personal communication, see "Notes"). Escapement during these studies was relatively low compared to an average of 4,800 salmon that occurred between 1967 and 1991.

Distribution of Redds in the Spawning Reach, Fall 1995

A total of 415 redds was observed during 1995, with the highest density (50) occurring at the uppermost Riffle TM1. In the downstream area between the Knights Ferry Recreational Area and the bridge at Orange Blossom Road, there was an average of five redds per riffle. Downstream of the Orange Blossom Bridge to Jacob Meyers Park in Riverbank, the average number of redds per riffle was less than two. No redds were observed in the lowermost three miles of this reach. During 1994, a total of 714 redds was observed between Two Mile Bar and Jacob Meyers Park that were distributed similarly to those in 1995.

As in 1994, most of the redds observed in 1995 were constructed near the head (upstream boundary) of the riffles, even though the entire riffle appeared to be suitable for spawning. Of the 337 redds that were observed at the 129 riffles between the Knights Ferry Recreation Area and Jacob Meyers Park, 72.6% (244 redds) occurred within the uppermost 30-ft section of the riffles, 13.4% (45 redds) occurred in the middle 30-ft section of the riffles, and 14.0% (47 redds) occurred in the lowermost section of the riffles, some of which were 200 ft long.

Redd Distribution at the Intensively Studied Riffles

The distribution and number of redds observed at most of the intensively studied riffles were similar from 1994 to 1997. The highest density typically occurred at Riffle TM1 (50 redds in 1995), moderate densities (6 to 18 per riffle) occurred at riffles R2, R10, R14, R32, R43, R47, R68, and R80 between Knights Ferry and Oakdale, while few or no redds were observed at riffles

R29, R58, and R78. Riffle TM3 had a moderate number of redds in 1995 (11) and 1997 (7), but only two redds had been completed by 19 November 1996. Riffles R92 and R99 each had nine redds in fall 1994, but none in fall 1995 when escapement was relatively low.

Of the 113 redds that were mapped with the longitudinal transects at the study riffles in fall 1995, 73 (64%) occurred where the streambed's gradient was increasing, 11 (10%) occurred where the streambed's gradient was decreasing, and 29 (26%) occurred where the streambed was relatively flat. Redd distribution and streambed configuration of Riffle R10 in fall 1995 were typical for the Stanislaus River (Figure 3).

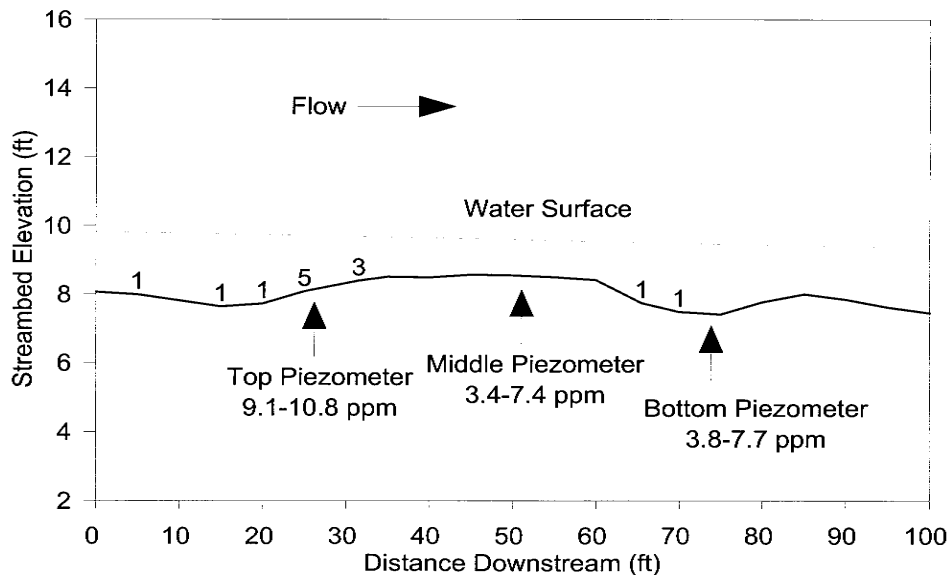


Figure 3 Map of Riffle R10 in the Stanislaus River showing the number of redds, locations of piezometers, range of DO concentrations observed between 11 November 1995 and 4 February 1996, and the water surface elevation relative to the streambed elevation recorded along a mid-channel longitudinal transect

1994 DWR Restoration Sites at the Horseshoe Recreation Area

At Riffles 27 and 28, few of the redds were constructed entirely in the added mitigation gravel obtained from the Merced River floodplain, whereas several redds were usually observed near the mitigation gravel in natural substrate. In fall 1994, all 11 redds observed at these riffles were constructed in the natural cobble substrate adjacent to the mitigation gravel. In fall 1995, only one redd at each riffle was constructed entirely in the mitigation gravel at R27 and R28. Two redds were observed immediately upstream of Riffle R27. Nine redds were constructed in cobble substrate upstream of the mitigation gravel, and two others were constructed in predominately cobble substrate where a

fallen cottonwood tree had scoured away all of the mitigation gravel in the middle of Riffle R28 (Figure 4). No redds were observed in the large deposit of mitigation gravel approximately 20 ft downstream of Riffle R28 that had been moved by the high streamflows that occurred in spring 1995.

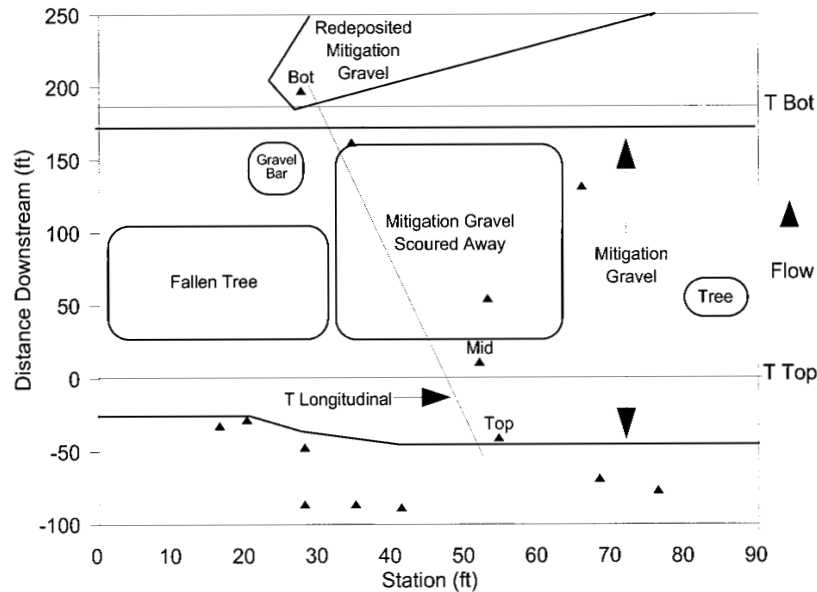


Figure 4 Map of Riffle R28, the lower mitigation site at the Horseshoe Road Recreation Area, in the Stanislaus River showing the locations of fall-run chinook salmon redds (black triangles), piezometers (black triangles identified as Top, Mid, and Bot sites), the permanent transects (T Top and T Bot) used to record the location of redds, the longitudinal transect (T Longitudinal) used to measure streambed elevations in fall 1995, and the location of mitigation gravel placed in summer 1994

By November 1996, all of the mitigation gravel from the lower one-third of Riffle R27 and from the entire riffle at R28 had been scoured away, presumably during high flows in spring 1996. The mitigation gravel that had been deposited immediately downstream of Riffle R28 in spring 1995 had been entirely scoured away in spring 1996. No redds or spawning fish were observed at Riffles R27 or R28 by 1 November 1996. Two redds were observed approximately 20 ft upstream of Riffle R28 on 1 November 1996.

In 1997, a 15-ft-long, 2-ft-high natural gravel berm had been deposited across the width of the river channel at the upstream boundary of Riffle R27, presumably as a result of the prolonged flows (5,000 to 8,000 cfs) in spring 1997. Nine redds and six pairs of spawning chinook salmon were observed in the newly deposited natural gravel on 29 October 1997; none were observed in the mitigation gravel that remained in the middle of the original riffle. On 3 December 1997, there were seven additional redds in the newly deposited natural gravel and one redd in the mitigation gravel. No redds were observed at

Riffle R28, although three adult salmon were observed near the top of the riffle on 29 October.

1997 DFG Restoration Sites in Goodwin Canyon

Chinook salmon spawned at all four locations where gravel from the Stanislaus floodplain had been added to the river in summer 1997. Most of the spawning occurred where gravel bars were placed across the width of the river in shallow, moderately swift water, but fish also spawned in the newly added gravel in pools where water velocities were quite low. On 29 October 1997, five redds were observed at both sites where gravel bars were placed across the width of the river in shallow (one to two feet deep), moderately swift water (about 2 ft/s). No redds were observed in gravel that had been mobilized and deposited in high gradient areas where the water was swift (>4 ft/s) or in the deep pools. On 3 December, there were three new redds at one shallow site, whereas the other shallow site appeared to be completely covered with redds (at least ten more redds). Two to three redds were also observed at each of the pool sites. However, no redds were observed where the new gravel had been redeposited in very swift water.

Evidence of Redd Superimposition

Seven piezometers had to be replaced in fall 1996, when salmon presumably constructed redds on top of them. The top piezometer at Riffle TM3 and the middle right piezometer at Riffle R10 and their thermographs had been excavated by adult salmon between the 31 October and the 11 November surveys. Pipe-piezometers were also lost from one redd (number 8) in Riffle R10, two redds (numbers 6 and 8) in Riffle R14, and from two redds (numbers 15 and 22) in Riffle R43 due to redd superimposition between the 11 November and 19 November surveys. In several cases, the pipe-piezometers were found several yards downstream of the original site indicating that the tail spills had been completely re-excavated. A superimposition rate of 24% (5 of 21 redds with pipe-piezometers) is surprisingly high, considering escapement was estimated to be only 168 fish. One possible explanation is that the substrate throughout the spawning reach in the Stanislaus River is cemented and the salmon construct redds in areas loosened by piezometer construction or redd building.

Intragravel Dissolved Oxygen

Fall 1995 Surveys

During the five surveys in November and December 1995, intragravel DO concentrations were relatively constant and suitable for egg incubation (>80% saturation) at most of the 32 piezometer sites (Table 1). The mean difference between the maximum and minimum levels of intragravel DO concentrations

at the 32 piezometer sites during the five fall 1995 surveys was 1.3 ppm and none varied by more than a difference of 3.2 ppm. During the five surveys, intragravel DO concentrations were less than 5 ppm (about 50% saturation) at six sites (18.8%) and less than 8 ppm (about 80% saturation) at eleven sites (34.4%).

Mortality of chinook salmon eggs in Mill Creek, California, increased rapidly at oxygen concentrations below 13 ppm, averaging 3.9% at 13 ppm and 37.9% at less than 5 ppm (Gangmark and Bakkala 1960). Davis (1975), who reviewed the oxygen requirements of salmonids, reported a mean threshold of incipient oxygen response for hatching eggs and larval salmonids at 8.1 ppm, which was 76% of saturation. Silver and others (1963) reported that DO concentrations less than 11.7 ppm reduced the growth of chinook salmon embryos. A criterion of 8 ppm for intragravel oxygen concentration was adopted by the Environmental Protection Agency (EPA) and the U.S. Fish and Wildlife Service for the State Water Resources Control Board 1992 Water Rights Hearings for the Mokelumne River.

By the early February 1996 survey, intragravel DO concentrations had declined markedly at several piezometer sites (Table 1) after the runoff from four major storms in January 1996 increased base flows by a daily average of 200 to 500 cfs for several days after each storm. Intragravel DO concentrations at nine piezometer sites, declined to between 25% and 75% of the fall 1995 levels. During the February survey, intragravel DO concentrations were less than 5 ppm at 11 piezometer sites (34.4%) and less than 8 ppm at 16 sites (50%). The large declines were most frequently observed at the bottom piezometers, although the greatest decreases in DO concentration occurred at the top piezometers at Riffles 43 and 99. In addition, most of the piezometers where low DO concentrations occurred during the November and December surveys were located downstream of Riffle R32. However by February 1996, DO concentrations had substantially decreased at Riffles 2 and 10 and there were further declines at the downstream riffles. During the fall 1995 surveys, only one storm resulted in runoff (<80 cfs) between the fourth and fifth surveys and intragravel DO concentrations during the fifth survey were not low compared to the previous surveys at most of the piezometer sites. Gangmark and Bakkala (1960) demonstrated that flooding conditions in Mill Creek, California, were associated with low oxygen concentrations (<5 ppm) in spawning gravel and low intragravel flow rates.

DO concentrations remained high (>8 ppm) throughout all the 1995 surveys and February 1996 survey at all piezometer sites at Riffles TM1, R27, R28, and R32, which include both restoration sites at the Horseshoe Road Recreation Area. Other riffles where DO concentrations at individual piezometer sites remained above 8 ppm during all surveys include the top piezometers at rif-

files R2, R10, R80, and R99, and the middle or bottom piezometers at riffles R43, R68, R80, R99.

Fall 1996 Surveys

During the October and November 1996 surveys when no appreciable storm runoff occurred, a higher percentage of piezometer sites had intragravel DO concentrations below the EPA standard of at least 8 ppm compared to the percentages observed in November and December 1995. In 1996, eleven (46%) of the piezometer sites had DO concentrations less than 8 ppm, whereas three sites (13%) had concentrations below 5 ppm (Table 2). Low DO concentrations did not occur upstream of Riffle R14 and the lowest levels were usually observed at either the middle or bottom piezometers.

Intragravel DO concentrations at piezometers in the actual redds in riffles R10 and R14 were above 8 ppm during both November 1996 surveys (Table 2). However of the six redds sampled at Riffle R43, three had DO concentrations between 5.6 and 6.9 ppm and one had concentrations below 2 ppm during both surveys.

The distribution of salmon redds and intragravel DO concentrations at Riffles R10, R14, and R43 suggests while salmon typically spawned where intragravel DO concentrations were suitable for incubation (> 8 ppm), high densities of spawning salmon influenced the intragravel DO concentrations in nearby areas. Riffle R14 (Figure 5) provides an example where the fish appeared to avoid the area near the bottom piezometer where intragravel DO concentrations ranged between suboptimal and lethal. Almost all of the redds were constructed upstream of the riffle's crest where the piezometer in the artificial redd indicated that conditions were very suitable. DO concentrations were very similar between the two adjacent piezometers in the middle section of R14, one in an actual redd and the other in an artificial redd, which suggests the artificial redds provided a suitable surrogate for actual redds.

Riffle R10 provides an example where spawning activity slightly improved the intragravel conditions at some nearby piezometers (Figure 6). On 31 October 1996, the intragravel DO concentration at the bottom left piezometer in Riffle R10 was 8 ppm, whereas the concentrations at the other piezometers ranged between 9.5 and 12.1 ppm. By 11 November, after three new redds had been constructed within 80 feet upstream of the bottom left piezometer, intragravel DO concentrations increased to 10 ppm at the bottom left piezometer, whereas the concentrations at the other piezometers remained relatively constant or declined slightly. Intragravel DO concentrations remained high at the bottom left piezometer compared to the other piezometers during the 19 November survey (Table 2).

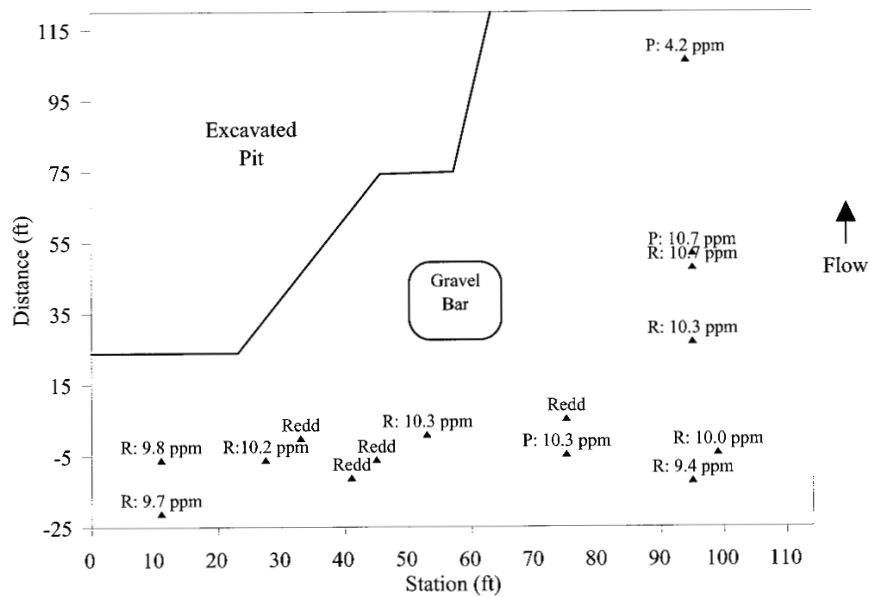


Figure 5 Map of Riffle R14 in the Stanislaus River showing reds (Redd) and the intragravel DO concentrations (ppm) at the piezometers in artificial reds (P) and fall-run chinook salmon reds (R) measured on 11 November 1996

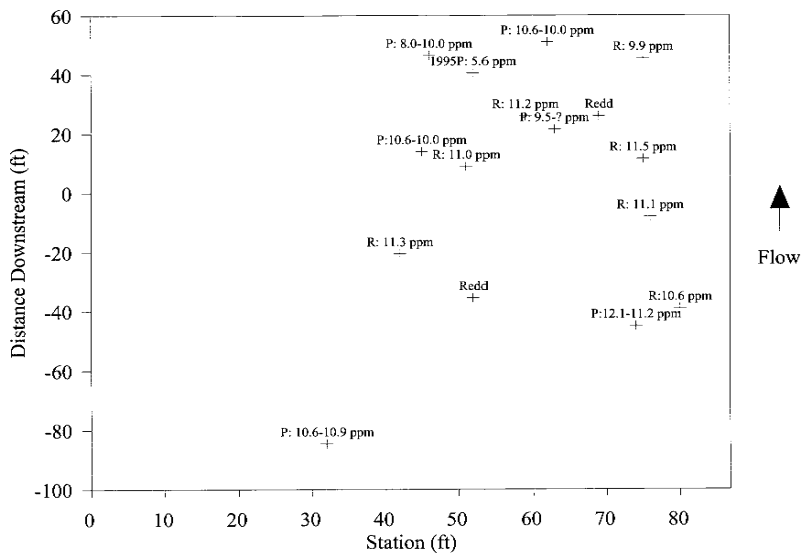


Figure 6 Map of Riffle R10 in the Stanislaus River showing the intragravel DO concentrations (ppm) at the piezometers in artificial reds (P) and fall-run chinook salmon reds (R) in fall 1996. The first DO concentration shown for the piezometers was measured during the 31 October survey and the second was measured during the 11 November survey. The DO concentrations for the reds were recorded during the 11 November survey. The DO concentration at the bottom piezometer installed in fall 1995 (1995P) was measured during the 19 November survey when atmospheric conditions reduced the concentrations by about 13% relative to the 11 November survey.

Riffle R43 provided an atypical example where redds were constructed in suitable areas that later became unsuitable (Figure 7). By 11 November 1996, intragravel DO concentrations below 8 ppm occurred at two salmon redds and one artificial redd located in the top and middle sections near the left streambank. By 19 November, another actual redd and artificial redd developed suboptimal intragravel DO concentrations. The area where the lowest intragravel DO concentrations occurred was adjacent to a grassy field with a large orchard about 100 feet from the water's edge. The left streambank of the bottom section was shielded from the orchard by a dense growth of willows. The ACOE recreation area was on the right bank of the riffle, which was vegetated with willows. The water depth gradually increased from about one foot along the left streambank to about four feet near the right streambank. These features suggest that willow growth may improve the quality or reduce the quantity of groundwater inflow from aquifers. The unusual pattern of intragravel DO concentrations in Riffle R43 also suggests that piezometers in artificial redds provide a suitable measure of conditions in actual redds.

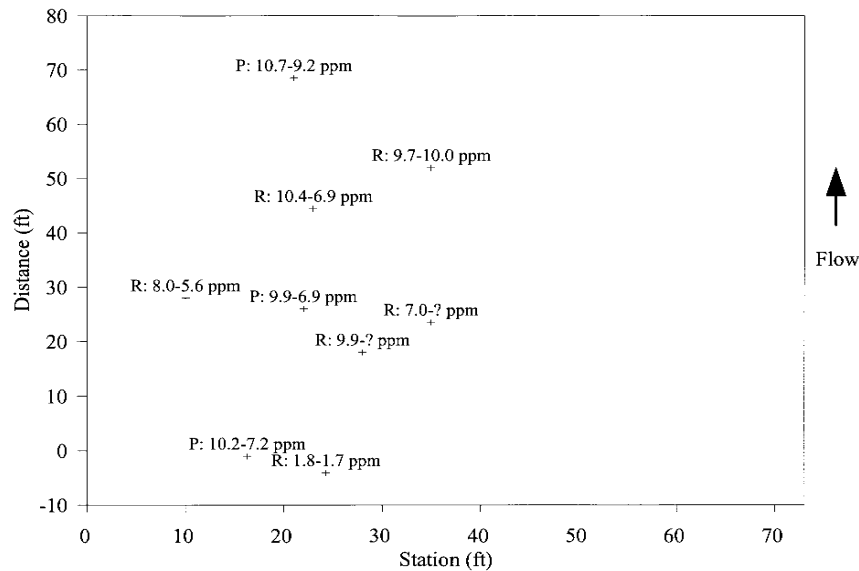


Figure 7 Map of Riffle R43 in the Stanislaus River showing the intragravel DO concentrations (ppm) at the piezometers in artificial redds (P) and fall-run chinook salmon redds (R) in fall 1996. The first DO concentration shown for the piezometers was measured during the 31 October survey and the second was measured during the 19 November survey. The first DO concentration shown for the redds was measured during the 11 November survey and the second was measured during the 19 November survey.

No redds were completed in riffles R29, R58, and R78, where intragravel DO concentrations at most piezometer sites gradually declined to minimally suitable levels (Table 2). One two-foot long salmon was observed constructing a redd in the vicinity of the top piezometer in Riffle R29 on 27 October 1996.

However, this redd and another were abandoned by 1 November when intragravel DO concentrations were measured at 90% and 92% at the top and middle piezometers respectively.

Fall 1997 Surveys

In fall 1997, intragravel DO concentrations and VHGs were measured at two pipe-piezometers installed in a newly deposited gravel berm at the head of Riffle R78. The gravel berm, deposited in a large horseshoe-shape during the spring 1997 flows, had an unexpectedly high proportion of fine substrates and no redds were observed there on 29 October or 3 December 1997. On 3 December, intragravel DO concentrations were 74.8% (8.9 ppm) and 79.8% (9.5 ppm) of saturation and the VHGs were +1.0 and +0.18 at the left and right piezometers, respectively. The high VHG at the left piezometer suggests that the low DO concentrations were caused by a very high rate of groundwater inflow. The presence of several large sewage treatment ponds adjacent to the right bank of this riffle probably contributed to this problem.

Additional evidence that intragravel DO concentrations were affected more by oxygen-poor groundwater from aquifers than by the intrusion of fine sediments was provided by samples collected in fall 1996 at two undisturbed piezometers originally installed in fall 1995. Since the substrate at these sites had been undisturbed since fall 1995, the accumulation of fine sediments and decomposing organic matter would be expected to have been greater in fall 1996 than in fall 1995. As expected, the intragravel DO concentrations at the bottom piezometers at riffles R2 and R10 in fall 1996 were 75.4% and 53.3% respectively, which is about 10% lower than the average concentrations observed in November and December 1995 (Table 2). Presumably this was due to the accumulation of fine sediments and decomposing organic matter. Conversely, the fall 1996 DO concentrations were about 20% higher than those observed in February 1996, when four major rainstorms presumably increased groundwater flow into the gravel (Table 2). Since the storm-influenced increase in groundwater flow would have been temporary, the increase in DO concentrations observed at both sites in November was probably in response to the reduction in groundwater inflow after the January storm effects subsided.

Intragravel Water Temperature

Fall 1995 Surveys

Temperature measurements made by withdrawing water samples from the piezometers with a 50-ml syringe, placing 100 ml of sample into a plastic bottle, and using a mercury thermometer, were inaccurate when compared to data recorded by thermographs. The inaccuracy was caused by the slow col-

lection rate with a syringe and the plastic sample bottle, resulting in an overestimation of surface water temperatures by about 0.5 °F and an overestimation of intragravel water temperatures by about 1.0 to 2.5 °F as measured in fall 1996. Apparently the plastic sample bottle absorbed heat from the air, biologist's hands, thermometer, and the fanny pack used to hold the sample bottle. All readings from both thermographs and mercury thermometers used in the 1995 and 1996 studies were accurate as their measurements were within 0.2 °F when all were simultaneously placed in one gallon of water for ten minutes. The most highly suspect data were collected during 11–13 November 1995, when intragravel temperatures were measured to be 4 to 6 °F higher than surface water temperatures at all piezometer sites. The inaccuracy was probably worst during this survey because air temperatures were relatively high in early November compared to the other surveys and because more heat would have been transferred to the sample bottles by (1) using the large probe of the YSI meter to measure temperatures and (2) holding the plastic sample bottle by its neck. The variability in the overestimation observed in fall 1996 makes it impossible to determine whether intragravel water temperatures were actually elevated at any piezometer site in November 1995.

Temperature data collected during the 20–22 December 1995 survey may have been sufficiently accurate to show the effects of oxygen-poor groundwater inflow from warm aquifers. During this survey, heavy fog and low air temperatures may have reduced the temperature of the measuring equipment (and fingers) sufficiently to minimize heat absorption by the sample. Intragravel temperatures were less than 0.5 °F higher than the surface samples at many piezometer sites (Table 1), although intragravel temperatures were about 2 °F higher than surface temperatures a few of the piezometer sites. At most of the sites with elevated temperatures, intragravel DO levels were relatively low suggesting that relatively warm, oxygen-poor groundwater was influencing these sites.

The effect of groundwater inflow was apparent not only during the 20–22 December 1995 survey, when the first major rainstorm had just ended, but also during the 2–7 February 1996 survey, after five major storms had saturated the floodplain soils. The greatest difference in temperature occurred at Riffle R10 on 4 February about two hours after an intense rain storm had ended (Table 1). At Riffle R10, the intragravel temperature was 3.5 °F higher at the middle piezometer than at either the top or bottom piezometers at the same site. Two samples were taken at the middle site to confirm the difference in temperature on 4 February, whereas the temperature difference was only 0.5 to 1.0 °F higher at the middle site compared to the top and bottom sites at Riffle R10 during the previous surveys. Samples collected at the other riffles during the February survey occurred between one and two days after storm events and the observed temperature differences were lower than those

observed at Riffle R10 (Table 1). This suggests substantial effects due to groundwater inflow may occur for only a few days after intense storm events. The differences in water temperature between the intragravel samples and the surface samples during the 20–22 December and 2–7 February surveys were both used as indices of groundwater inflow for the statistical analyses.

The effect of groundwater inflow on incubating salmonid eggs has been reported by other researchers. Curry and others (1994) reported that short-term declines in streamflow releases, which simulated a hydroelectric peaking regime, increased groundwater inflow into brook trout redds approximately 24 hours after the flow had declined. McNeil (1969) and Leitritz and Lewis (1980) reported that groundwater generally has a low DO concentration due to biochemical oxygen demand. This appeared to be true for the Stanislaus River as well, because the index of groundwater inflow based on water temperature differences was negatively correlated with intragravel oxygen concentration. Sowden and Power (1985) suggested the abnormally low egg survival (0.3% to 21.5%) observed for rainbow trout (*Oncorhynchus mykiss*) in a groundwater-fed streambed was partially caused by temporary declines in intragravel DO concentrations to lethal levels (minimums of 3.1 to 4.5 ppm). Unfortunately, they did not monitor groundwater-inflow throughout their study to determine whether pulses in groundwater inflow caused the temporary declines in DO concentration.

Vertical Hydraulic Gradient

The vertical hydraulic gradient (VHG) was atypical at most of the Stanislaus River piezometer sites. In typical rivers described by Lee and Cherry (1978), Creuze des Chatelliers and others (1994), and Dahm and Valett (1996), VHG is negative upstream of obstacles to surface flow, such as the crest of a riffle, and positive in areas downstream of flow obstacles, particularly at the tails of riffles. However, negative VHGs were observed only at the top piezometer of Riffle TM3 and the top right piezometer of Riffle R10 during the 31 October 1996 survey (Table 2); only one measurement was recorded at the top piezometer of Riffle TM3 because the device was displaced by spawning salmon. During the 11 November survey, VHGs were also positive at four new pipe-piezometers installed temporarily within 20 feet upstream of the riffle crest in riffles TM1 and TM3, where the streambed gradient was relatively steep (positive 7% to 9%). Unexpectedly, the middle left piezometer of Riffle R10 became negative on the last survey on 19 November. This site was on just upstream of the mildly upsloped riffle crest (positive 1.4% gradient), an unlikely area for downwelling. Based on these results, there appears to be relatively little downwelling of oxygenated surface water into the Stanislaus' riffles, but instead an upwelling of flow over a majority of the riffle's surface.

Changes in VHG at piezometer sites were unrelated to changes in intragravel DO concentrations, patterns in intragravel water temperatures, storm runoff, or precipitation (Table 2). Variability in VHGs has been known to result from changes in streambed permeability and morphology (Lee and Cherry 1978), streamflow (Lee and Cherry 1978), the depth of the water table (Price 1996), and atmospheric pressure in confined aquifers (Price 1996). Perhaps the effects of ongoing redd construction on streambed permeability and morphology that occurred throughout this study, and changes in groundwater flow from aquifers caused some of the variability in VHG measurements in the Stanislaus River.

Nitrate Concentration

Intragravel nitrate concentrations were usually higher than the surface water concentrations downstream of Orange Blossom Bridge (riffles R43 to R99) during both the 11–12 December and 20–22 December surveys 1995 (Table 2). The highest intragravel concentrations occurred at the top piezometers at Riffles R68 and R80 and the bottom piezometer at Riffle R99 during both of these surveys.

A few hours after an intensive rain storm had ceased, surface concentrations of nitrates were relatively high (1.0 ppm) at Riffle R68 and the downstream riffles on 11 December 1995 compared to Riffle R43 (the last site sampled on 11 December) and most of the riffles sampled on 12 December. The surface concentration was also high (1.0 ppm) at Riffle R47 compared to all the other riffles (0.25 ppm) during the 20–22 December survey. These results suggest nitrogenous compounds were entering the river primarily between the Orange Blossom Bridge and the town of Oakdale.

Two indices of nitrate concentration were used for the statistical analyses in fall 1995: the intragravel concentration and the difference in concentration between the intragravel sample and the surface sample during the 11–12 December 1995 survey (Table 2). The difference between the intragravel and surface concentrations was used to evaluate the relationship between groundwater and nitrate concentrations.

The high intragravel nitrate concentrations occurred further upstream in fall 1996 than during fall 1995. Intragravel nitrate concentrations in fall 1996 at riffles R29, R43, R58, and R78 were at least double (0.8 to 1.0 mg/L) the concentration of the surface water sample collected at Riffle R29 (0.4 mg/L) or the intragravel samples collected at the upstream riffle sites (0.5 to 0.6 mg/L).

Percent Fines, Crushed Rock, and Asian Clams in The Substrate in Fall 1995

The percent fines less than 2 mm in diameter for the entire substrate sample collected averaged 13% for the 32 piezometer sites and ranged between 0.13%

at the bottom piezometer site at Riffle R27 and 33.4% at the top piezometer site at Riffle R92 in fall 1995 (Table 1). The percent fines less than 1 mm for the entire substrate sample was strongly correlated ($r = 0.95$, $P = 0.0000$) with those less than 2 mm.

Predicted survival probabilities for chinook salmon eggs using Tappel and Bjornn's (1983) laboratory study averaged 76.5% in the reach above the Orange Blossom Bridge, 58.6% in the lower spawning reach between the bridge and Riverbank, and 95.4% at two restoration sites near the U.S. Army Corps of Engineers' Horseshoe Road park where gravel was added in 1994 (Table 1). Predicted egg survival probabilities averaged 72.3% upstream of riffle crests and 62.1% downstream of riffle crests at four natural riffles, Riffles R2, R10, R32, and R68, which had pronounced crests.

The total weight of substrate samples averaged 8,270 g and ranged between 4,486 g for the top piezometer at Riffle R2 and 13,483 g for the top piezometer at Riffle R32 (Table 1). There was a Pearson correlation coefficient (r) of 0.58 with a probability level of 0.0005 between sample weight and the percent fines less than 2 mm, which suggests that larger samples included deeper substrates, which contained a relatively high percentage of fines. However, including the sample weight in the multiple regression analysis had no significant effect on the final model.

The proportion of angular rock in the substrate samples was three to four times higher at the Horseshoe Road mitigation sites, Riffles R27 and R28, compared to the natural riffles. Approximately 60% of the rocks between 16 and 64 mm at Riffles R27 and R28 had sharp edges, indicating that they had been recently broken, whereas usually less than 20% of the rocks had sharp edges at the natural riffles. The amount of crushed rock at the Goodwin Canyon sites appeared to be similar to the substrate at the Horseshoe Road sites based on a casual comparison.

Some of the substrate samples at the piezometer sites at Riffles R47, R68, and R92 had high densities of Asian clams that ranged between 2 and 32 mm in diameter. At the top piezometer site at Riffle R92, there were 71 clams between 16 and 32 mm, 283 clams between 8 and 16 mm, and 15 clams between 4 and 8 mm per square-foot of streambed. Other sites, such as the top piezometer at Riffle R28 had high numbers of small clams: 306 between 2 and 4 mm and 868 between 4 and 8 mm per square-foot. Most of the clams in the samples had died prior to collection as evidenced by a strong putrid smell during sample collection. The clams, which normally live near the surface of the streambed, probably died as a result of becoming buried well below the surface during the installation of the piezometers. It is also likely that clams would be buried and die as a result of salmon building their redds. The total

weight of the dried clam shells was used as an index of their biomass for statistical analyses.

Regression Analyses

Differences in DO concentration among the piezometer sites in fall 1995 were highly correlated with environmental factors. Based on the final multiple regression model, 80.4% (adj- R^2) of the variation in the mean DO concentrations during the November and December 1995 surveys was explained by groundwater effects, the weight of Asian clams, the percent fines less than 2 mm in diameter, and the mean column velocity at the piezometer site. The index for groundwater inflow, which was the difference in water temperature between the intragravel and surface samples during the 20–22 December survey, was the most important variable in the final model; it was negatively correlated with DO concentrations (t -statistic = -3.65 , $P = 0.001$). Only slightly less important was the weight of Asian clam shells, which was also negatively correlated with DO concentrations (t -statistic = -3.41 , $P = 0.002$). The percent fines less than 2 mm, as computed from the contents of the entire substrate sample recommended by Chapman (1988), was also negatively correlated with DO concentrations (t -statistic = -2.80 , $P = 0.010$), although not as strongly as for groundwater inflow and clams. Although percent fines less than 2 mm based on the entire substrate sample was selected as the variable for the model, all four of the percent fines indexes were highly correlated (r) with DO concentrations (Table 3). Mean column water velocity was the least important variable in the final model and it was positively correlated with DO concentrations (t -statistic = 2.67 , $P = 0.014$).

The final multiple regression model of DO concentrations during the February 1996 survey indicated that 68.3% (adj- R^2) of the variation was explained by groundwater effects and the percent fines less than 2 mm in diameter. Both of these variables were equally important to the model as they had similar t -statistics of about -4.1 .

Although the gradient indexes were not selected for the regression models, low DO concentrations in February 1996 usually occurred where the streambed gradient immediately upstream of the piezometers ranged between -5% and 2% (Figure 8). This suggests that positive gradient, such as occurs at the tails of pools and at the heads of some riffles, minimized the occurrence of low DO concentrations to a greater degree than where streambed had the same gradient, but with a negative slope. This would explain why 77% of all redds observed throughout the spawning reach were located within the tails of pools and heads of riffles during both the 1994 and 1995 surveys. This skewed relationship also made it impossible to correctly evaluate the gradient indexes with linear regression analyses.

One exception occurred at the bottom piezometer at Riffle R92, where the gradient within 5 feet upstream of the piezometer was positive 3.4% and the DO concentration was low (4.5 ppm, 46% of saturation) during the February 1996 survey (Figure 8). This low DO concentration may be explained by an unusually high percentage of fines (<0.85 mm) and small gravel (<9.5 mm) which corresponds to a low gravel permeability and egg survival rate (Tappel and Bjornn 1983). High percentages of fines also occurred at the bottom piezometer of Riffle R10 and the top piezometer of Riffle R92, where DO concentrations were also low (<5 ppm) in February 1996.

Table 3 Dissolved oxygen concentrations (percent saturation), vertical hydraulic gradient, and stream gradient at 5-ft, 10-ft, and 20-ft distances upstream of piezometers at 29 piezometers in artificial redds (e.g., Top, Mid, Bot) and at 21 actual redds (e.g., Redd 20) at nine riffles in the Stanislaus River between 31 October and 19 November 1996

| <i>Piezometer Site</i> | <i>D. O. concentration (percent saturation)</i> | | | <i>Vertical hydraulic gradient</i> | | | <i>Streambed gradient</i> | | |
|------------------------|---|-----------------|-----------------|------------------------------------|-----------------|-----------------|---------------------------|--------------|--------------|
| | <i>10/31/96</i> | <i>11/11/96</i> | <i>11/19/96</i> | <i>10/31/96</i> | <i>11/11/96</i> | <i>11/19/96</i> | <i>5 ft</i> | <i>10 ft</i> | <i>20 ft</i> |
| TM1-BOTR | -- | 100.8 | -- | -- | 0.14 | -- | 5.0 | 7.6 | 5.4 |
| TM1-BOTL | -- | 99.2 | -- | -- | 0.14 | -- | 5.0 | 7.6 | 5.4 |
| TM3-TOP | 95.0 | 95.0 | 97.2 | -0.12 | 0.16 | 0.33 | 9.0 | 9.0 | 3.4 |
| TM3-MID | 96.7 | 96.7 | 92.6 | 0.33 | 0.20 | 0.13 | 5.0 | 10.0 | 0.0 |
| TM3-BOT | 93.3 | 92.5 | 92.6 | 0.40 | 0.41 | 0.32 | 2.8 | 0.1 | -0.2 |
| R2-TOP | -- | 100.0 | -- | -- | 0.27 | -- | 9.1 | 8.7 | 5.0 |
| R2-BOT | -- | 75.4 | -- | -- | 0.24 | -- | -5.8 | -5.2 | -2.7 |
| R10-TOPR | 97.6 | 93.3 | 90.5 | -0.10 | 0.06 | 0.07 | 12.0 | 6.9 | 4.5 |
| R10-TOPL | 85.5 | 90.8 | 89.5 | 0.12 | 0.16 | 0.11 | 4.4 | 2.6 | 4.8 |
| R10-MIDR | 76.6 | -- | -- | 0.21 | -- | -- | 5.4 | 0.7 | 1.5 |
| R10-MIDL | 85.5 | 83.3 | 92.4 | 0.18 | 0.13 | -0.17 | -4.6 | 0.4 | 1.4 |
| R10-BOTR | 85.5 | 83.3 | 77.1 | 0.11 | 0.21 | 0.10 | -1.8 | -4.8 | -2.5 |
| R10-BOTL | 64.5 | 83.3 | 88.6 | 0.13 | 0.11 | 0.16 | -3.6 | -2.8 | -2.0 |
| R10-BOT1995 | -- | -- | | | 53.3 | 0.05 | -1.4 | -3.3 | -5.4 |
| R10-REDD 20 | -- | 88.3 | 85.7 | -- | 0.05 | 0.04 | 12.6 | 6.8 | 7.2 |
| R10-REDD 12 | -- | 94.2 | 84.8 | -- | 0.12 | 0.15 | 11.4 | 8.5 | 3.2 |
| R10-REDD 14 | -- | 82.5 | 85.7 | -- | 0.27 | 0.23 | 12.0 | 9.6 | 2.5 |
| R10-REDD 11 | -- | 93.3 | 93.3 | -- | 0.37 | 0.23 | 11.8 | 7.8 | 3.9 |
| R10-REDD 10 | -- | 95.8 | 85.7 | -- | 0.25 | 0.13 | 1.2 | 1.1 | 0.3 |
| R10-REDD 2 | -- | 91.7 | 83.8 | -- | 0.25 | 0.12 | 8.8 | 5.2 | 6.5 |

Table 3 Dissolved oxygen concentrations (percent saturation), vertical hydraulic gradient, and stream gradient at 5-ft, 10-ft, and 20-ft distances upstream of piezometers at 29 piezometers in artificial redds (e.g., Top, Mid, Bot) and at 21 actual redds (e.g., Redd 20) at nine riffles in the Stanislaus River between 31 October and 19 November 1996 (Continued)

| <i>Piezometer Site</i> | <i>D. O. concentration (percent saturation)</i> | | | <i>Vertical hydraulic gradient</i> | | | <i>Streambed gradient</i> | | |
|------------------------|---|-----------------|-----------------|------------------------------------|-----------------|-----------------|---------------------------|--------------|--------------|
| | <i>10/31/96</i> | <i>11/11/96</i> | <i>11/19/96</i> | <i>10/31/96</i> | <i>11/11/96</i> | <i>11/19/96</i> | <i>5 ft</i> | <i>10 ft</i> | <i>20 ft</i> |
| R10-REDD 9 | -- | 92.5 | -- | -- | 0.26 | -- | 9.6 | 6.5 | 3.3 |
| R14-TOP | 98.3 | 96.3 | 100.0 | 0.09 | 0.11 | 0.07 | 3.2 | 1.1 | 1.5 |
| R14-MID | 100.0 | 100.0 | 97.1 | 0.25 | 0.05 | 0.09 | 2.4 | -0.8 | -0.4 |
| R14-BOT | 69.5 | 39.3 | 37.9 | 0.07 | 0.09 | 0.04 | -1.2 | -1.0 | -0.8 |
| R14-REDD 12 | -- | 90.7 | 90.3 | -- | 0.08 | 0.08 | 5.8 | 5.5 | 7.2 |
| R14-REDD 6 | -- | 95.3 | -- | -- | 0.16 | -- | 12.6 | 4.4 | 8.5 |
| R14-REDD 1 | -- | 96.3 | 99.0 | -- | 0.11 | 0.05 | 10.8 | 6.7 | 4.4 |
| R14-REDD 5 | -- | 93.5 | 97.1 | -- | 0.04 | 0.05 | 15.8 | 11.2 | 4.4 |
| R14-REDD 10 | -- | 91.6 | 91.3 | -- | 0.19 | 0.23 | 6.2 | 3.6 | 4.6 |
| R14-REDD 4 | -- | 87.9 | 88.3 | -- | 0.05 | 0.04 | 6.6 | 2.0 | -0.4 |
| R14-REDD 8 | -- | 96.3 | -- | -- | 0.18 | -- | 13.2 | 3.9 | 2.0 |
| R14-REDD 17 | -- | 100.0 | 97.1 | -- | 0.23 | 0.10 | 0.0 | -0.8 | -0.4 |
| R29-TOP | 90.1 | 80.7 | 77.5 | 0.12 | 0.18 | 0.21 | 2.0 | 3.7 | 3.7 |
| R29-MID | 91.9 | 81.7 | 80.4 | 0.17 | 0.14 | 0.10 | -1.8 | -3.1 | -0.7 |
| R29-BOT | 55.0 | 86.2 | 45.1 | 0.17 | 0.12 | 0.13 | -2.0 | -2.0 | -1.1 |
| R43-TOP | 87.9 | 88.2 | 72.0 | 0.11 | 0.15 | 0.14 | 6.6 | 3.0 | 1.7 |
| R43-MID | 85.3 | 38.2 | 69.0 | 0.20 | 0.18 | 0.13 | 0.4 | -1.1 | 0.1 |
| R43-BOT | 92.2 | 88.2 | 92.0 | 0.20 | 0.38 | 0.30 | -4.2 | -3.3 | -5.8 |
| R43-REDD 16 | -- | 72.7 | 56.0 | -- | 0.19 | 0.16 | 7.4 | 1.2 | 0.0 |
| R43-REDD 22 | -- | 63.6 | 102.0 | -- | 0.14 | 0.22 | 17.4 | 7.9 | 5.0 |
| R43-REDD 15 | -- | 90.0 | 104.0 | -- | 0.18 | 0.30 | 8.2 | 6.3 | 2.1 |
| R43-REDD 18 | -- | 94.5 | 69.0 | -- | 0.29 | 0.33 | 9.0 | 7.6 | 2.7 |
| R43-REDD 13 | -- | 88.2 | 100.0 | -- | 0.17 | 0.15 | 19.4 | 2.1 | 0.0 |
| R43-REDD 30 | -- | 16.4 | 17.0 | -- | 0.13 | 0.11 | 5.4 | 2.8 | 2.1 |
| R58-TOP | 77.0 | 71.4 | 76.0 | 0.17 | 0.19 | 0.13 | 7.2 | 4.9 | 6.7 |
| R58-MID | 83.2 | 85.7 | 82.0 | 0.30 | 0.20 | 0.18 | -1.8 | -1.4 | -0.6 |
| R58-BOT | 77.0 | 64.8 | 69.0 | 0.18 | 0.11 | 0.15 | 2.0 | 0.0 | -0.8 |
| R78-TOP | 85.3 | 88.5 | 85.4 | 0.27 | 0.24 | 0.13 | 3.8 | 2.3 | 0.8 |
| R78-MID | 94.8 | 94.2 | 84.4 | 0.10 | 0.07 | 0.11 | -4.0 | -2.5 | -1.5 |
| R78-BOT | 65.5 | 61.5 | 71.9 | 0.10 | 0.11 | 0.07 | -1.6 | -1.1 | -0.8 |

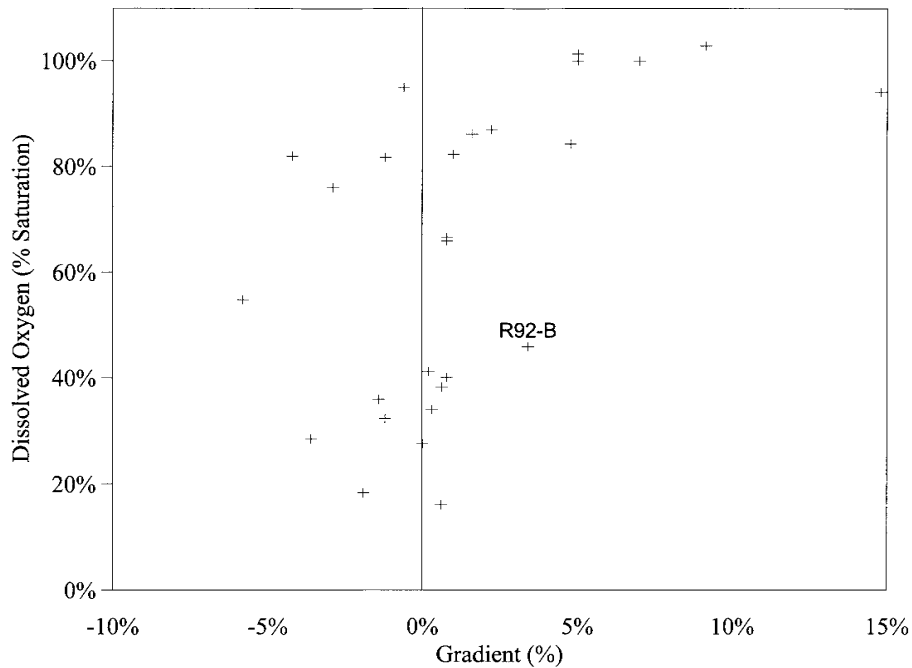


Figure 8 The relationship between intragravel DO concentrations measured at piezometer sites during the February 1996 survey and the gradient of the streambed within five feet upstream of the piezometer sites in the Stanislaus River study riffles TM1, R2, R10, R32, R43, R47, R68, R80, R92, and R99, and the bottom piezometer in Riffle R28

The most obvious explanation as to why high DO concentrations occur and salmon mostly spawn where streambed gradients are high and positive is that these areas are where downwelling of surface water typically occurs and downwelling would dilute the adverse effects of groundwater inflow and decaying clams. However, measurements of VHG upstream of riffle crests where the undisturbed streambed gradient at riffles TM1, TM3, R2, R14, R29, and R43 exceeded a positive 2% in fall 1996 indicated that upwelling occurred at these sites instead of downwelling (Table 2). Pipe-piezometers were also installed at two sites at Riffles R27 and R78 on 3 December 1997, and the VHG at these sites were also positive. Perhaps conditions, including the percentage of fines and groundwater inflow, are so extreme in the Stanislaus River that downwelling occurs at either a few, small locations or at a distance greater than 20 feet upstream from the riffle's crest.

Conclusions

Due to low intragravel DO concentrations and high concentrations of fine sediments, a majority of the riffle area in the Stanislaus River, particularly downstream of the Orange Blossom Bridge, was marginally suitable for spawning and incubation habitat for fall-run chinook salmon in 1995 and 1996. Survival of chinook salmon eggs would be expected to average 76.5% at the natural riffles at the Orange Blossom Bridge (Riffles TM1 to R43) and upstream, but only 58.6% at the riffles between the Orange Blossom Bridge and Riverbank (Riffles R47 to R99) based on a model from laboratory tests developed by Tappel and Bjornn (1983). These results are high in comparison to emergence trap studies on the Tuolumne River that indicate that egg-survival-to-emergence rates ranged between 0% and 68% (mean of 34%; EA Engineering, Science, and Technology 1992). Survival rates for Tappel and Bjornn's (1983) laboratory study may have been abnormally high for two reasons. First intragravel DO levels remained near saturation during all tests and so alevins would have been larger and stronger than those incubating in natural gravels where DO levels are lower. Second, embryos were incubated in a hatchery for 52 days before they were planted in test gravel mixtures to minimize handling mortality. Again this would have produced larger and stronger embryos compared to those incubated in natural gravels. Further research is recommended to accurately determine the relationship between gravel size and chinook salmon egg survival under natural conditions of intragravel flow and DO.

Intragravel DO concentrations were below EPA standards (80% of saturation) at 35% of piezometer sites in fall 1995 and at 42% of the sites in fall 1996. Intragravel DO concentrations declined to below EPA standards at 58% of the piezometer sites immediately following a February 1996 series of intense rain storms that made the river very turbid. Low intragravel DO levels were probably caused by the combined influence of groundwater inflow and fine sediment intrusion. If groundwater inflow increased as a result of the rain storms, the reduced intragravel DO levels associated with the February 1996 rain storms were probably temporary. On the other hand, it is also likely that the intrusion of fine sediments reduced gravel permeability, which reduced downwelling of surface flows. Regardless of the cause, intrusion of fine sediments and increased groundwater inflow did not reduce the DO levels at the 1994 restoration sites, which remained near saturation.

The predominance of nearly flat, silty riffles and fine sediment intrusion during rain storms when eggs are incubating may limit the production of chinook salmon in the Stanislaus River. A stock-recruitment analysis indicates that between 1945 and 1995, the number of spawners up to about 2,500 fish was directly correlated with the number of fish from their brood that returned to spawn in the Stanislaus River as adult fish (CMC 1996). However, once the

number of spawners exceeded 2,500 fish, there was no corresponding increase in the number of returning fish. These results suggest that the Stanislaus River has enough suitable spawning habitat for only about 1,250 pairs of adult chinook salmon.

The restoration sites where gravel was added in 1994 and 1997 provided suitable incubation habitat, but only the 1997 sites were immediately used by spawners. It is possible that the source of the gravel used for restoration affected the salmon's use of spawning sites. Crushed gravel from the Merced River, 0.5 to 4 inches in diameter, that was placed at two sites in 1994 was not used by the spawners for three years until high flows washed natural Stanislaus River gravel into the site. In contrast, gravel obtained near the Stanislaus River (0.5 to 5 inches in diameter) and placed in Goodwin Canyon in 1997 was used immediately by many salmon. Although the source and type of rock used in the 1997 Goodwin Canyon project may have been more suitable for the spawners, the salmon may have used the sites because gravel is relatively scarce in Goodwin Canyon. Additional studies are needed to determine whether the salmon did not use the 1994 sites because the rock was imported from the Merced River, the rock was crushed, or if the gravel's size distribution was unnatural.

Acknowledgements

The studies were funded by the Stockton East Water District. I thank S. Li, T. Salamunovich, B. Emery, and R. Fuller for assisting with the field work, and K. Lentz and S. Spaulding for their critical review of the manuscript.

References

- Analytical Software. 1994. Statistix user's manual, version 4.1. Tallahassee (FL): Analytical Software.
- Bring J. 1994. How to standardize regression coefficients. *Am Statis* 48(3):209-13.
- [CMC] Carl Mesick Consultants. 1996. The effects of minimum instream flow requirements, release temperatures, Delta exports, and stock on fall-run chinook salmon production in the Stanislaus and Tuolumne rivers. Draft report prepared for Thomas R. Payne and Associates, Neumiller and Beardslee, and Stockton East Water District.

- [CMC] Carl Mesick Consultants. 1997. A fall 1996 study of spawning habitat limitations for fall-run chinook salmon in the Stanislaus River between Goodwin Dam and Riverbank. Draft report prepared for Neumiller and Beardslee and Stockton East Water District.
- [CMC and others] Carl Mesick Consultants, Aquatic Systems Research, and Thomas R. Payne & Associates. 1996. Spawning habitat limitations for fall-run chinook salmon in the Stanislaus River between Goodwin Dam and Riverbank. Draft report prepared for Neumiller and Beardslee and Stockton East Water District.
- Chapman DW. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. *Trans Am Fish Soc* 117(1):1-21.
- Creuze des Chatelliers M, Poinart D, Bravard JP. Chapter 6: geomorphology of alluvial groundwater ecosystems. In: Gibert J, Danielopol DL, Stanford JA, editors. *Groundwater ecology*. Academic Press. p 175-7.
- Curry RA, Gehrels J, Noakes DLG, Swainson R. 1994. Effects of river flow fluctuations on groundwater discharge through brook trout, *Salvelinus fontinalis*, spawning and incubation habitats. *Hydrobiologia* 277:121-34.
- Dahm CN, Valett HM. 1996. Chapter 6: hyporheic zones. In: Hauer FR, Lamberti GA, editors. *Methods in stream ecology*. Academic Press. p 107-19.
- Davis JC. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. *J Fish Res Board Can* 32:2295-332.
- [DWR] California Department of Water Resources. 1994. San Joaquin River tributaries spawning gravel assessment: Stanislaus, Tuolumne, Merced rivers. Draft memorandum prepared by the Department of Water Resources, Northern District, for the California Department of Fish and Game. Contract nr. DWR 165037.
- Gangmark HA, Bakkala RG. 1960. A comparative study of unstable and stable (artificial channel) spawning streams for incubating king salmon at Mill Creek. *California Fish and Game* 46:151-64.
- Lee DR, Cherry JA. 1978. A field exercise on groundwater flow using seepage meters and piezometers. *J Geol Edu* 27:6-10.
- Leitritz E, Lewis RC. 1980. Trout and salmon culture (hatchery methods). California Department of Fish and Game. *Fish Bulletin* 164.
- McNeil WJ. 1969. Survival of pink and chum salmon eggs and alevins. In: Northcote TG, editor. *Symposium on salmon and trout in streams*. Vancouver, BC: University of British Columbia Press. p 101-17.
- Price M. 1996. *Introducing groundwater*. London (UK): Chapman & Hall.

Silver SJ, Warren CE, Doudoroff P. 1963. Dissolved oxygen requirements of developing steelhead trout and chinook salmon embryos at different water velocities. *Trans Am Fish Soc* 92:327-43.

Sokal RR, Rohlf FJ. 1995. *Biometry: the principles and practice of statistics in biological research*. New York (NY): WH Freeman.

Sowden TK, Power G. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. *Trans Am Fish Soc* 114:804-12.

Tappel PD, Bjornn TC. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. *N Am J Fish Manage* 3:123-35.

Young MK, Hubert WA, Wesche TA. 1991. Selection of measures of substrate composition to estimate survival to emergence of salmonids and to detect changes in stream substrates. *N Am J Fish Manag* 11(3):339-46.

Notes

George Neillands. California Department of Fish and Game fishery biologist, Fresno, California. Personal communication with the author on 23 January 1997.

Distribution and Abundance of Chinook Salmon and Resident Fishes of the Lower Tuolumne River, California

Tim Ford and Larry R. Brown

Abstract

The Tuolumne River chinook salmon (*Oncorhynchus tshawytscha*) population represents one of the southernmost populations of the species and is of considerable management interest. This paper compiles and analyzes data available through 1997 for chinook salmon and other fish species occurring in the lower Tuolumne River. Estimates of adult fall-run chinook salmon varied from about 100 to 130,000 from 1940 to 1997 (mean: 18,300; median: 7,100). Age composition varied widely from 1981 to 1997; however, three-year-old fish usually dominated the population. The percentage of females in the population varied from 25% to 67% during 1971–1997. The percentage of tagged adult salmon increased from less than 2% before 1987 to an average of 20% during 1992–1997. Density of juvenile chinook salmon generally declined each year after a winter peak in fry abundance. Average, minimum, and maximum fork length of juvenile chinook salmon typically increased after February; although, declines occurred in some years because of large captures of fry in late spring. Few juvenile chinook salmon resided in the river over the summer during 1988–1993. A total of 33 taxa of fish (12 native and 21 introduced), including chinook salmon, was captured during various sampling programs. Native species were most frequent in upstream areas above river kilometer (rkm) 80. Introduced species dominated areas downstream of rkm 50. The resident fish community appeared to vary in response to annual differences in flow conditions with native species becoming more abundant in the year following a high flow year. There was no discernible seasonal change in fish communities when early summer (early June) and late summer (mid September) samples from the same sites were compared. Monitoring of the Tuolumne River chinook salmon population has provided valuable data on both chinook salmon and populations of other fish species.

Introduction

The chinook salmon (*Oncorhynchus tshawytscha*) populations in the tributaries to the San Joaquin River, including the Tuolumne River, constitute the southernmost extant populations of the species (Moyle 1976). The San Joaquin River tributary populations of fall-run chinook salmon, along with other Central Valley fall-run populations are presently considered candidate species under the federal Endangered Species Act (NMFS 1999). Even before candidate status, San Joaquin fall-run chinook salmon were of great management concern and were managed as a distinct stock. Historic declines in San Joaquin fall-run chinook salmon numbers and current threats to their survival have been attributed to a number of factors including habitat loss, habitat suitability, survival of emigrants, harvest, genetic effects of hatcheries, and water quality (USFWS 1995).

The earliest estimates of fall-run chinook salmon spawning escapement in the Tuolumne River date from 1940, with more detailed information collected since 1981. Since 1973, several other types of studies have been conducted within the lower 84 km of the Tuolumne River (from La Grange Dam to the confluence with the San Joaquin River) available for salmon spawning. Most of these studies have focused on winter-spring sampling when juvenile fall-run chinook salmon are abundant; but biologists have also gathered considerable data on the distribution and abundance of other fish species. A few studies have focused primarily on the resident fishes. The purpose of this paper is to compile and analyze data available through 1997 for chinook salmon and other fish species occurring in the lower Tuolumne River. The salmon data are clearly important to the proper management of Tuolumne River fall-run chinook salmon. Data on the other species can be used to develop understanding of interactions between salmon and other species, environmental conditions when salmon are not present, and the biology of species that become of management concern, such as splittail (*Pogonichthys macrolepidotus*, federally listed as threatened) and hardhead (*Mylopharodon conocephalus*, a California species of special concern) (Moyle and others 1995).

Methods

Adult Fall-run Chinook Salmon

Chinook salmon spawning runs in the Tuolumne River have been monitored to some degree since 1940, with estimates of adult escapement available for all years since 1951. Counts of migrating adult salmon were made at a weir in Modesto at river kilometer (rkm) 25.9 by the California Department of Fish and Game (DFG) in 1940, 1941 (partial count), 1942, and 1944, and by the U.S. Fish and Wildlife Service (USFWS) in 1946 (Fry 1961). DFG conducted carcass surveys for estimating escapements after 1946 (Fry 1961; Fry and Petrovich 1970), except that no estimate was made in 1950 due to an early flood. The results of spawning surveys since 1971 are described in a series of reports submitted by Turlock and Modesto irrigation districts (TID and MID) as part of the Federal Energy Regulation Commission (FERC) license process (EA 1991, 1997; TID and MID 1998). Tagging of some carcasses to obtain information on carcass recovery rates began in 1967, and since 1979, the DFG estimates are based on variations of Peterson or Schaefer mark-recapture formulas.

Carcass surveys were generally conducted in the reach of the Tuolumne River from La Grange at rkm 81.6 downstream to rkm 54.6 (Reed Rock Plant or Nielsen Ranch) just upstream of Waterford (Figure 1). Within this reach, data were segregated into three smaller sections that have varied over time. Since 1981 these sections have been divided at Basso Bridge (rkm 76.4) and Turlock Lake State Recreation Area (rkm 67.4). In some years, additional reaches were surveyed, including an upstream reach from rkm 81.6 to rkm 83.1 near La Grange Powerhouse and/or a downstream reach from rkm 54.6 to rkm 42.0 near Geer Road. Since 1981, population estimates for river sections not included in weekly carcass surveys were usually estimated by counting the number of redds in the section and then multiplying by the number of salmon per redd observed in the surveyed sections.

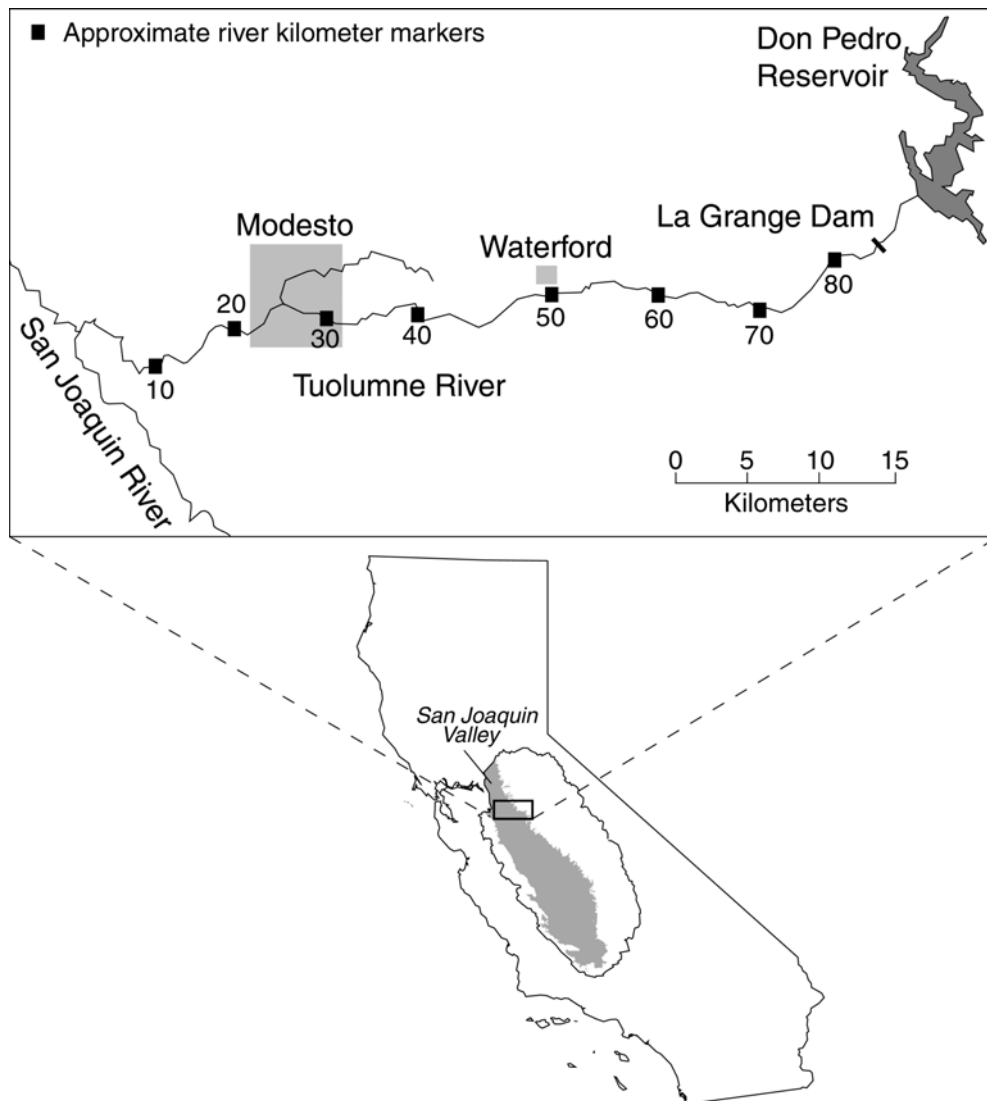


Figure 1 Location map for the lower Tuolumne River, California

DFG conducted weekly carcass surveys, generally by boat, using two- or three-person crews. Salmon carcasses were recovered by gaff for tagging and examination. Carcass mark-recapture sampling was conducted by attaching a marker to the upper jaw of some of the carcasses with a metal hog ring. Tagged carcasses were released in moving water for recovery during subsequent surveys. All other carcasses, including those marked with tags from earlier releases, were counted and chopped by machete to avoid double counts. Before 1988, only fresh carcasses were used for tagging and recovery. Beginning in 1988, both fresh (indicated by clear eyes) and non-fresh carcasses

were tagged, with a distinction made between “adult salmon” and “grilse” (two-year olds). Carcasses under 60 cm fork length (FL) (considered grilse) were not tagged. From 1989 to 1991, fresh grilse carcasses were also tagged, but non-fresh grilse were not. Beginning in 1992, all carcasses were tagged. Fork length, sex, and condition (fresh or non-fresh) of measured carcasses were recorded. Snouts of carcasses possibly having coded-wire tags (CWT), externally indicated by a missing adipose fin, were saved for tag recovery. Redd counts for individual riffles and live salmon counts for the survey reach were also recorded. The annual survey periods are shown in Table 1.

Initial run timing was based on the first report, by TID and MID staff, of adult salmon near La Grange. Age composition of the run was estimated from visual examination of length frequency histograms for each sex. A spawning use index was calculated from redd counts in carcass survey sections using the following formula.

$$\text{Spawning use index} = \frac{\% \text{ of total redds in a survey section}}{\% \text{ of total stream length surveyed in that section}}$$

Juvenile Fall-run Chinook Salmon and Other Species

Winter-spring Seining Surveys

Winter-spring seining surveys for juvenile salmon were conducted annually by TID and MID in 1986–1997 (EA 1991, 1996; TID and MID 1998). The sampling interval and number of locations and sample periods varied depending on the year. These studies also documented the distribution and abundance of other fish species and represent the longest continuous juvenile salmon monitoring effort in the San Joaquin River system, upstream of the Sacramento-San Joaquin Delta.

The locations sampled each year are shown in Table 2. Seining was conducted with 1.2 to 1.8 m high, 3.2 mm mesh nylon seine nets in lengths of 6.1, 9.1, or 15.2 m. The same general areas were sampled during each visit during a given year to facilitate comparative analysis throughout the sampling period. Sample areas varied somewhat as a result of changes in flow. Seine hauls were generally made in the direction of the current and parallel to shore, although offshore-to-onshore hauls were sometimes used. In general, three hauls were made during each visit to a site. The three hauls sampled an area of approximately 140 to 186 m².

Table 1 Salmon survey periods, peak live counts, and arrival dates^a

| Year | Survey dates | | Peak live count | | Population estimate (x 1,000) | Peak live percentage (%) | Date fish first observed at La Grange |
|---|--------------|--------|-----------------|--------|----------------------------------|--------------------------|---------------------------------------|
| | Start | End | Date | No. | | | |
| 1940 | 26 Sep | 02 Dec | 04 Nov | 5,447 | 122.0 | 4.5 | --- |
| 1941 | 21 Sep | 18 Nov | 13 Nov | 2,807 | 27.0 | 10.4 | --- |
| 1942 | 13 Sep | 30 Nov | 01 Nov | 3,386 | 44.0 | 7.7 | --- |
| 1944 | 30 Sep | 30 Nov | 06 Nov | 10,039 | 130.0 | 7.7 | --- |
| 1946 | 11 Oct | 20 Nov | 04 Nov | 6,002 | 61.0 | 9.8 | --- |
| -- No data available from 1947 to 1956 -- | | | | | | | |
| 1957 | 05 Nov | 03 Jan | --- | --- | 8.0 | --- | -- |
| 1958 | 06 Nov | 09 Jan | --- | --- | 32.0 | --- | --- |
| 1959 | 03 Nov | 01 Jan | --- | --- | 46.0 | --- | --- |
| 1960 | 12 Nov | 13 Jan | --- | --- | 45.0 | --- | --- |
| 1961 | --- | --- | --- | --- | 0.5 | --- | --- |
| 1962 | 08 Nov | 04 Jan | --- | --- | 0.2 | --- | --- |
| 1963 | 10 Feb | --- | --- | --- | 0.1 | --- | --- |
| 1964 | 04 Nov | 18 Dec | --- | --- | 2.1 | --- | --- |
| 1965 | 19 Nov | 12 Jan | --- | --- | 3.2 | --- | --- |
| 1966 | 08 Nov | 18 Jan | 09 Nov | 271 | 5.1 | 5.3 | --- |
| 1967 | 18 Oct | 13 Jan | 21 Nov | 184 | 6.8 | 2.7 | --- |
| 1968 | 11 Nov | 15 Dec | 22 Nov | 1,490 | 8.6 | 17.3 | --- |
| 1969 | 20 Nov | 12 Jan | --- | --- | 32.2 | --- | --- |
| 1970 | 19 Nov | 20 Jan | 20 Nov | 1,517 | 18.4 | 8.2 | --- |
| 1971 | 15 Nov | 27 Dec | 16 Nov | | 21.9 | 9.7 | --- |
| 1972 | 13 Nov | 23 Jan | 27 Nov | 349 | 5.1 | 6.8 | --- |
| 1973 | 05 Nov | 17 Jan | --- | --- | 2.0 | --- | --- |
| 1974 | --- | --- | --- | --- | 1.2 | --- | --- |
| 1975 | 06 Nov | 31 Dec | 06 Nov | 154 | 1.6 | 9.6 | --- |

^a Data for 1940–1946 are from Modesto; all later count data are from weekly carcass surveys in the spawning reach. Dashes (--) indicate no data. Population estimates are subject to revision.

Table 1 Salmon survey periods, peak live counts, and arrival dates^a (Continued)

| Year | Survey dates | | Peak live count | | Population estimate (x 1,000) | Peak live percentage (%) | Date fish first observed at La Grange |
|---------------------------|--------------|--------|-----------------|-------|----------------------------------|--------------------------|---------------------------------------|
| | Start | End | Date | No. | | | |
| 1976 | 03 Nov | 29 Dec | 15 Nov | 241 | 1.7 | 14.2 | --- |
| 1977 | 29 Nov | 20 Dec | --- | --- | 0.5 | --- | --- |
| 1978 | 26 Oct | 19 Dec | 24 Nov | 81 | 1.3 | 6.2 | --- |
| 1979 | 05 Nov | 17 Dec | 02 Nov | 153 | 1.2 | 12.8 | --- |
| 1980 | 12 Nov | 18 Dec | 12 Nov | 112 | 0.6 | 18.7 | --- |
| 1981 | 04 Nov | 16 Dec | --- | --- | 14.3 | --- | 14 Oct |
| 1982 | 08 Nov | 29 Nov | 15 Nov | 545 | 7.1 | 7.7 | 29 Sep |
| 1983 | 07 Nov | 01 Dec | 15 Nov | 263 | 14.8 | 1.8 | 13 Oct |
| 1984 | 01 Nov | 30 Nov | 01 Nov | 1,084 | 13.8 | 7.9 | 04 Oct |
| 1985 | 29 Oct | 20 Dec | 12 Nov | 2,986 | 40.3 | 7.4 | 24 Sep |
| 1986 | 27 Oct | 05 Dec | 03 Nov | 1,123 | 7.3 | 15.4 | 10 Sep |
| 1987 | 28 Oct | 16 Dec | 17 Nov | 2,155 | 14.8 | 14.6 | 06 Oct |
| 1988 | 25 Oct | 29 Dec | 14 Nov | 1,066 | 6.3 | 16.9 | 17 Oct |
| 1989 | 24 Oct | 29 Dec | 09 Nov | 291 | 1.3 | 22.8 | 15 Oct |
| 1990 | 23 Oct | 26 Dec | 19 Nov | 44 | 0.1 | 45.8 | 24 Oct |
| 1991 | 22 Oct | 02 Jan | 25 Nov | 24 | 0.1 | 45.3 | 06 Nov |
| 1992 | 05 Nov | 21 Dec | 19 Nov | 49 | 0.1 | 38.3 | 31 Oct |
| 1993 | 14 Oct | 18 Dec | 06 Nov | 94 | 0.4 | 24.2 | 26 Sep |
| 1994 | 03 Nov | 05 Jan | 21 Nov | 226 | 0.5 | 45.2 | 26 Oct |
| 1995 | 27 Oct | 30 Dec | 03 Nov | 270 | 1.0 | 27.0 | 05 Oct |
| 1996 | 22 Oct | 04 Dec | 31 Oct | 636 | 3.3 | 19.3 | -- |
| 1997 | 14 Oct | 23 Dec | 12 Dec | 1258 | 7.2 | 17.5 | 09 Oct |
| 1971–1997 cumulative data | | | | | | | |
| First | 14 Oct | 29 Nov | 31 Oct | --- | --- | --- | 10 Sep |
| Last | 29 Nov | 23 Jan | 27 Nov | --- | --- | --- | 06 Nov |
| Median | 02 Nov | 20 Dec | 11 Nov | --- | --- | --- | 11 Oct |

^a Data for 1940–1946 are from Modesto; all later count data are from weekly carcass surveys in the spawning reach. Dashes (--) indicate no data. Population estimates are subject to revision.

Table 2 Primary winter-spring seining locations for each year of sampling^a

| Location | River kilometer | Year | | | | | | | | | | | | |
|------------------------------|-----------------|------|----|----|----|----|----|----|----|----|----|----|----|----|
| | | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | |
| Old La Grange Bridge | 81.3 | X | X | X | X | X | X | X | X | X | -- | -- | X | X |
| Riffle 4B | 77.9 | X | X | X | X | X | X | -- | -- | -- | X | X | X | X |
| Riffle 5 | 77.1 | -- | X | X | X | X | X | X | X | X | -- | -- | -- | -- |
| Tuolumne River Resort | 68.2 | -- | -- | X | X | X | X | X | X | X | X | X | X | X |
| Turlock Lake State Rec. Area | 67.6 | X | X | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Reed Gravel | 54.7 | X | X | X | X | X | X | -- | -- | -- | -- | -- | -- | -- |
| Hickman Bridge | 50.8 | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Charles Road | 40.1 | -- | X | X | X | X | X | X | X | -- | -- | -- | X | X |
| Legion Park | 27.7 | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Riverdale Park | 19.8 | -- | X | X | X | X | X | -- | -- | -- | -- | -- | -- | -- |
| McCleskey Ranch | 9.7 | X | X | X | X | X | X | X | X | X | -- | -- | -- | -- |
| Shiloh Bridge | 5.8 | X | X | X | X | X | X | -- | X | -- | X | X | X | X |
| Total locations | | 8 | 11 | 11 | 11 | 11 | 11 | 7 | 8 | 5 | 5 | 6 | 7 | |
| Mean interval (days) | | 9 | 7 | 10 | 11 | 10 | 21 | 28 | 18 | 19 | 19 | 21 | 15 | |
| Number of sample periods | | 18 | 21 | 14 | 13 | 14 | 8 | 5 | 7 | 7 | 8 | 8 | 10 | |

^a Mean interval is the mean number of days between samples. Dashes (--) indicate location not sampled.

Captured salmon were anesthetized, measured (FL in mm), and then revived before being released. If more than 100 salmon were caught, a random subsample of approximately 100 salmon was measured and the remaining salmon were counted and released. The number of fish caught, and fork lengths were recorded. Other fish species were counted and recorded separately.

Minimum, maximum, and average fork length of juvenile chinook salmon were plotted for each year and sample period. Density was calculated as the number of salmon captured per square meter of area seined. Seining data were stratified by river section and summed for the entire river. Three river sections were used for comparison: upper section (La Grange Powerhouse,

rkm 83.7 to rkm 59.5), middle section, and lower section (Dry Creek, rkm 26.4 to mouth, rkm 0).

All fish species other than chinook salmon were included in the analyses of resident fish species. Total catch was summarized as species percentage abundance for all fish captured in all samples. Seining data were used for three types of analyses: frequency of occurrence of species at specific sites along the river, number of species captured per sampling effort, and resident fish assemblage structure.

Frequency of occurrence was determined on the basis of the number of samples collected at a site, from 1986 to 1997. Frequency of occurrence was the percentage of the total number of samples that included a particular species. The total number of samples at a site varied from 33 to 129. For each sample at each site, the number of species captured other than chinook salmon was determined. A mean value and standard deviation was then calculated for each site based on all samples from all years of sampling.

Assemblage structure of the resident fishes was described using detrended correspondence analysis (DCA). DCA is a multivariate ordination technique based on reciprocal averaging that results in an ordination of species based on occurrence at sites and an ordination of sites based on the species assemblage at each site. DCA was conducted with species percentage data. Only sites sampled consistently through the study were included. Review of the data resulted in selection of eight sites for analysis. These sites were sampled consistently from 1987 to 1993 and then more sporadically through 1997. Because of the low number of species captured per sample, all fish captured at a site each year were combined into a single sample and then the percentage of each species in the combined sample calculated. Years when a site was sampled fewer than four times were excluded from analysis. Species were only included in the analysis if they were present in at least 10% of the samples and comprised at least 5% of the fish captured in at least one sample. One-way analysis of variance (ANOVA) was used to test for annual differences in mean site scores on DCA axes 1 and 2.

Fyke Netting

Winter-spring fyke netting for juvenile salmon was conducted by the USFWS in 1973, 1974, 1977, and 1980. DFG performed the sampling in 1981, 1982, 1983, and 1986 (EA 1991). The locations and sampling periods are in Table 3. The fyke nets used were 7.6 m long with a 0.9 x 1.5 m opening and 12.2 m long with a 1.5 x 2.7 m opening. The variable mesh netting tapered to 0.3 x 0.3 m at the cod end into an attached aluminum holding box. Nets were usually deployed for two to four nights per week and checked once every 24 hours. The number and size of captured juvenile salmon were recorded as was the

number of individuals of other fish species. Resident fish captured during fyke netting were summarized as percentage abundance of each species captured at each site for each year of sampling.

Table 3 Fyke net locations and sampling periods for each year sampled^a

| <i>Location</i> | <i>Rkm</i> | 1973 | 1974 | 1977 | 1980 | 1981 | 1982 | 1983 | 1986 |
|---------------------|------------|--------------|--------------|---------------|---------------|---------------|---------------|--------------|---------------|
| Turlock Lake SRA | 68.2 | 2/15– 6/8 | 2/13– 6/7 | 2/14– 5/18 | 1/28– 6/13 | 2/17– 5/14 | 1/19– 4/30 | 1/26– 6/1 | 2/05– 3/28 |
| Hickman Spill | 52.3 | -- | -- | -- | 3/27– 6/13 | -- | 1/19– 4/30 | -- | -- |
| Putnam Gravel | 49.2 | 2/14– 6/8 | 2/13– 6/7 | 2/14– 5/18 | -- | -- | -- | -- | -- |
| Charles Road | 40.2 | -- | -- | -- | 1/28 3/26 | -- | -- | -- | -- |
| McCleskey Ranch | 9.7 | 2/27– 6/8 | 2/13– 6/7 | 2/14– 5/18 | 1/28– 6/13 | -- | 2/1– 4/30 | -- | -- |

^a Dashes (--) indicate location not sampled.

Rotary Screw Traps

Springtime juvenile salmon sampling was conducted with two 2.44-meter diameter rotary screw traps (RST) in 1995 (26 April to 1 June) by TID and MID and in 1996 (18 April to 29 May) by DFG at rkm 5.8 (Shiloh Road) (EA 1997). Only one trap was fished after 19 May in 1995 and after 17 May in 1996. The traps were located out of the main current in 1995 due to high flows and floating debris. The 1996 deployment was in the main current.

The two traps were fished side-by-side and were usually checked in the morning and evening, except when more frequent checks were required to remove debris. All fish and debris were removed from the RSTs each time they were checked. The fish were separated by species and counted. All of the juvenile salmon, or a subsample, were measured. Lengths of other fish species were estimated or occasionally measured.

Salmon data were summarized as daily catch per trap, because one or two traps were fished at a time. Resident fish captured during rotary screw trapping were summarized as percentage abundance of each species captured each year.

Summer Surveys

Summer surveys of resident fishes were conducted, generally during May to September, from 1988 to 1994. Unlike other sampling efforts, which focused on chinook salmon, these surveys were designed to document the distribution of all fish species throughout the river (Table 4). Two other sampling methods, electrofishing and snorkeling, in addition to seining, provided a greater likelihood of capturing other fish species. Seining was only conducted in the first year, 1988, because few species were captured. Snorkeling was sometimes limited due to water clarity and generally was not effective downstream of rkm 40. Only snorkeling was conducted in 1994. All years included both “early summer” and “late summer” sampling periods (Table 5) when intensive sampling was conducted to detect the presence of juvenile chinook salmon.

Table 4 Summer survey locations for each year sampled^a

| <i>Location</i> | <i>Rkm</i> | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 |
|-----------------------------------|------------|------|------|------|------|------|------|------|
| Riffle A3 | 83.0 | X | X | X | X | X | X | X |
| Riffle A7 | 81.6 | X | X | X | -- | -- | -- | -- |
| Riffle 2 | 80.3 | X | X | X | X | X | X | X |
| Riffle 5 | 78.7 | X | X | X | X | X | -- | X |
| Riffle 9 | 74.7 | X | X | X | X | X | X | X |
| Riffle 23BC | 68.1 | X | X | X | X | X | -- | -- |
| Riffle 33 | 62.3 | X | X | X | -- | -- | -- | -- |
| Riffle 39/40 | 57.8 | X | X | X | X | X | X | X |
| Riffle 53 | 51.5 | X | -- | -- | -- | -- | -- | -- |
| Riffle 58 | 50.7 | -- | X | X | X | X | X | X |
| Charles Road | 40.1 | X | X | X | X | X | X | X |
| Legion Park | 29.3 | X | X | X | -- | -- | -- | -- |
| Riverdale Park | 19.8 | X | X | X | X | X | -- | -- |
| McCleskey Ranch | 9.7 | X | X | X | -- | -- | -- | -- |
| Shiloh Bridge | 5.8 | X | X | X | X | X | X | -- |
| Total number of locations sampled | | 14 | 14 | 14 | 10 | 10 | 7 | 7 |

^a Dashes (--) indicate not sampled.

Table 5 Primary summer survey sampling periods

| <i>Year</i> | <i>Early summer</i> | <i>Late summer</i> |
|-------------|---------------------|--------------------|
| 1988 | 05 May – 02 Jun | 20 – 22 Sep |
| 1989 | 23 May – 02 Jun | 05 – 15 Sep |
| 1990 | 28 May – 06 Jun | 18 – 28 Sep |
| 1991 | 10 – 14 Jun | 06 – 13 Sep |
| 1992 | 01 – 10 Jun | 21 – 29 Sep |
| 1993 | 07 – 10 Jun | 25 – 27 Oct |
| 1994 | 13 – 14 Jul | 03 – 04 Oct |

Snorkeling was conducted by one or more persons. Observers would proceed through a specified area and record on dive slates the species, numbers, and sizes of all fish observed. In 1988, electrofishing was conducted with a Smith-Root Model 12 backpack electroshocker. In all other years, a gas-powered DC generator mounted on a tow barge with three hand-held anodes was used. Block nets were sometimes used to isolate sample areas. Stream reaches snorkeled and electrofished ranged from 50 to 150 m in length.

Salmon catch data from the primary sampling periods were summarized by sampling method, date, and location. For the other species, total catch for each sampling method was summarized as percentage abundance of species using data from all samples. Snorkeling and electrofishing data were used in additional resident fish analyses.

Frequency of occurrence was calculated as described for the winter-spring seining data. Only sites sampled at least five times were included in frequency of occurrence analyses. Analysis of the number of species captured per sampling effort was also calculated as described for the seining data.

Assemblage structure of the resident fishes was described using detrended correspondence analysis (DCA) of the electrofishing data, as described for the seining data. A total of 10 sites was sampled consistently and included in the analysis. To determine if there were any seasonal changes in fish assemblage structure, analyses were conducted using two samples per year. An early summer sample was defined as the sample collected closest to 1 June of each year. A late summer sample was defined as the sample collected closest to mid-September of each year. Two-way ANOVA was used to test for annual and seasonal (that is, early versus late summer) differences in site scores on DCA axes 1 and 2.

Results

Adult Fall-run Chinook Salmon

Since 1940, the salmon runs varied from about 100 to 130,000 with an average estimate of 18,300 and a median estimate of 7,100 (Figure 2, Table 6). The date of the first observation of adult salmon at La Grange ranged from 10 September to 6 November with a median of 11 October for the period 1981–1997 (Table 1). The peak weekly count of live salmon during 1971–1997 ranged from 31 October to 27 November with a median date of 11 November.

Age composition of the 1981–1997 runs varied widely (Figure 3). Occasionally a strong year class would dominate consecutive years (arriving as two-year olds the first year and three-year olds the second) such as occurred in 1981–1982, 1987–1988, and 1996–1997. From 1981–1997 there were six years when two-year olds were most abundant and 11 years when three-year olds were most abundant. Four-year olds were always less than one-third of the 1981–1997 runs and five-year olds were always less than 5%.

The percentage of females varied from 25% to 67% during the period 1971–1997 (Figure 4). Sex composition varied with the age composition. Years with a high percentage of two-year olds tended to have a lower percentage of females (Figure 5). The percentage of adult salmon with coded-wire tags increased from less than 2% before 1987 up to an average of 20% during 1992–1997 (Figure 6). Redd counts during 1981–1997 varied from 51 to 3,034 (Table 7). Spawning use indices varied from 2.85 to 0.27, declining in a downstream direction (Table 7).

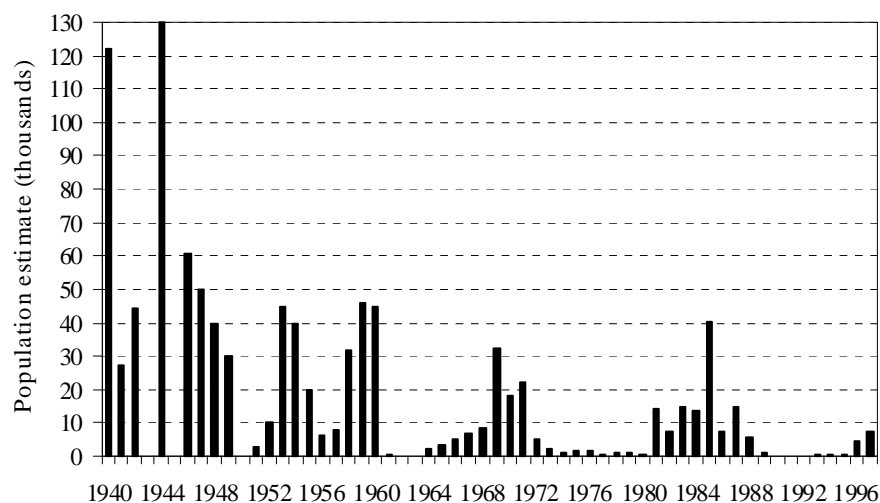


Figure 2 Estimates of adult fall-run chinook salmon in the Tuolumne River. There was only a partial count in 1941 and no counts in 1943, 1945, and 1950.

Table 6 Tuolumne River adult fall-run chinook salmon population estimates^a

| <i>Year</i> | <i>Population estimate (x 1,000)</i> | <i>Year</i> | <i>Population estimate (x 1,000)</i> | <i>Year</i> | <i>Population estimate (x 1,000)</i> |
|-------------|--------------------------------------|-------------|--------------------------------------|-------------|--------------------------------------|
| 1940 | 122.0 | 1960 | 45.0 | 1980 | 0.6 |
| 1941 | 27.0 | 1961 | 0.5 | 1981 | 14.3 |
| 1942 | 44.0 | 1962 | 0.2 | 1982 | 7.1 |
| 1943 | -- | 1963 | 0.1 | 1983 | 14.8 |
| 1944 | 130.0 | 1964 | 2.1 | 1984 | 13.8 |
| 1945 | -- | 1965 | 3.2 | 1985 | 40.3 |
| 1946 | 61.0 | 1966 | 5.1 | 1986 | 7.3 |
| 1947 | 50.0 | 1967 | 6.8 | 1987 | 14.8 |
| 1948 | 40.0 | 1968 | 8.6 | 1988 | 6.3 |
| 1949 | 30.0 | 1969 | 32.2 | 1989 | 1.3 |
| 1950 | -- | 1970 | 18.4 | 1990 | 0.1 |
| 1951 | 3.0 | 1971 | 21.9 | 1991 | 0.1 |
| 1952 | 10.0 | 1972 | 5.1 | 1992 | 0.1 |
| 1953 | 45.0 | 1973 | 2.0 | 1993 | 0.5 |
| 1954 | 40.0 | 1974 | 1.2 | 1994 | 0.5 |
| 1955 | 20.0 | 1975 | 1.6 | 1995 | 0.7 |
| 1956 | 6.0 | 1976 | 1.7 | 1996 | 4.6 |
| 1957 | 8.0 | 1977 | 0.5 | 1997 | 7.1 |
| 1958 | 32.0 | 1978 | 1.3 | | |
| 1959 | 46.0 | 1979 | 1.2 | | |

^a There was only a partial count done in 1941 and no counts done in 1943, 1945, and 1950.

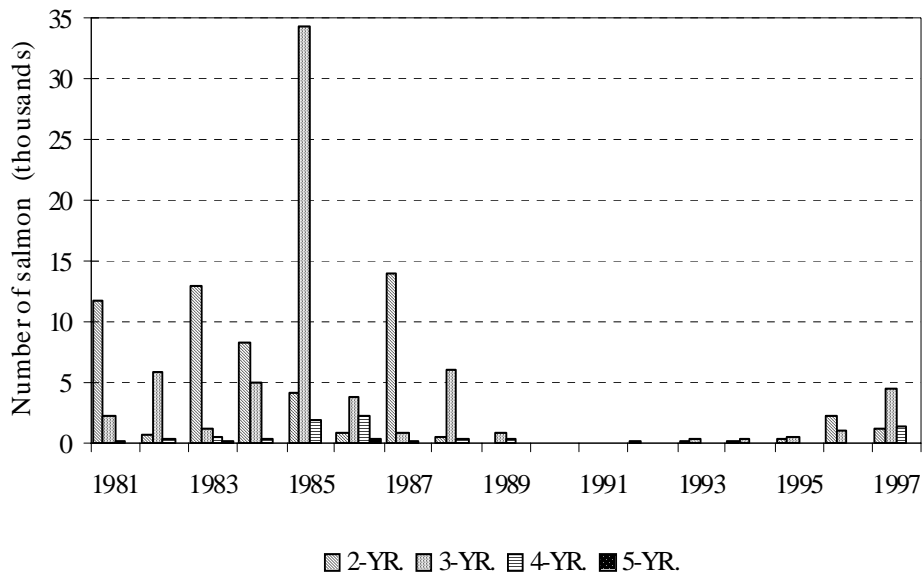
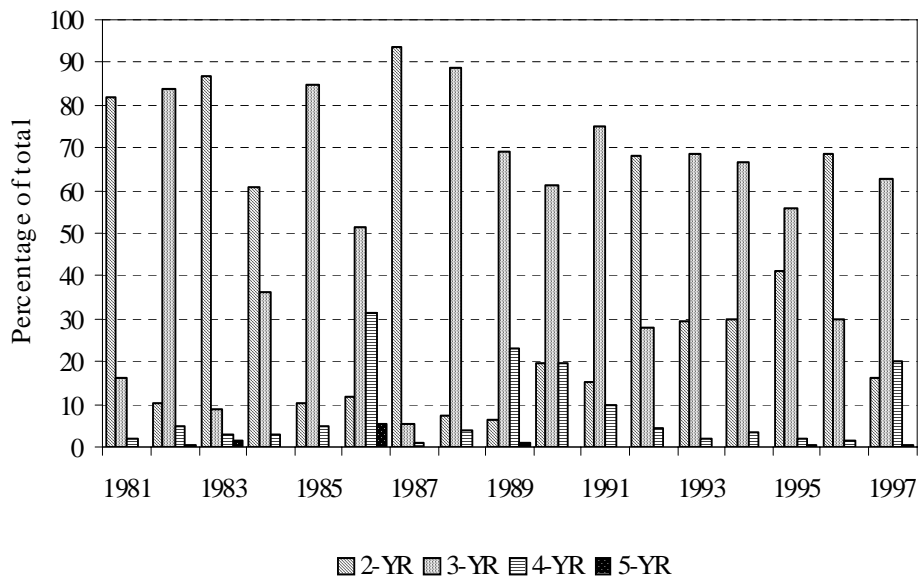


Figure 3 Estimated percentage and number of age classes in salmon runs based on fork length frequencies

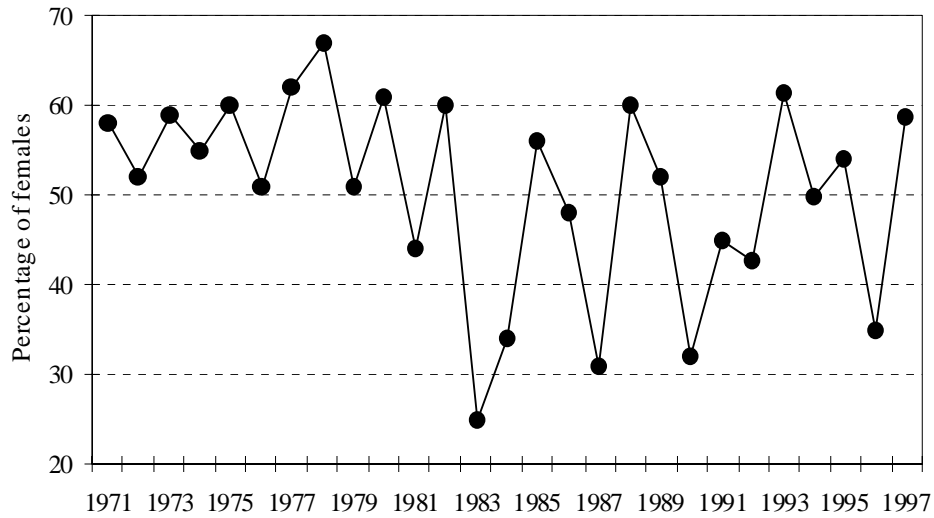


Figure 4 Percentage of females in Tuolumne River salmon runs

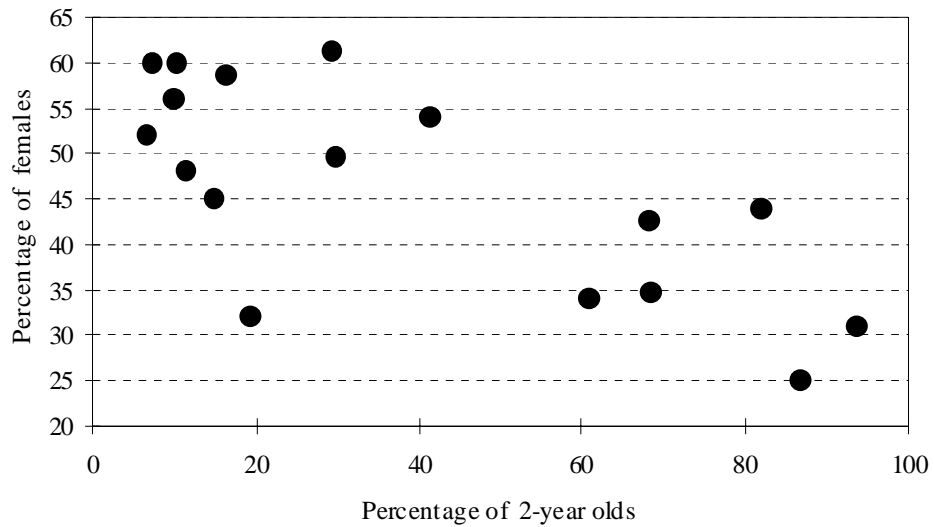


Figure 5 Percentage of females plotted against estimated percentage of two-year olds for 1981–1997 salmon runs

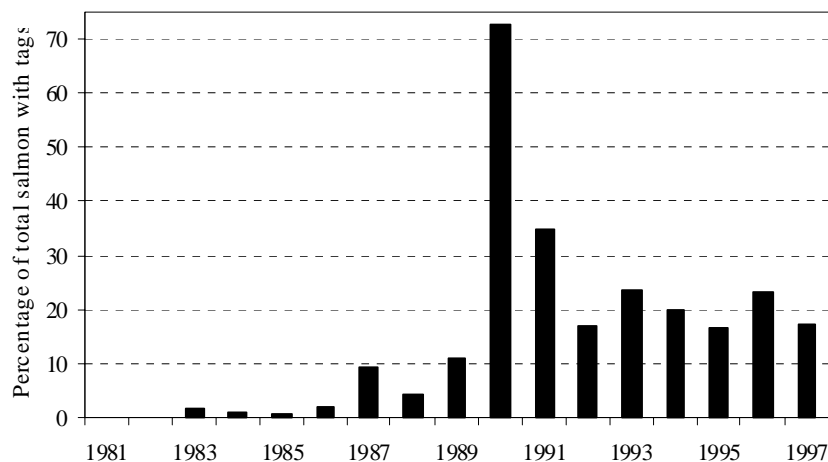


Figure 6 Estimated percentage of adult salmon with coded-wire tags in 1981–1997 salmon runs

Table 7 Total redd counts for each survey reach and the entire spawning reach^a

| Year | Survey reach (rkm to rkm) | | | | | No. of redds counted | Estimated no. of females | Females per redd |
|--|---------------------------|-------------|-------------|-------------|-------------|----------------------|--------------------------|------------------|
| | 42.0 – 54.6 | 54.6 – 67.4 | 67.4 – 76.4 | 76.4 – 81.6 | 81.6 – 83.1 | | | |
| 1981 | 137 | 440 | 461 | 510 | 128 | 1,676 | 6,292 | 3.8 |
| 1982 | -- | 218 | 308 | 467 | 106 | 1,099 | 4,200 | 3.8 |
| 1983 | 18 | 155 | 180 | 110 | 2 | 465 | 3,700 | 8.0 |
| 1984 | 37 | 265 | 428 | 358 | 55 | 1,143 | 4,658 | 4.1 |
| 1985 | 140 | 605 | 874 | 1,230 | 185 | 3,034 | 22,568 | 7.4 |
| 1986 | 68 | 365 | 271 | 428 | 116 | 1,248 | 3,792 | 3.0 |
| 1987 | 77 | 209 | 216 | 246 | 102 | 850 | 4,619 | 5.4 |
| 1988 | 376 | 431 | 402 | 552 | 141 | 1,902 | 4,080 | 2.1 |
| 1989 | 76 | 149 | 130 | 181 | 48 | 584 | 676 | 1.2 |
| 1990 | 6 | 21 | 21 | 10 | 0 | 58 | 28 | 0.5 |
| 1991 | 7 | 13 | 9 | 16 | 6 | 51 | 27 | 0.5 |
| 1992 | 10 | 7 | 7 | 17 | 12 | 53 | 55 | 1.0 |
| 1993 | 17 | 49 | 61 | 78 | 45 | 250 | 238 | 1.0 |
| 1994 | 21 | 82 | 95 | 79 | 45 | 322 | 249 | 0.8 |
| 1995 | 25 | 56 | 61 | 48 | 39 | 229 | 522 | 2.3 |
| 1996 | 19 | 58 | 84 | 125 | 57 | 343 | 1,139 | 3.3 |
| 1997 | 26 | 171 | 272 | 404 | 108 | 981 | 4,224 | 4.3 |
| Mean percentage of redds in survey reach | | | | | | | | |
| | 8.4% | 23.7% | 26.5% | 31.0% | 10.4% | | | |
| Spawning use index for survey reach | | | | | | | | |
| | 0.27 | 0.76 | 1.21 | 2.45 | 2.85 | | | |

^a The ratio of female salmon to the number of redds is given for the entire spawning reach. The use index (% redds / % length) was calculated using data summed over all years.

Juvenile Fall-run Chinook Salmon

Density of juvenile salmon, as determined from winter-spring seining, declined each year after a winter peak in fry abundance (Figure 7). Juvenile salmon were abundant in the lower river section below Dry Creek (rkm 26.4) only in the high flow years of 1986, 1995, and 1997 (Figures 8 and 9). All measures of juvenile salmon size typically increased after February (Figures 10, 11, and 12), although in some years average size declined from April to May (Figure 10), because large numbers of smaller fry were captured.

The catch rate of the rotary screw traps was lower in 1995 than in 1996 (Figure 13). Peaks in juvenile salmon abundance were less obvious in 1995 compared to 1996.

No juvenile salmon were captured during the summer flow study in 1991, 1992, and 1994 (Table 8). Most juvenile salmon were captured in the early period with the largest catches upstream of rkm 74. Few juvenile salmon were captured in the late sampling as compared to the early periods. All but one of the juvenile salmon observed during the late period were found upstream of rkm 74.

Resident Fishes

A total of 33 taxa of fish, including chinook salmon, was captured during the various sampling programs (Table 9). Of the 33 taxa, 12 taxa are native to California and 21 are introduced. All lampreys captured were identified as Pacific lamprey; however, not every individual was examined in detail and it is possible that river lamprey (*Lampetra ayersi*) was also present. Similarly, several black bullheads (*Ameiurus melas*) were identified but the remaining *Ameiurus* species were combined into the general category of bullhead catfish.

The six methods of sampling used in the studies varied in effectiveness with regard to the capture of resident fish species. Winter-spring methods included seining, rotary screw trapping and fyke netting. Winter-spring seining generally caught few species in addition to chinook salmon during any single sampling effort (Figure 14). Mean number of species captured per sampling period varied from 1.0 to 2.4 species with standard deviations ranging from 0.8 to 1.2. However, over the course of the study winter-spring seining captured 28 of the 33 taxa present in the river (Table 10). Rotary screw trapping at rkm 5.6 resulted in a mean of 2.4 species (standard deviation 1.8) captured per sampling effort (usually daily), which was comparable to the seining results for that site (mean = 2.0, standard deviation = 1.2). Rotary screw trapping captured about 23 taxa; however, there may have been additional species included in some of the general categories used (Table 11). Fyke netting also captured few species during any single sampling effort with the mean number of species captured at the five sites ranging from 1.1 to 1.7. Standard deviations ranged from 1.0 to 1.5. Fyke netting captured about 27 taxa (Tables 12 and 13).

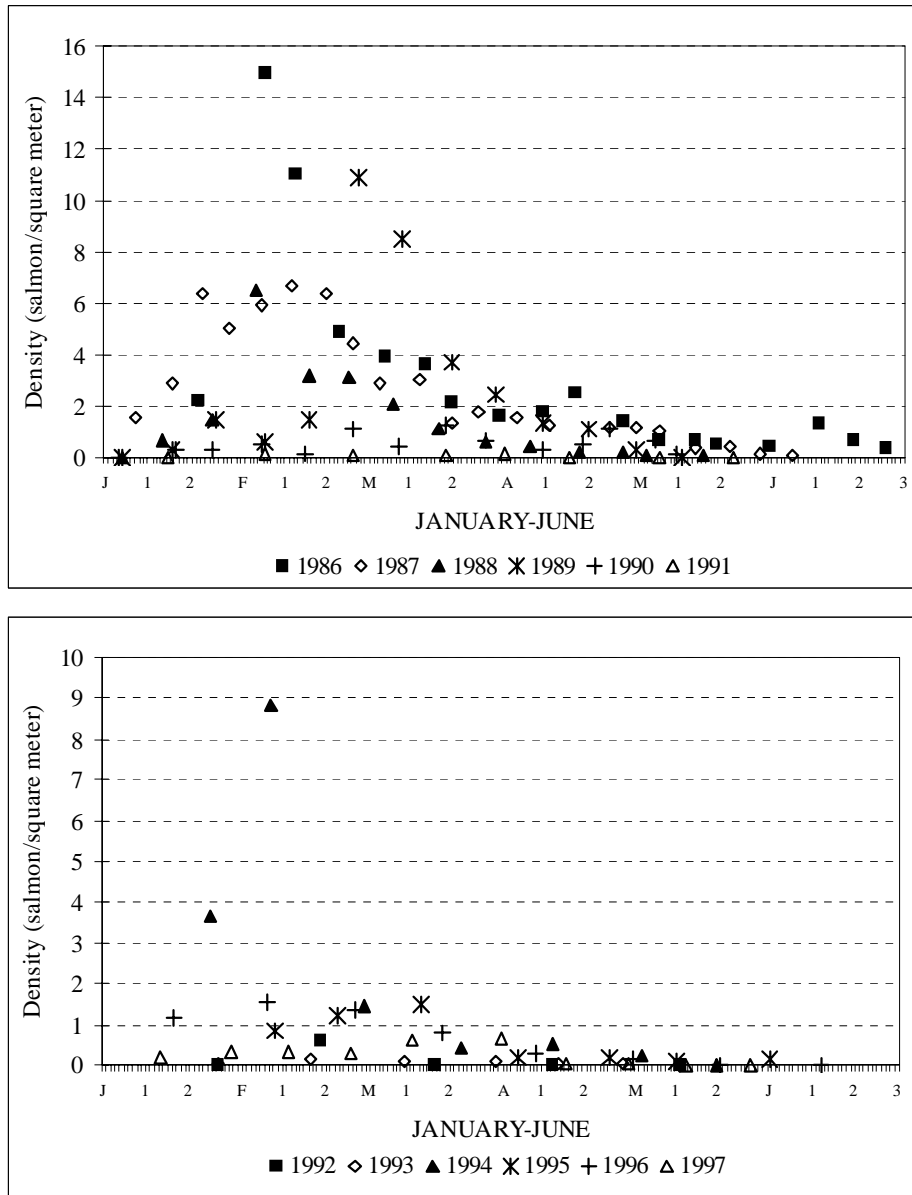


Figure 7 Densities of salmon from seining surveys from 1986 to 1997

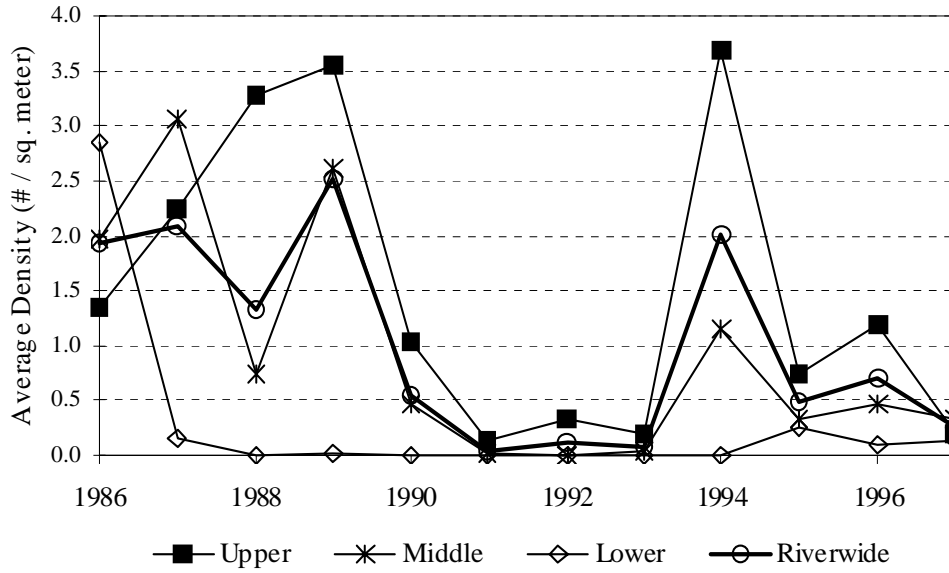


Figure 8 Densities of juvenile salmon captured during seining surveys for upper, middle, and lower sections of the river and for the entire river

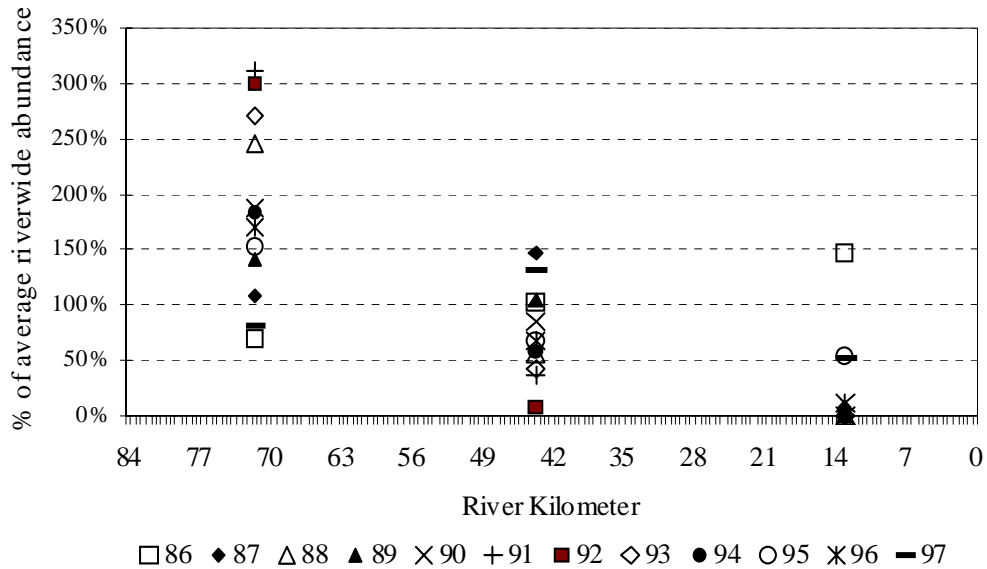


Figure 9 Densities of juvenile salmon in upper, middle, and lower sections standardized as percentage of the annual riverwide density and plotted at section midpoints

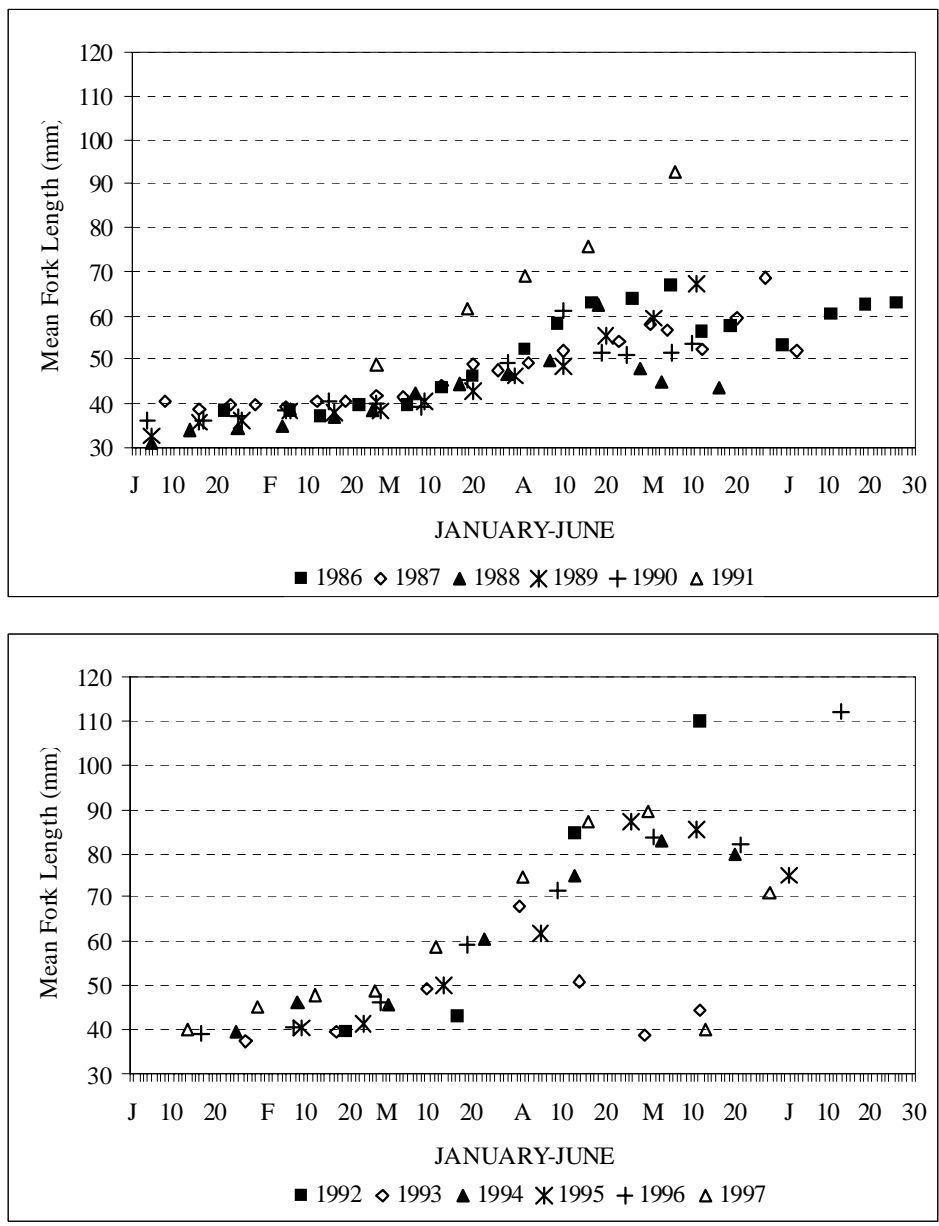


Figure 10 Mean fork length of salmon captured during seining surveys from 1986 to 1997

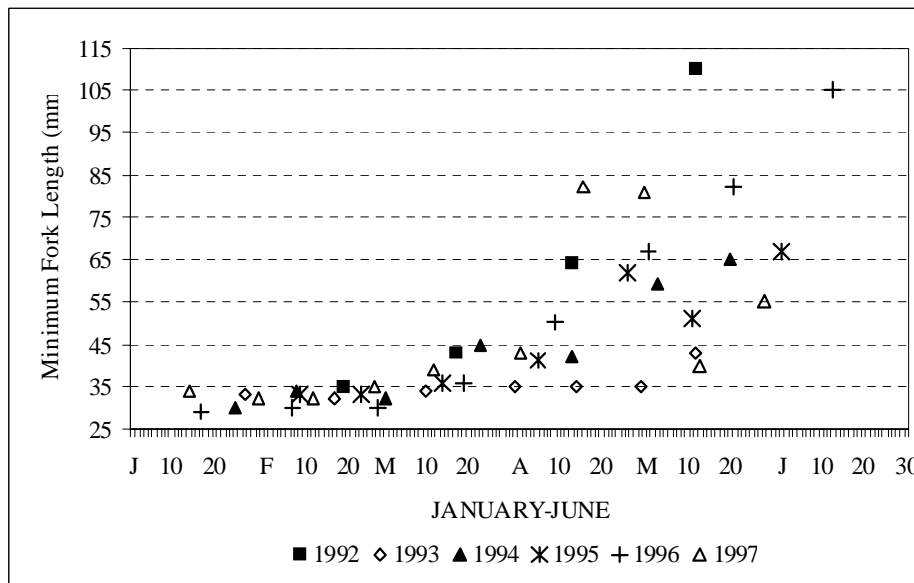
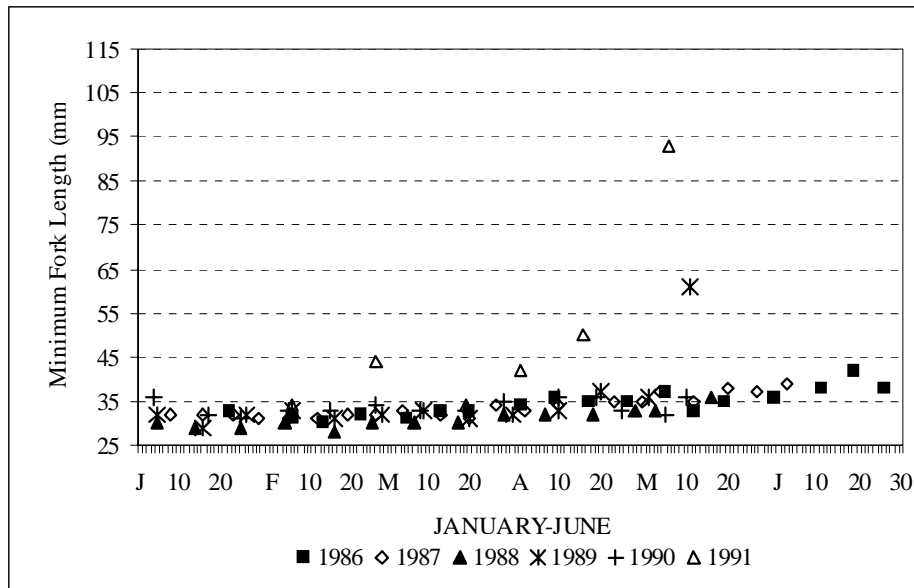


Figure 11 Minimum fork length of salmon captured during seining surveys from 1986 to 1997

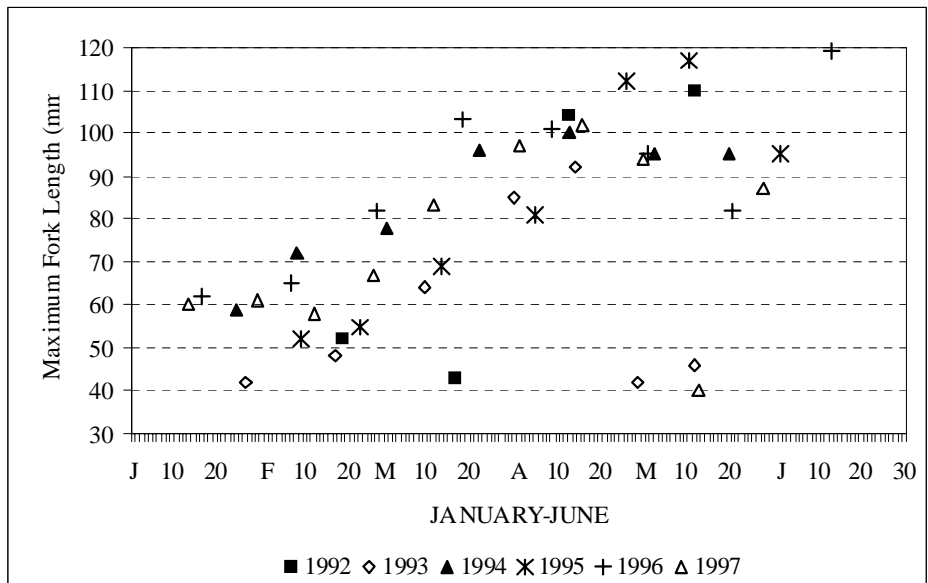
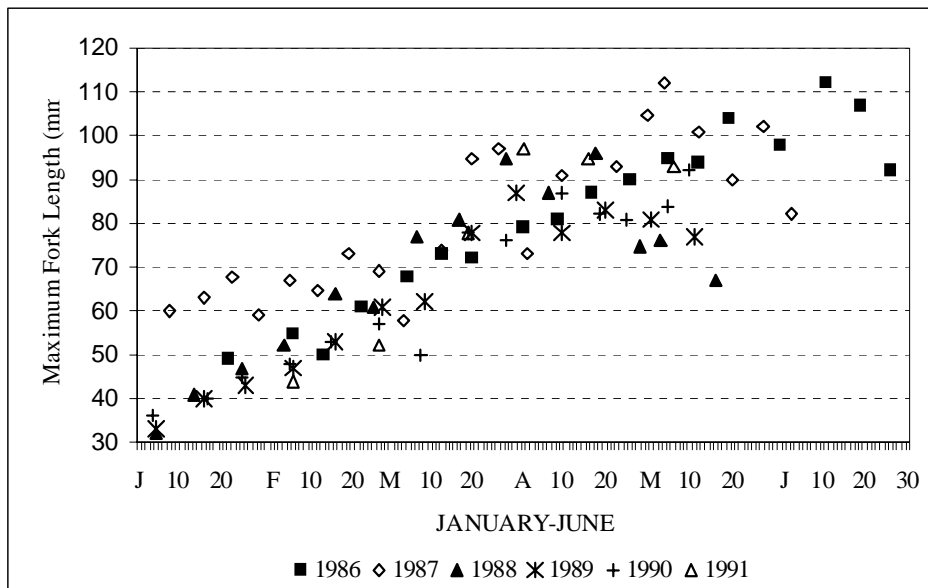
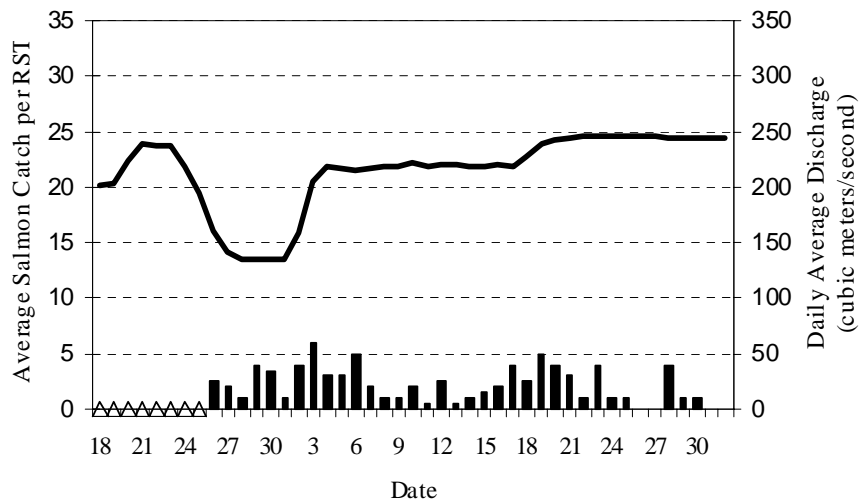
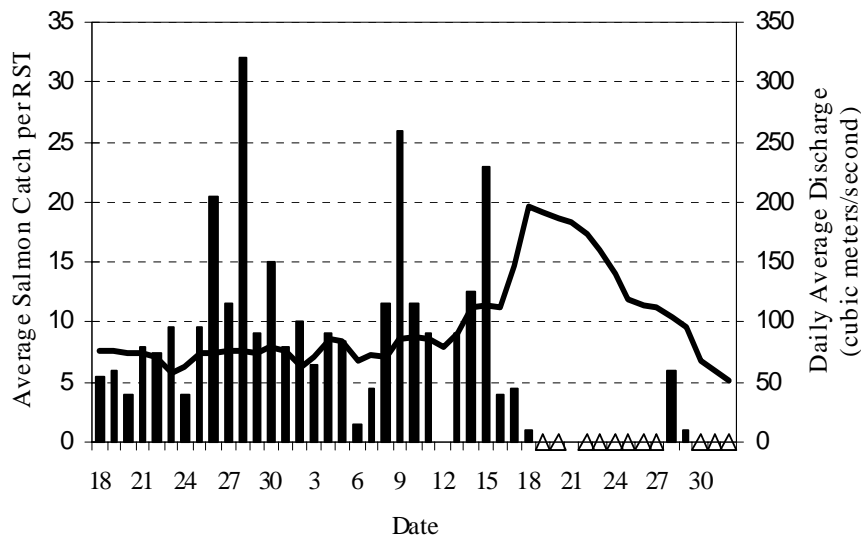


Figure 12 Maximum fork length of salmon captured during seining surveys from 1986 to 1997



■ 1995 Chinook Catch — La Grange Flow △ Not sampled



■ 1996 Chinook Catch — La Grange Flow △ Not sampled

Figure 13 Rotary screw trap salmon catch data from 1995 and 1996 at Shiloh Road (rkm 5.8) during 18 April to 1 June. Days when sampling did not occur are indicated by a triangle.

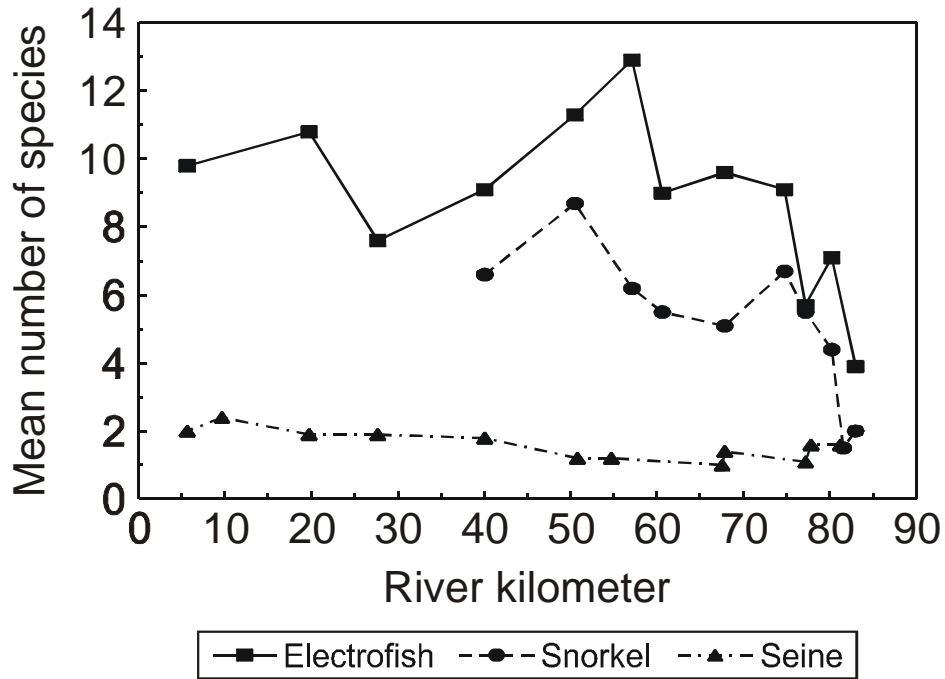


Figure 14 Mean number of species, excluding chinook salmon, captured during annual winter-spring seining and summer snorkeling and electrofishing

Table 8 Number of juvenile salmon captured during primary summer survey periods, listed by date, method, location, and river kilometer

| <i>Date</i> | <i>Sampling method</i> | <i>Location</i> | <i>River kilometer</i> | <i>Number captured</i> |
|-------------|------------------------|-----------------|------------------------|------------------------|
| 05 May 88 | Seine | RA3 | 83.0 | 3 |
| 05 May 88 | Snorkel | RA3 | 83.0 | 3 |
| 13 May 88 | Snorkel | OLGB | 81.3 | 22 |
| 06 May 88 | Seine | R2 | 80.3 | 1 |
| 06 May 88 | Snorkel | R2 | 80.3 | 1 |
| 13 May 88 | Snorkel | R3B | 79.0 | 1 |
| 13 May 88 | Snorkel | R4A | 78.5 | 1 |
| 13 May 88 | Snorkel | R4B | 77.9 | 1 |
| 24 May 88 | Electroshocking | R5 | 77.2 | 1 |
| 13 May 88 | Snorkel | R5 | 77.2 | 25 |
| 06 May 88 | Electroshocking | R5 | 77.2 | 8 |
| 06 May 88 | Snorkel | R5 | 77.2 | 104 |
| 11 May 88 | Electroshocking | R9 | 74.8 | 3 |
| 11 May 88 | Snorkel | R9 | 74.8 | 3 |

Table 8 Number of juvenile salmon captured during primary summer survey periods, listed by date, method, location, and river kilometer (Continued)

| <i>Date</i> | <i>Sampling method</i> | <i>Location</i> | <i>River kilometer</i> | <i>Number captured</i> |
|-------------|------------------------|-----------------|------------------------|------------------------|
| 11 May 88 | Seine | TRR | 67.9 | 1 |
| 12 May 88 | Snorkel | R33 | 60.7 | 1 |
| 23 May 89 | Electroshocking | RA3 | 83.0 | 2 |
| 23 May 89 | Snorkel | RA3 | 83.0 | 127 |
| 23 May 89 | Electroshocking | RA7 | 81.6 | 6 |
| 24 May 89 | Electroshocking | R2 | 80.3 | 1 |
| 24 May 89 | Electroshocking | R5 | 77.2 | 5 |
| 01 Jun 89 | Electroshocking | R9 | 74.8 | 5 |
| 25 May 89 | Electroshocking | TRR | 67.9 | 2 |
| 25 May 89 | Electroshocking | R33 | 60.7 | 10 |
| 01 Jun 89 | Electroshocking | R39 | 57.1 | 2 |
| 02 Jun 89 | Electroshocking | R58 | 50.5 | 2 |
| 26 May 89 | Electroshocking | CROAD | 40.1 | 1 |
| 09 Jul 89 | Electroshocking | RA3 | 83.0 | 1 |
| 29 May 90 | Electroshocking | RA3 | 83.0 | 20 |
| 05 Jun 90 | Snorkel | RA3 | 83.0 | 12 |
| 29 May 90 | Electroshocking | RA7 | 81.6 | 50 |
| 30 May 90 | Electroshocking | R2 | 80.3 | 16 |
| 30 May 90 | Electroshocking | R5 | 77.2 | 8 |
| 31 May 90 | Electroshocking | R9 | 74.8 | 37 |
| 31 May 90 | Electroshocking | TRR | 67.9 | 4 |
| 01 Jun 90 | Electroshocking | R33 | 60.7 | 4 |
| 01 Jun 90 | Electroshocking | R39 | 57.1 | 3 |
| 02 Jun 90 | Electroshocking | R58 | 50.5 | 13 |
| 18 Sep 90 | Electroshocking | RA3 | 83.0 | 1 |
| 18 Sep 90 | Electroshocking | RA7 | 81.6 | 2 |
| 08 Jun 93 | Electroshocking | RA3 | 83.0 | 1 |
| 07 Jun 93 | Snorkel | RA3 | 83.0 | 35 |
| 07 Jun 93 | Snorkel | R2 | 80.3 | 2 |
| 09 Jun 93 | Electroshocking | R58 | 50.5 | 1 |
| 08 Jun 93 | Snorkel | CROAD | 40.1 | 1 |
| 27 Oct 93 | Snorkel | RA3 | 83.0 | 10 |
| 25 Oct 93 | Snorkel | RA7 | 81.6 | 7 |
| 25 Oct 93 | Snorkel | R1A | 81.3 | 7 |
| 27 Oct 93 | Snorkel | R2 | 80.3 | 11 |
| 25 Oct 93 | Snorkel | R5 | 77.2 | 3 |
| 27 Oct 93 | Snorkel | R9 | 74.8 | 7 |
| 25 Oct 93 | Electroshocking | R58 | 50.5 | 1 |

Table 9 Common name, scientific name, origin, and code for species captured during Tuolumne River fish monitoring

| <i>Common name</i> | <i>Scientific name</i> | <i>Origin^a</i> | <i>Code^b</i> |
|------------------------------------|------------------------------------|---------------------------|-------------------------|
| Petromyzontidae (lampreys) | | | |
| Pacific lamprey | <i>Lampetra tridentata</i> | N | LMP |
| Clupeidae (shad and herring) | | | |
| Threadfin shad | <i>Dorosoma petenense</i> | I | -- |
| Salmonidae (salmon and trout) | | | |
| Chinook salmon | <i>Oncorhynchus tshawytscha</i> | N | -- |
| Rainbow trout | <i>Oncorhynchus mykiss</i> | N | -- |
| Cyprinidae (minnows) | | | |
| Common carp ^c | <i>Cyprinus carpio</i> | I | CP |
| Fathead minnow | <i>Pimephales promelas</i> | I | -- |
| Golden shiner | <i>Notemigonus crysoleucas</i> | I | GSH |
| Goldfish | <i>Carassius auratus</i> | I | GF |
| Hardhead | <i>Mylopharodon conocephalus</i> | N | HH |
| Hitch | <i>Lavinia exilicauda</i> | N | -- |
| Red shiner | <i>Cyprinella lutrensis</i> | I | RSH |
| Sacramento blackfish | <i>Orthodon microlepidotus</i> | N | -- |
| Sacramento splittail | <i>Pogonichthys macrolepidotus</i> | N | -- |
| Sacramento pikeminnow | <i>Ptychocheilus grandis</i> | N | SQ |
| Catostomidae (suckers) | | | |
| Sacramento sucker | <i>Catostomus occidentalis</i> | N | SKR |
| Ictaluridae (catfish) | | | |
| Black bullhead | <i>Ameiurus melas</i> | I | -- |
| Bullhead catfish ^d | <i>Ameiurus spp.</i> | I | BCF |
| Channel catfish | <i>Ictalurus punctatus</i> | I | CCF |
| White catfish | <i>Ameiurus catus</i> | I | WCF |
| Poeciliidae (livebearers) | | | |
| Western mosquitofish | <i>Gambusia affinis</i> | I | GAM |
| Atherinidae (silversides) | | | |
| Inland silverside | <i>Menidia beryllina</i> | I | ISS |
| Percichthyidae (temperate basses) | | | |
| Striped bass | <i>Morone saxatilis</i> | I | -- |
| Centrarchidae (basses and sunfish) | | | |
| Black crappie | <i>Pomoxis nigromaculatus</i> | I | -- |
| Bluegill | <i>Lepomis macrochirus</i> | I | BG |
| Green sunfish | <i>Lepomis cyanellus</i> | I | GSF |
| Largemouth bass | <i>Micropterus salmoides</i> | I | LMB |
| Redear sunfish | <i>Lepomis microlophus</i> | I | RSF |
| Smallmouth bass | <i>Micropterus dolomieu</i> | I | SMB |
| Warmouth | <i>Lepomis gulosus</i> | I | -- |
| White crappie | <i>Pomoxis annularis</i> | I | -- |
| Percidae (perch) | | | |
| Bigscale logperch | <i>Percina macrolepida</i> | I | -- |
| Embiotocidae (surf perch) | | | |
| Tule perch | <i>Hysterocarpus traski</i> | N | -- |
| Cottidae (sculpins) | | | |
| Prickly sculpin | <i>Cottus asper</i> | N | -- |
| Riffle sculpin | <i>Cottus gulosus</i> | N | RSCP |

^a N = native, I = introduced.

^b Dashes (--) indicate no code was assigned.

^c A single mirror carp, a variety of common carp, was captured.

^d Because of difficulty in field identification of bullhead catfish, they were combined into a single category.

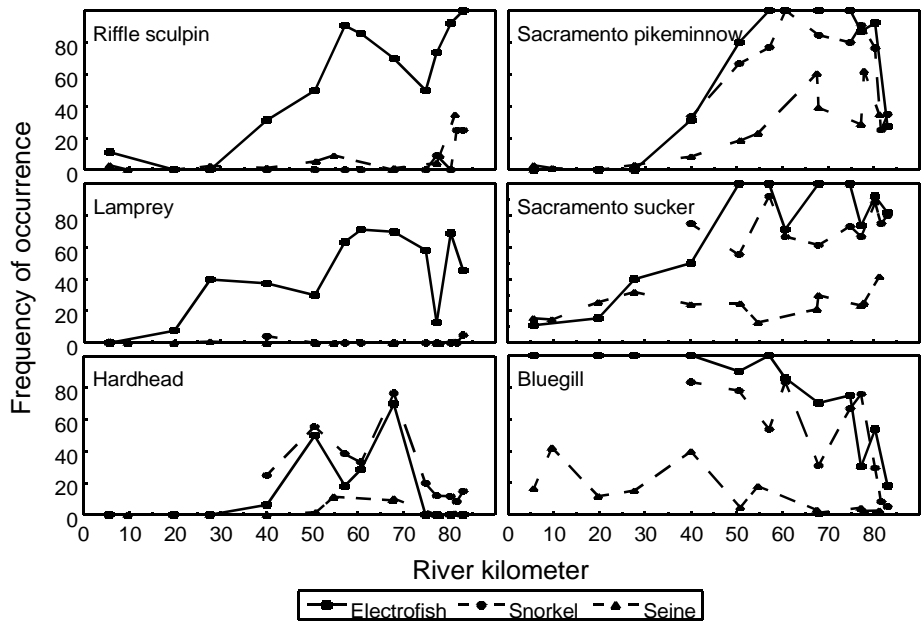


Figure 15A Frequency of occurrence plots for common native species (and bluegill) included in detrended correspondence analysis of annual winter-spring seining and summer electroshocking and snorkeling

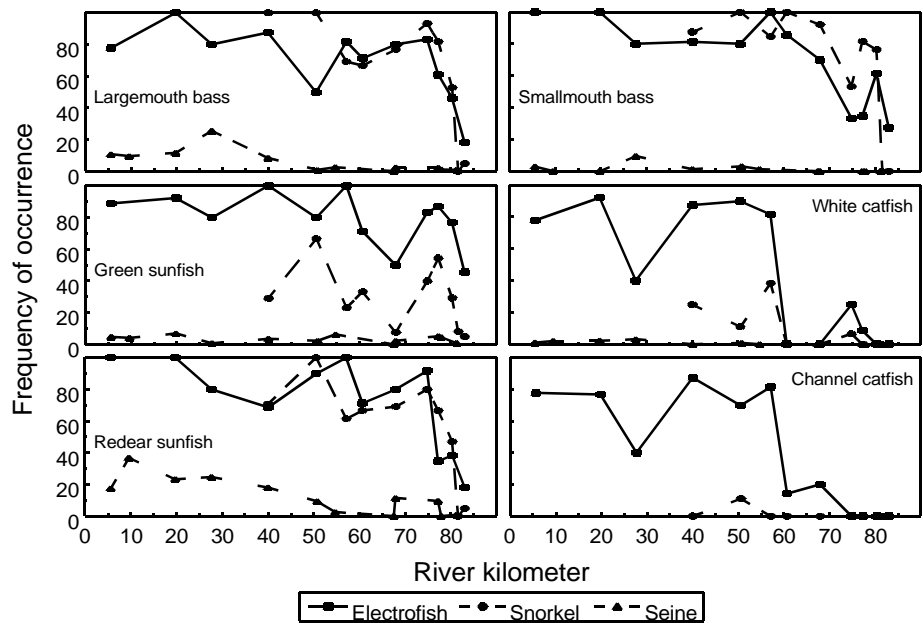


Figure 15B Frequency of occurrence plots for common centrarchid and ictalurid species included in detrended correspondence analysis of annual winter-spring seining and summer electroshocking and snorkeling

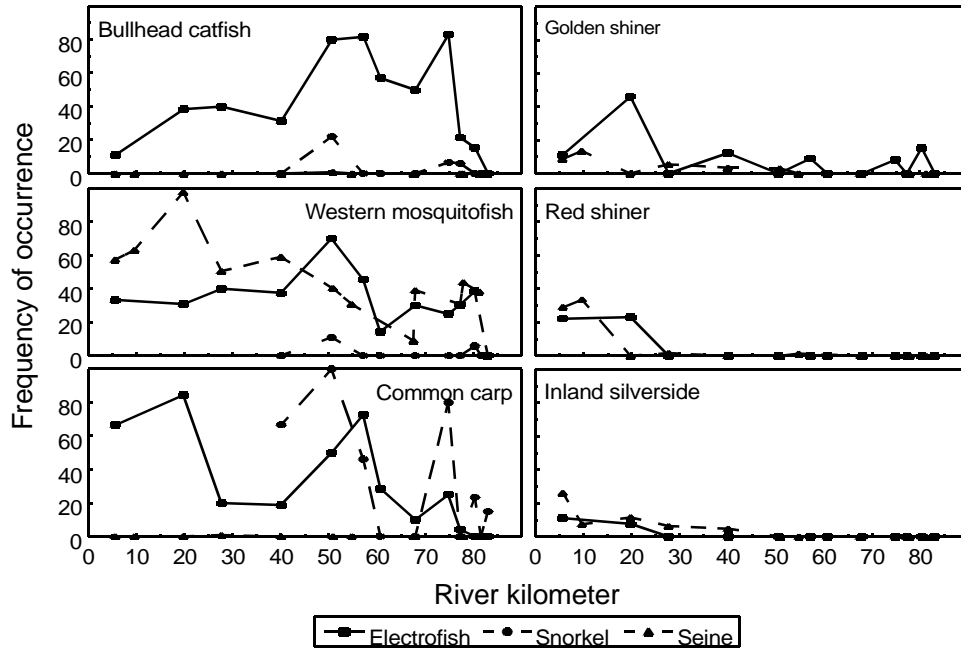


Figure 15C Frequency of occurrence plots for other common introduced species included in detrended correspondence analysis of annual winter-spring seining and summer electroshocking and snorkeling

Table 10 Percentages of fishes (excluding chinook salmon) captured during winter-spring salmon seining surveys (Jan–Jun, 1986–1997) and summer survey electroshocking (May–Oct, 1988–1993), snorkeling (May–Oct, 1988–1993), and seining (May–Sep 1988)

| Taxon | Winter-spring survey | | Summer survey | |
|------------------------|----------------------|---------|-----------------|------------|
| | Seining | Seining | Electroshocking | Snorkeling |
| Bigscale logperch | <0.1 | 0 | <0.1 | 0 |
| Black bullhead | <0.1 | 0 | <0.1 | 0 |
| Black crappie | <0.1 | 0 | 0 | 0 |
| Bluegill | 2.4 | 9.5 | 10.6 | 7.3 |
| Bullhead catfish | <0.1 | 0 | 1.6 | 0.7 |
| Centrarchids (unknown) | 0.6 | 0.1 | 1.9 | 2.0 |
| Channel catfish | 0 | <0.1 | 1.9 | <0.1 |
| Common carp | <0.1 | 0 | 0.6 | 1.0 |
| Cyprinids (unknown) | 0.1 | 0 | 0 | 3.1 |
| Golden shiner | 2.1 | 0.1 | 0.2 | 0 |
| Goldfish | <0.1 | <0.1 | 0.7 | 0.8 |
| Green sunfish | 0.2 | 0.2 | 9.7 | 2.0 |
| Hardhead | 1.0 | 0 | 0.7 | 2.2 |
| Hitch | 0 | 0 | 0.1 | <0.1 |
| Inland silverside | 1.3 | 0.6 | <0.1 | 0 |
| Largemouth bass | 1.1 | 2.5 | 5.7 | 8.6 |
| Pacific lamprey | <0.1 | 0 | 1.1 | <0.1 |
| Prickly sculpin | <0.1 | 0 | 0 | 0 |
| Rainbow trout | 0.1 | 0 | <0.1 | <0.1 |
| Redear sunfish | 5.0 | 2.0 | 8.0 | 17.1 |
| Red shiner | 6.2 | 0 | 0.1 | 0 |
| Riffle sculpin | 1.9 | 0.1 | 19.0 | 0.1 |
| Sacramento blackfish | <0.1 | 0 | 0.1 | <0.1 |
| Sacramento pikeminnow | 7.3 | 1.6 | 10.2 | 12.2 |
| Sacramento splittail | 0.1 | 0 | <0.1 | 0 |
| Sacramento sucker | 35.4 | 0.9 | 13.3 | 36.9 |
| Smallmouth bass | 0.2 | 1.6 | 4.5 | 5.6 |
| Striped bass | 0 | 0 | <0.1 | 0 |
| Threadfin shad | 0.3 | 0 | <0.1 | 0 |
| Tule perch | 0 | 0 | <0.1 | 0 |
| Warmouth | <0.1 | 0 | 0.1 | <0.1 |
| Western mosquitofish | 34.4 | 80.5 | 1.0 | <0.1 |
| White crappie | <0.1 | 0 | 0 | 0 |
| White catfish | 0.1 | 0.2 | 8.6 | 0.2 |
| Number of samples | 1,077 | 37 | 148 | 194 |
| Total fish captured | 21,736 | 3,611 | 23,774 | 26,371 |

Table 11 Percentage abundance of fish species, excluding chinook salmon, captured in rotary screw traps at river kilometer 5.6 in 1995 (25 April to 30 May) and 1996 (18 April to 29 May)^a

| <i>Taxon</i> | 1995 | 1996 |
|-----------------------|------|------|
| Native taxa | | |
| Cottidae | 0 | 1.0 |
| Hardhead | 0 | 0.3 |
| Hitch | 0 | 0.3 |
| Sacramento blackfish | 0 | 0.3 |
| Sacramento pikeminnow | 1.5 | 0.7 |
| Sacramento sucker | 5.5 | 3.9 |
| Introduced taxa | | |
| Black bullhead | 0.1 | 0 |
| Bluegill | 0.1 | 8.5 |
| Bullhead catfish | 0 | 0.7 |
| Centrarchidae | 0.4 | 0.7 |
| Channel catfish | 0.1 | 0.3 |
| Common carp | 0.1 | 0 |
| Golden shiner | 0.3 | 3.6 |
| Goldfish | 4.5 | 3.9 |
| Green sunfish | 0.3 | 0.7 |
| Ictaluridae | 0 | 13.1 |
| Inland silverside | 0.4 | 33.4 |
| Largemouth bass | 0.3 | 18.4 |
| Red shiner | 1.7 | 0.7 |
| Threadfin shad | 0 | 0.3 |
| Warmouth | 0 | 0.3 |
| Western mosquitofish | 2.9 | 7.2 |
| White catfish | 2.0 | 0.7 |
| White crappie | 0 | 1.0 |
| Unknown | | |
| Cyprinidae | 79.7 | 0 |
| Total number of fish | 715 | 305 |

^a Some fish were not identified to species but were identified to the lowest possible taxon.

Table 12 Percentages of fish taxa (excluding chinook salmon) captured by fyke nets at various river kilometer locations, 1973–1980

| <i>Year</i> | <i>1973</i> | | | <i>1974</i> | | | <i>1977</i> | | | <i>1980</i> | | | |
|-----------------------|-------------|------|------|-------------|------|------|-------------|------|------|-------------|------|------|------|
| <i>Rkm</i> | 9.7 | 49.2 | 67.6 | 9.7 | 49.2 | 67.6 | 9.7 | 49.2 | 67.6 | 9.7 | 42.0 | 54.7 | 67.6 |
| Native taxa | | | | | | | | | | | | | |
| <i>Cottus</i> sp. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0 | 0 |
| Hardhead | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.9 | 0 |
| Hitch | 0 | 0 | 0 | 0 | 0 | 0 | 5.4 | 0 | 1.8 | 0 | 0 | 1.9 | 0 |
| Pacific lamprey | 0 | 0 | 0 | 2.5 | 2.9 | 12.6 | 6.8 | 9.9 | 0.9 | 5.2 | 1.6 | 28.8 | 10.8 |
| Sacramento blackfish | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sacramento splittail | 0 | 0 | 0 | 11.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sacramento pikeminnow | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.8 | 0 | 0 | 0 | 1.4 |
| Sacramento sucker | 0 | 0 | 0 | 0.6 | 86.0 | 16.5 | 0 | 60.6 | 2.7 | 0 | 0.4 | 0 | 17.6 |
| Introduced taxa | | | | | | | | | | | | | |
| Bigscale logperch | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Black bullhead | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.4 | 0 | 0 | 0 | 0 | 0 |
| Black crappie | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bluegill | 0 | 0 | 0 | 4.2 | 2.1 | 16.5 | 8.1 | 2.8 | 17.9 | 16.8 | 5.6 | 23.1 | 28.4 |
| Bullhead catfish | 0 | 50 | 20 | 0 | 0 | 1.6 | 0 | 1.4 | 0 | 0 | 0 | 3.8 | 0 |
| Centrarchidae | 0 | 0 | 0 | 0.3 | 2.4 | 3.1 | 0 | 0 | 20.5 | 0 | 0 | 7.7 | 0 |
| Channel catfish | 0 | 0 | 40 | 0 | 0 | 0 | 2.7 | 0 | 0 | 1.1 | 0 | 0 | 0 |
| Common carp | 12.5 | 0 | 0 | 0.6 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.7 |
| Golden shiner | 0 | 0 | 0 | 1.4 | 0.2 | 0 | 1.4 | 0 | 0 | 0.2 | 0 | 0 | 1.4 |
| Goldfish | 0 | 0 | 0 | 2.0 | 0.1 | 0 | 13.5 | 2.8 | 0.9 | 0 | 0 | 0 | 0 |
| Green sunfish | 0 | 0 | 0 | 0.6 | 0 | 3.1 | 1.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ictaluridae | 87.5 | 0 | 20 | 40.3 | 1.6 | 6.3 | 1.4 | 0 | 1.8 | 69.7 | 0.8 | 17.3 | 14.9 |
| Largemouth bass | 0 | 0 | 0 | 6.2 | 0.7 | 28.3 | 1.4 | 0 | 2.7 | 0.2 | 0.4 | 0 | 9.5 |
| <i>Pomoxis</i> sp. | 0 | 0 | 0 | 0.6 | 0.2 | 0 | 1.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Redear sunfish | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.7 | 0 | 0 | 0 | 0 |
| Smallmouth bass | 0 | 0 | 0 | 1.7 | 3.7 | 3.9 | 0 | 12.7 | 6.3 | 0 | 0 | 0 | 0 |
| Striped bass | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Threadfin shad | 0 | 0 | 0 | 25.6 | 0 | 0 | 37.8 | 1.4 | 34.8 | 3.5 | 90.4 | 11.5 | 0 |
| Warmouth | 0 | 50 | 0 | 1.4 | 0 | 6.3 | 1.4 | 0 | 4.5 | 0 | 0.4 | 1.9 | 13.5 |
| Western mosquitofish | 0 | 0 | 0 | 0.3 | 0.1 | 1.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| White catfish | 0 | 0 | 20 | 0 | 0 | 0 | 16.2 | 7.0 | 0.9 | 3.3 | 0 | 0 | 0 |
| Days sampled | 23 | 24 | 22 | 28 | 29 | 29 | 24 | 26 | 28 | 57 | 31 | 35 | 54 |
| Total fish | 8 | 2 | 5 | 355 | 1452 | 127 | 74 | 71 | 112 | 459 | 250 | 52 | 74 |

Table 13 Percentages of fish taxa (excluding chinook salmon) captured by fyke nets at various river kilometer locations, 1981–1986

| <i>Year</i> | <i>1981</i> | <i>1982</i> | | | <i>1983</i> | <i>1986</i> |
|------------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| <i>River kilometer</i> | <i>67.6</i> | <i>9.7</i> | <i>51.5</i> | <i>67.6</i> | <i>67.6</i> | <i>67.6</i> |
| Native taxa | | | | | | |
| <i>Cottus</i> sp. | 0 | 0 | 0 | 0 | 0 | 0 |
| Hardhead | 0 | 0 | 0.3 | 10.4 | 0 | 2.9 |
| Hitch | 0 | 0.9 | 1.9 | 0.9 | 2.2 | 0 |
| Pacific lamprey | 100.0 | 50.4 | 52.9 | 39.6 | 28.3 | 82.2 |
| Sacramento blackfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Sacramento splittail | 0 | 0 | 0 | 0 | 0 | 0 |
| Sacramento pikeminnow | 0 | 0.9 | 8.0 | 9.4 | 0 | 0 |
| Sacramento sucker | 0 | 0 | 0 | 0 | 0 | 0 |
| Introduced taxa | | | | | | |
| Bigscale logperch | 0 | 2.6 | 0 | 0 | 0 | 0 |
| Black bullhead | 0 | 0 | 0 | 0 | 0 | 0 |
| Black crappie | 0 | 0 | 0.6 | 0 | 0 | 0.6 |
| Bluegill | 0 | 20.9 | 23.0 | 14.2 | 39.1 | 12.6 |
| Bullhead catfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Centrarchidae | 0 | 0 | 0 | 0 | 2.2 | 0 |
| Channel catfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Common carp | 0 | 0 | 1.1 | 0 | 0 | 0 |
| Golden shiner | 0 | 0 | 0 | 0 | 0 | 0 |
| Goldfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Green sunfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Ictaluridae | 0 | 14.1 | 3.3 | 16.0 | 26.1 | 0.6 |
| Largemouth bass | 0 | 0.4 | 0.3 | 3.8 | 0 | 0.6 |
| <i>Pomoxis</i> sp. | 0 | 0 | 0 | 0 | 0 | 0.6 |
| Redear sunfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Smallmouth bass | 0 | 0 | 0 | 0 | 0 | 0 |
| Striped bass | 0 | 0 | 0 | 0 | 0 | 0 |
| Threadfin shad | 0 | 9.8 | 8.3 | 0 | 2.2 | 0 |
| Warmouth | 0 | 0 | 0.3 | 5.7 | 0 | 0 |
| Western mosquitofish | 0 | 0 | 0 | 0 | 0 | 0 |
| White catfish | 0 | 0 | 0 | 0 | 0 | 0 |
| Days sampled | 8 | 16 | 23 | 24 | 11 | 15 |
| Total number of fish | 4 | 234 | 361 | 106 | 46 | 174 |

Although the three winter-spring methods captured similar numbers of species, catches were dominated by different species. Seining catches were dominated by western mosquitofish (34.4%) and Sacramento sucker (35.4%) (Table 10). No other species exceeded 10% of the catch. The rotary screw trap catch was dominated by unidentified cyprinids (79.7%) in 1995 (Table 11). Of the fish identified to species, Sacramento sucker (5.5%) and goldfish (4.5%) were most common. The catch in 1996 was dominated by unidentified catfish (13.1%), inland silverside (33.4%), and largemouth bass (18.4%) (Table 11). Fyke netting results were variable among sites and years (Tables 12 and 13). Unidentified catfish commonly exceeded 10% of the catch in the lower river (rkm 6.0 and 26.1). Threadfin shad was common (>10%) in 1974 and 1977, as were bluegill in 1980 and 1982. Other species common in at least one year included common carp, splittail, goldfish, white catfish, and Pacific lamprey. Catfish of all kinds were common at more upstream sites. Pacific lamprey, Sacramento sucker, bluegill, warmouth, threadfin shad, and hardhead were common in some years.

Seining was initially included in the summer flow study but was suspended after the first year (1988) because the catch consisted primarily of western mosquitofish with few other species captured (Table 10). Summer seining only captured 15 taxa with only western mosquitofish exceeding 10% of the catch. Summer snorkeling and electroshocking captured many more species than winter-spring seining (Figure 14) and the other methods. Mean number of species (mean \pm standard deviation) ranged from 1.5 ± 1.3 to 8.7 ± 2.2 for snorkeling and from 3.9 ± 1.6 to 12.9 ± 2.2 for electroshocking. Snorkeling and electroshocking captured 22 and 30 taxa, respectively. Snorkeling was limited to the more upstream reaches of the river where visibility was sufficient to identify and count the fish present.

Fish Species Distributions

Only the annual winter-spring seining and summer electroshocking and snorkeling surveys sampled enough sites to give good information on resident fish species distributions. Percentage abundance of species in the winter-spring seining and summer surveys indicates that a number of species were relatively rare in the system (Table 10). The native species hitch, prickly sculpin, rainbow trout, Sacramento blackfish, Sacramento splittail, and tule perch never exceeded 1% of the total catch with any of the methods used. The introduced species black crappie, bigscale logperch, goldfish, striped bass, threadfin shad, white crappie and warmouth were similarly rare.

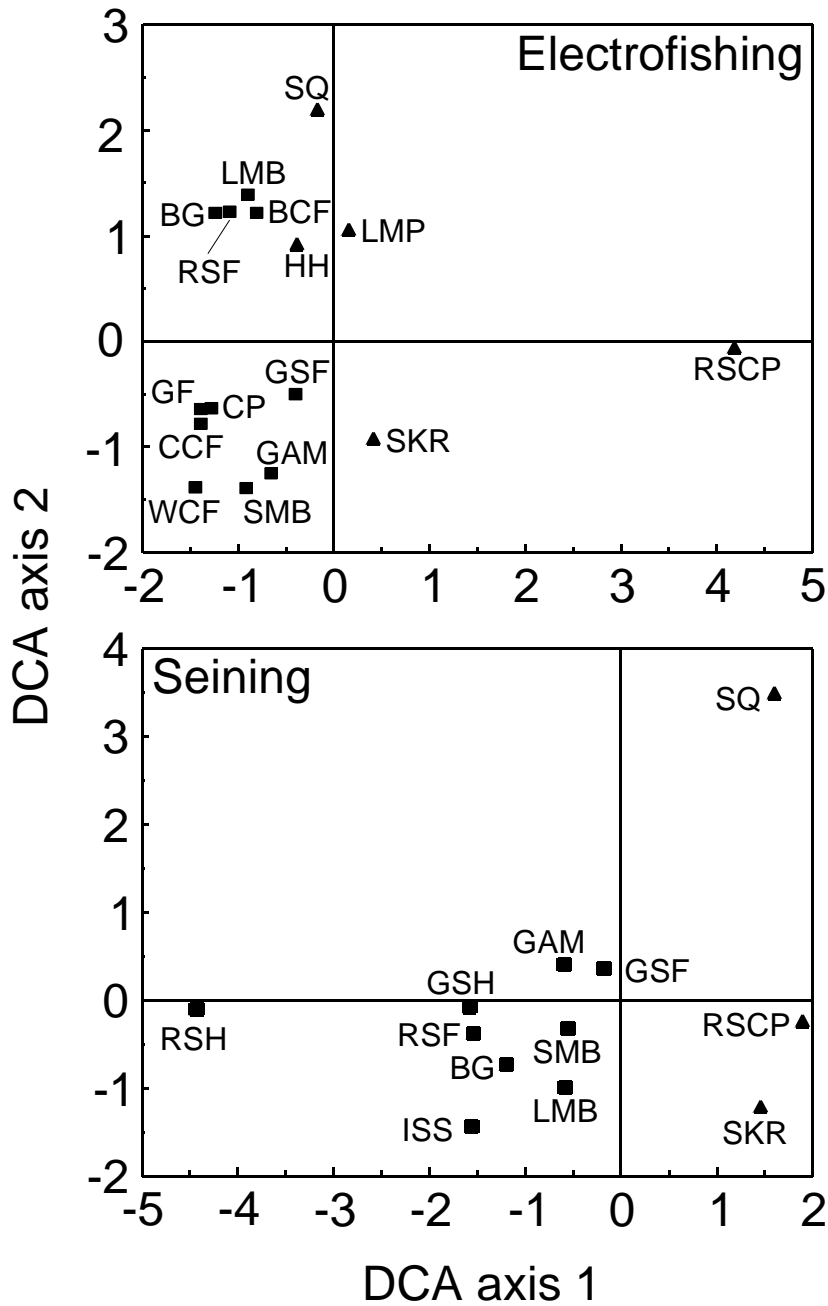


Figure 16 Species scores on DCA axes 1 and 2 resulting from analysis of the summer electrofishing data and winter-spring seining data. Species codes as in Table 9. Triangles indicate native species and squares indicate introduced species.

Frequency of occurrence plots for the common species included in DCA analyses indicated that the species were not evenly distributed in the river, particularly during the summer (Figure 15A). The common native species exhibited two basic patterns of distribution. In the summer electrofishing surveys, Sacramento sucker, lamprey, and riffle sculpin occurred most frequently at upstream sites above about rkm 50. Lamprey and riffle sculpin were rarely captured in the winter-spring seining or summer snorkeling. Sacramento suckers were fairly evenly distributed in the river in the winter-spring seining survey but in the summer surveys were most frequent upstream of rkm 50. The other two common native species, hardhead and Sacramento pikeminnow were most frequently captured upstream of about rkm 50, but there was a subsequent decline in frequency of occurrence around rkm 80.

The common introduced centrarchids exhibited very similar patterns in frequency of occurrence (Figures 15A and 15B). All of the species were well distributed throughout the river during the summer as indicated by both electroshocking and snorkeling. The occurrence of all species declined sharply around rkm 80 with somewhat lower frequencies of occurrence observed upstream of rkm 50. Only bluegill and redear sunfish were regularly captured during winter-spring seining. The winter-spring pattern was similar to the summer pattern with the species occurring most frequently downstream of rkm 50.

The remaining common introduced species exhibited a mixture of distributions. White catfish and channel catfish commonly occurred in summer electrofishing samples at downstream sites but became rare at about rkm 60 (Figure 15B). Both species were rarely captured during snorkeling or winter-spring seining surveys. Similarly, summer snorkeling or winter-spring seining rarely captured bullhead catfish (Figure 15C). Unlike the other catfish, bullheads were less frequently captured at the upstream and downstream ends of the study area compared to the middle section between about rkm 40 and 80. Warmouth, a centrarchid (not shown in Figure 15C), showed a very similar pattern of distribution. Red shiner and inland silverside were relatively rare, but were clearly most frequently captured in the downstream reaches of the river (Figure 15C). Red shiner was not captured upstream of rkm 30 and inland silverside was never captured above rkm 50. Western mosquitofish was fairly evenly distributed along the river in the summer electrofishing survey, but was captured most frequently at downstream sites in the winter-spring seining survey. The remaining common introduced species, common carp, goldfish (not shown but similar to carp), and golden shiner occurred sporadically at certain sites along the river. All occurred rarely at sites near rkm 80 and upstream sites.

Although the data are insufficient to determine distribution in the Tuolumne River, two additional native species deserve mention. A single tule perch was

captured during a summer electrofishing survey at rkm 19.8 in June 1991. Splittail was occasionally captured below rkm 30 during winter-spring seining and summer electrofishing. Single individuals were captured during seining at rkm 9.7 in March of 1988 and 1989. In May 1987, seven splittail were captured at rkm 27.7, and five were captured at rkm 5.6. A single individual was captured in a May electrofishing survey at rkm 5.6. Forty-one splittail were captured during fyke netting at rkm 9.7 in 1974.

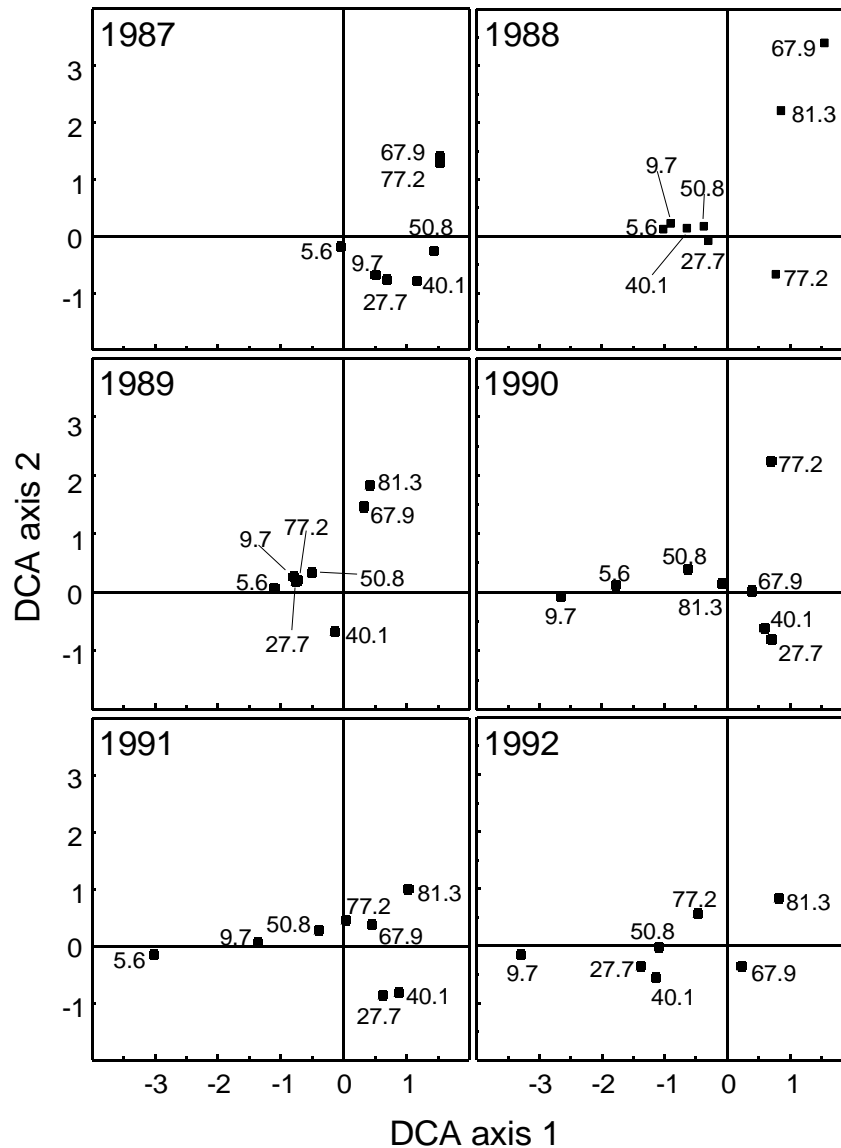


Figure 17A Site scores on DCA axes 1 and 2. Scores were derived from analysis of annual winter-spring seining data. Numbers indicate site location as kilometers from the San Joaquin River.

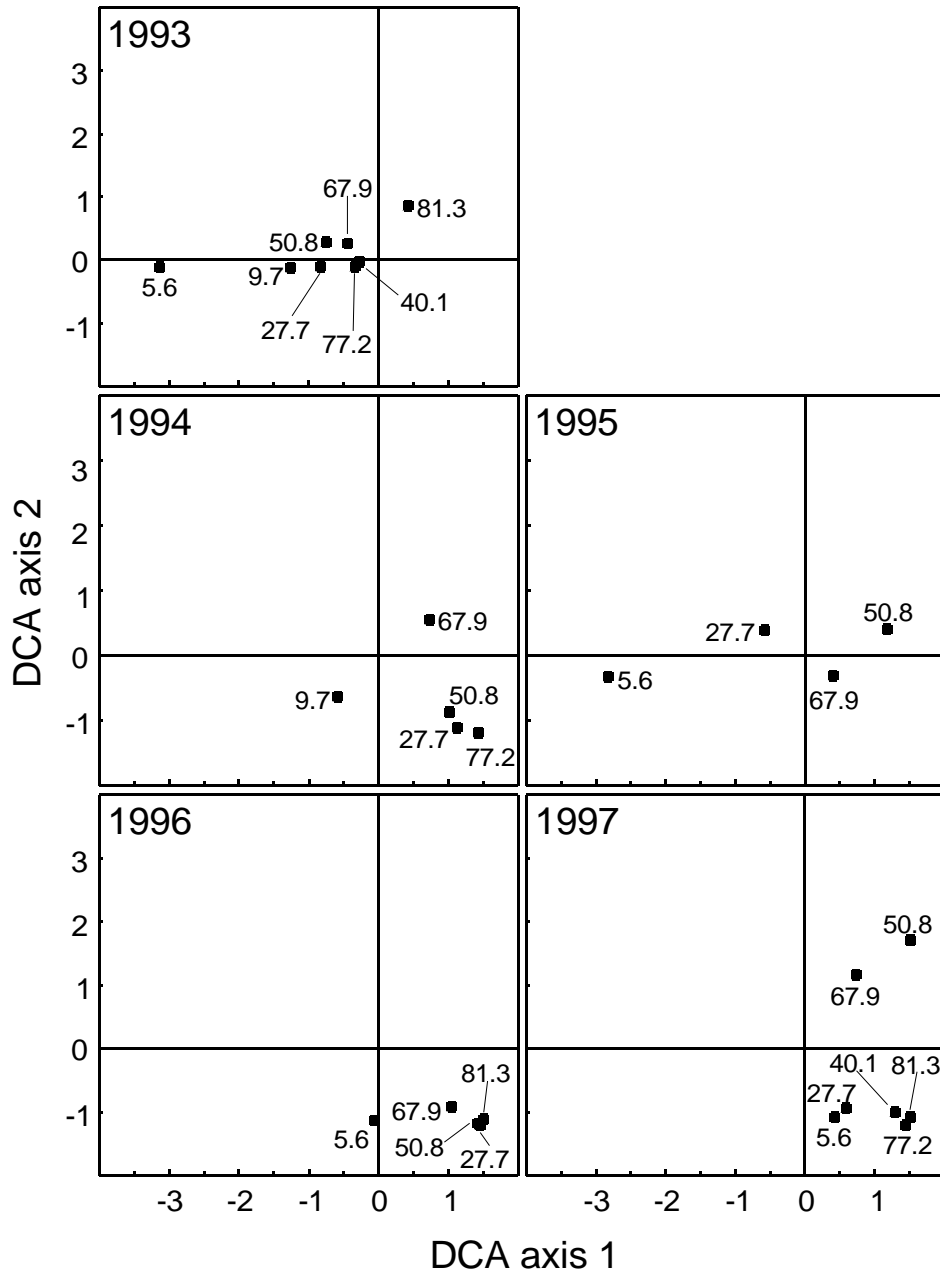


Figure 17B Site scores on DCA axes 1 and 2. Scores were derived from analysis of annual winter-spring seining data. Numbers indicate site location as kilometers from the San Joaquin River.

Fish Species Assemblages

The initial analysis of the winter-spring seining data was heavily influenced by a single sample collected at rkm 50.5 in 1987. Riffle sculpin dominated (94%) this sample. Because the high percentage of riffle sculpin was unusual compared to all other samples collected, it was omitted and the analysis conducted again.

The first four axes of the DCA of the winter-spring seining data explained a total of 51.6% of the variance in the species percentage abundances (Table 14). The distribution of species scores along DCA axis 1 suggests that the species form three groups based on similar percentage abundances (Figure 16). The native species are grouped to the right with positive scores, a large group of introduced species that occur together occurs near the center with scores between 0 and -2, and red shiner occurs alone to the left with the highest negative score. DCA axis 2 primarily separates Sacramento pikeminnow (positive score) from the two other native species (negative scores).

Table 14 Percentage of variance in species percentage abundances explained by detrended correspondence analysis of winter-spring seining data and summer survey electrofishing data

| <i>Data set</i> | <i>Detrended correspondence axis</i> | | | |
|------------------------|--------------------------------------|----------|----------|----------|
| | <i>1</i> | <i>2</i> | <i>3</i> | <i>4</i> |
| Winter-spring seining | 21.7 | 16.1 | 8.6 | 5.2 |
| Summer electroshocking | 26.2 | 9.9 | 5.6 | 4.6 |

The plots of site scores on DCA axes 1 and 2 indicate annual variability in winter-spring resident species assemblages (Figure 17). In 1987, all sites except rkm 5.6 were located to the right of the plot with positive scores on DCA axis 1. Native species were found at all sites, with high percentages of Sacramento pikeminnow at rkm 67.9 and 77.2. In 1988 and 1989, only sites above rkm 60 were found to the right of the plot with positive scores on DCA axis 1. The remaining sites clustered in the area of the plot characterized by the large group of introduced species with scores between 0 and -2. Western mosquitofish dominated the catch at these sites, but bluegill was commonly caught in both years and redear sunfish in 1989. Sacramento pikeminnow and suckers remained common at the upstream sites. From 1990 through 1993 the sites at rkm 5.6 and 9.7 were located to the left of the plot with the most negative scores on DCA axis 1 reflecting high percentages of red shiner. The sites above rkm 60 continued to have relatively high percentages of pikeminnow and sucker but redear sunfish became widespread resulting in a mixture of native and introduced species. Although not all sites were sampled after 1993, the assemblage appeared to shift back to the pattern seen in 1987. However, red

shiner and occasionally inland silverside continued to be found in high percentages at the most downstream sites, particularly rkm 5.6. Redear sunfish became much less abundant and less frequent at the most upstream sites. The shifts in percentage abundances of the species indicated by the shifts in site scores are reflected in the annual mean percentage abundances of the three groups identified from the species plot (Table 15).

The one-way ANOVA supported the observed variability in assemblage structure. Significant differences among years were found ($P = 0.001$). Tukey HSD pairwise tests indicated that DCA axis 1 scores in 1987 were significantly higher than in 1992 and 1993 ($P < 0.05$). Similarly DCA axis 1 scores in 1997 were higher than 1993 ($P < 0.05$). The other years appear to represent transitional states between the high and low years. There were no significant differences for DCA axis 2.

Table 15 Mean percentage (\pm standard deviation) of species groups for all sites sampled in each year^a

| <i>Year</i> | <i>N</i> | <i>Red shiner</i> | <i>Introduced species^b</i> | <i>Native species^c</i> |
|-------------|----------|-------------------|---------------------------------------|-----------------------------------|
| 1987 | 8 | 0 | 19.6 \pm 25.4 | 74.7 \pm 24.4 |
| 1988 | 8 | 0 | 66.5 \pm 38.2 | 31.2 \pm 35.5 |
| 1989 | 8 | 0.6 \pm 0.7 | 82.0 \pm 20.2 | 17.5 \pm 20.6 |
| 1990 | 8 | 29.8 \pm 29.0 | 54.9 \pm 23.8 | 33.9 \pm 27.7 |
| 1991 | 8 | 22.3 \pm 29.2 | 52.1 \pm 25.6 | 39.4 \pm 32.2 |
| 1992 | 7 | 32.6 \pm 46.1 | 72.8 \pm 30.7 | 17.5 \pm 27.0 |
| 1993 | 8 | 27.0 \pm 33.4 | 74.1 \pm 21.7 | 15.3 \pm 15.4 |
| 1994 | 5 | 2.3 \pm 3.2 | 26.2 \pm 24.0 | 70.0 \pm 27.4 |
| 1995 | 4 | 25.8 \pm 36.5 | 54.7 \pm 32.8 | 29.9 \pm 35.1 |
| 1996 | 5 | 2.7 \pm 3.7 | 12.0 \pm 17.3 | 86.1 \pm 21.1 |
| 1997 | 7 | 5.1 \pm 6.4 | 12.4 \pm 14.4 | 83.7 \pm 18.9 |

^a Means were calculated on the basis of all sites sampled (N), except for red shiner. Means for red shiner were calculated based on data from the three most downstream stations, the only sites where red shiner were captured during the study. Species groups were identified by DCA analysis of the annual winter-spring seining data.

^b Introduced species include bluegill, largemouth bass, green sunfish, redbreast sunfish, smallmouth bass, white catfish, channel catfish, bullhead catfish, western mosquitofish, and common carp.

^c Native species include Sacramento pikeminnow, hardhead, Sacramento sucker, lamprey, and riffle sculpin.

The first four axes of the DCA of the summer electrofishing data explained 46.3% of the variance in the species percentage abundance data (Table 14). Based on species scores on the first two DCA axes, the fish species appeared to form three groups (Figure 16). The native species tended to have scores near 0 with riffle sculpin clearly different with a high positive score. The other native species tended to occur in high percentage abundance with species of introduced fishes. Hardhead, Sacramento pikeminnow and lamprey were found in association with largemouth bass, bluegill, redear sunfish, and bullhead catfish. These species had positive scores on DCA axis 2. Sacramento sucker was associated with green sunfish, western mosquitofish, smallmouth bass, goldfish, carp, channel catfish, and white catfish. These species had negative scores on DCA axis 2.

Plots of site scores on the first two DCA axes indicated that summer fish assemblages were relatively stable on an annual basis but there appeared to be some seasonal variability in species assemblages at some sites in some years (Figure 18). The overall range of scores did not change dramatically from year to year, suggesting the diversity of fish assemblages was relatively constant on an annual basis. These observations were supported by results of the two-way ANOVA. For both DCA axis 1 and 2, there was no significant effect of year, season, or year-by-season interaction (all $P > 0.05$).

The sites at rkm 80.3 and 83.0 were consistently located to the right of the plot with positive scores on DCA axis 1, consistent with high percentages of native species, particularly riffle sculpin. Sites between rkm 60 and rkm 80 were generally located in the upper left quadrant of the plot with positive scores on DCA axis 2, consistent with high percentages of Sacramento pikeminnow and associated species. The remaining sites were generally located in the lower left of the plot with negative scores on DCA axis 2. Despite these general trends there were exceptions, particularly in 1992.

Comparisons of scores for the early and late samples from the same site, indicated significant seasonal changes at some sites in some years. For example, there was little change in the species assemblage at site rkm 80.3 in 1989 and 1991 but in 1990 and 1992, the site scores indicate that higher percentages of introduced species were present by late summer. The site at rkm 77.2 had similar seasonal scores in three out of four years. There was a large shift in the species assemblage only in 1989. The most seasonally stable fish assemblages were at rkm 19.8, 40.1, and 67.9.

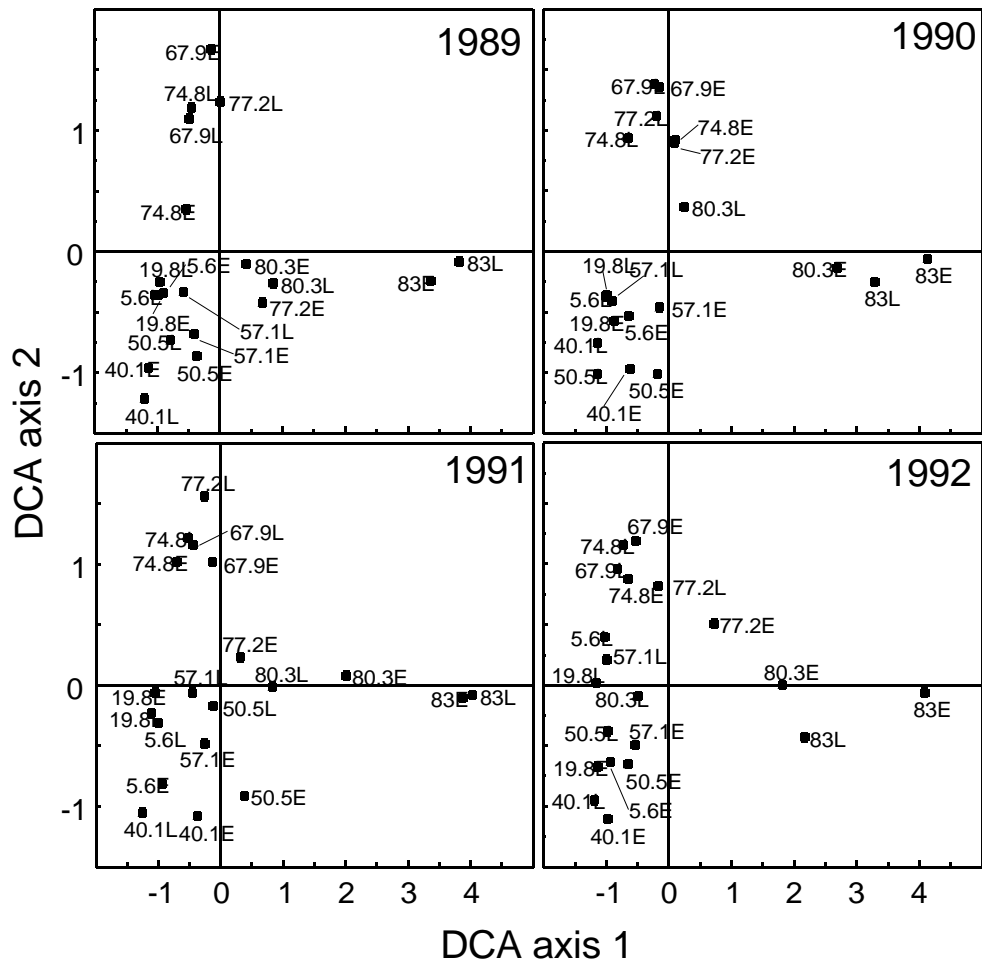


Figure 18 Site scores on DCA axes 1 and 2. Scores were derived from analysis of summer electrofishing data. Numbers indicate site location as kilometers from the San Joaquin River. The letters designate the early (E) or late (L) summer sample from each site.

Discussion

Adult Fall-run Chinook Salmon

The three years with run estimates greater than 50,000 occurred in the 1940s before completion of Friant Dam (1946) and the Tracy Pumping Plant (1951) in the Delta, both features of the Central Valley Project. The New Don Pedro Dam (1971) on the Tuolumne River and the State Water Project's Banks Pumping Plant (1968) in the Delta are other major water development factors affecting Tuolumne River salmon survival since the 1950s. Since that time, the runs have generally corresponded to overall hydrologic trends and streamflow conditions, with major declines following droughts in 1959–1961, 1976–1977, and 1987–1992. The high estimate of 40,300 in 1985 was associated with high juvenile survival in 1983, a very wet year. The effects of the ocean harvest on survival from juvenile to adult influence the trends.

The basis for the spawning run estimates has varied substantially over time, which means caution should be applied in considering their accuracy and comparability. The only direct counts were made at Modesto from 1940–1946 when fish passed over a weir. Since then all estimates are derived from carcass surveys in the upstream spawning reach. The estimates from 1947–1966 are questionable because no mark-recapture data were gathered. Carcass tagging began in 1967, but DFG estimates through 1978 are not entirely based on calculations from the tag recovery data. Methods have improved since 1979 due to the use of mark-recapture data, but various techniques and formulas have been used to calculate the population estimates and the variability of the estimates has not been fully analyzed. Expansions based on redd counts have been applied since 1981 to account for reaches not surveyed weekly for carcasses, but this was not done in prior years. The population estimates for recent years are still subject to revision as different statistical methods are applied.

The Tuolumne River is one of the few remaining major Central Valley salmon streams without a hatchery. However, hatchery salmon, as documented by the recovery of fish with CWTs, have become much more prevalent in the runs since 1986. Most of these CWT salmon originate from the Merced River Hatchery, with many returning from smolt survival releases made by DFG into the Tuolumne River. Others are mainly from releases into the Sacramento-San Joaquin Delta originating from other hatcheries in the Central Valley. The CWT recoveries represent a minimum for the hatchery salmon component of the runs because many unmarked Merced hatchery salmon are released as well. The determination of the status and dynamics of the wild population are not only complicated by the presence of hatchery fish, but the

hatchery fish may also pose a threat to the long-term survival of the wild population (NMFS 1998; NRC 1996).

Juvenile Fall-run Chinook Salmon

Based on the maximum size of fry seined in January, fry began to emerge from the gravel in December in some years and continued in some years into April and May. The later fry emergence could be, in part, the result of spawning after December but there were no spawning survey data from later than 5 January since 1986. Maximum fork length data indicated that salmon >70 mm FL (potentially smolts) were present as early as March of most years.

The limited presence of salmon in the summer flow study suggests that few juvenile salmon reared for extended periods in the Tuolumne River; however, these studies were conducted during a series of low flow years and may not be representative of all conditions. The minimum summer flow requirements were increased since the sampling took place (FERC 1996) so the river reach with suitable temperatures for summertime rearing is now more extensive.

Resident Fishes

Although the results suggest the different sampling methods varied substantially in their ability to sample the resident fish communities, it is difficult to separate differences due to method from differences due to year, season, and location. Also, because the major purpose of the winter-spring sampling effort was to document the distribution and abundance of juvenile chinook salmon, sampling of the resident fish assemblage only had secondary importance. In contrast, the purpose of the summer flow study was specifically to document the resident fish assemblage.

The three winter-spring sampling methods were very successful at capturing juvenile chinook salmon but less successful at capturing other species. A number of factors likely contribute to the low catches. Low water temperatures during the winter-spring period are likely associated with reduced activity levels for most of the resident species, the majority of which are considered warm-water species. Resident fish populations are probably at their lowest abundance at this time of year due to cumulative mortality of small, young fish over the previous summer and fall. Flows are often high during the winter-spring period, increasing the size of the river, making it more difficult to sample a significant portion of the habitat. High flows are also often associated with reduced sampling efficiency because of high water velocities, greater depths, and increased debris in the river.

There were some obvious differences among the three winter-spring methods used. Fyke netting was clearly most effective for sampling bottom-oriented species, particularly catfish and lamprey (Tables 12 and 13). Rotary screw

trapping emphasized pelagic species (Table 11). Seining emphasized stream-edge species, particularly western mosquitofish (Table 10). Although all the methods are somewhat biased as to the species sampled, seining has the advantage of simplicity. It is possible to sample many more locations by seining, making it possible to document species distributions as well as abundance. Electrofishing is another alternative but it was not used in winter-spring surveys and has the disadvantages of requiring expensive equipment and more likely causing mortality to captured salmon.

There were also some obvious differences among the three methods used during the summer flow study (Table 10). Seining was largely ineffective, except in capturing western mosquitofish, in the one year it was used. Presumably larger fish were able to detect and avoid the seine in the lower, clearer water present during the summer period. Electrofishing and snorkeling provided very similar data for larger more pelagic species. Snorkeling provided a more accurate assessment of large individuals, especially of the larger native species including Sacramento pikeminnow, hardhead, and Sacramento sucker. However, snorkeling tended to overlook bottom-oriented species such as catfish and sculpins and also small fishes such as red shiner and golden shiner. Snorkeling was also limited by water clarity to the upstream reaches of the river. Overall, of the three methods used, electrofishing appeared to provide the best data on the resident fish assemblage.

There are two species that were not captured, but their presence is expected based on angler reports or known occurrence in the San Joaquin River. These species are the native white sturgeon and the introduced American shad. Their absence in this data set could be due to low susceptibility to the sampling methods employed and intermittent occurrence in the river.

Fish Species Distributions

Fish species distributions, based on frequency of occurrence, were much more distinctive during the summer than during the winter-spring seining surveys (Figures 15A, 15B, and 15C). Winter-spring distributions were usually similar to the summer distributions. However, differences with river kilometer were generally of smaller magnitude because high values rarely exceeded 50% for winter-spring seining, yet were often 100% for summer electrofishing and snorkeling.

The summer sampling indicated several distribution patterns for fishes (Figure 15A, 15B, and 15C). There was a very sharp transition for many species around rkm 80. Most species (except Sacramento sucker, riffle sculpin, and lamprey), occurred much less frequently at locations upstream of about rkm 80. These most upstream locations represent a very distinct habitat. Significant broad gravel riffles dominate the reach, as do cooler water temperatures.

All three of these native species are commonly associated with such habitats in other areas of California (Moyle 1976; Moyle and others 1982).

Another transition occurs at about rkm 50 (Figure 15A, 15B, and 15C). Downstream of this point the native species occur less frequently in samples and most of the introduced species reach their maximum frequency of occurrence. This location approximately corresponds to a reach of river that has been significantly affected by gravel mining. The gravel pits serve as a velocity refuge during high flows for many of the introduced species found in the river. When flows decrease the introduced species can re-invade both upstream and downstream areas. The area between rkm 50 and rkm 80 represents an area of overlap between the areas dominated by native and introduced species.

Red shiner, inland silverside, and golden shiner exhibited another pattern of distribution. These species were most commonly found at the most downstream stations. These results are consistent with Brown (2000) who described the former two species as San Joaquin River mainstem species because they were most abundant in that river and only entered tributaries such as the Tuolumne River for short distances. These results were interpreted to indicate that these species consistently invade the tributaries and perhaps maintain populations there but conditions in more upstream areas are unfavorable in some way. Brown (2000) did not capture golden shiners in his study (sampling 1993–1995), suggesting a different process may be occurring for this species.

The data on splittail and tule perch indicate that other native species do occasionally make their way into the Tuolumne River. The data on splittail were particularly interesting because previously published studies of fishes in the San Joaquin River drainage indicated splittail only occurred rarely in the system (Saiki 1984; Brown and Moyle 1993). Sommer and others (1997) noted those studies were based on summer sampling. It appears that splittail move into the upper San Joaquin River to spawn in some years (Sommer and others 1997) and that either additional spawning or young-of-year rearing occurs in the lower reaches of the tributary rivers including the Tuolumne River. Brown (2000) captured young-of-year splittail in the lower reaches of both the Tuolumne and Merced rivers in 1995. Brown (2000) found tule perch to be abundant in the Stanislaus River but not in the mainstem San Joaquin River or the other tributaries. Saiki (1984) observed tule perch in the San Joaquin River but did not sample the tributaries extensively. Brown (2000) suggested that the high summer flows in the Stanislaus River combined with extensive beds of aquatic vegetation provided a type of habitat not widely available in other streams in the lower San Joaquin River drainage.

Fish Species Assemblages

No other long-term data sets are available for winter-spring resident fish assemblages in the San Joaquin River system (Brown 1997), making this data set unusual. The results of the DCA indicate that there is significant annual variability in the winter-spring resident fish assemblage that appears to be related to flow conditions. Examination of daily flow records suggests high percentages of native species are associated with high stream discharge in the winter of the previous year. Native species dominated in 1987 after the wet winter of 1985–1986. Introduced species became more dominant during the drought (1988–1992) with native species returning to high percentages at many sites in 1994 after the wet winter of 1993–1994. Native species continually occurred in high percentages starting in 1996 after the wet winter of 1994–1995.

The mechanism causing this switching is unclear. The native species are all riffle spawners and many of the introduced species are nesting species (Moyle 1976). It is likely that high outflows provide more appropriate spawning conditions for the native riffle spawners and poorer conditions for the introduced nesters. A number of recent analyses has suggested that natural flow regimes, including high winter-spring discharges, benefit native California stream species over introduced species (Baltz and Moyle 1993; Moyle and Light 1996a, 1996b; Brown and Moyle 1997). The spawning success hypothesis also explains why winter-spring assemblage structure lags behind the wet winter by a year. The bulk of the seining occurs before or during the spawning seasons of the majority of the resident species. The effect is seen in the seining data the following year, after the young have become large enough to be susceptible to the seine.

Another complication is the importance of red shiner in the analysis (Figure 16). Red shiner is a recent introduction and the species was actively invading the San Joaquin River system in 1986 (Jennings and Saiki 1990). It is likely that the invasion process is complete (Brown 2000); however, there are no conclusive data to that effect. It is unknown if the same patterns of annual change would be apparent in the absence of red shiner; however, it seems likely that inland silverside, which exhibits a similar pattern in frequency of occurrence (Figure 15C), might assume similar importance in the absence of red shiner.

The summer resident fish assemblage did not exhibit significant annual change, but the data were not as extensive as the winter-spring seining data, being limited to four years during the 1987–1992 drought. There was also little change in the winter-spring assemblage during the years (1989–1992) of summer sampling (compare Figures 17 and 18). Brown's study (2000) did include years with very different flow conditions and there were obvious differences in the summer fish assemblages. In the wet year (1995), native species were

present in downstream areas where they were absent or very rare during drier years (1993 and 1994). Despite the inability to use data from the present study to look at changes with flow conditions, the analysis did indicate some interesting patterns within the period analyzed.

In contrast to the winter-spring data, red shiner was only a minor component of the summer assemblage. As noted, this is consistent with Brown's (2000) observation that red shiner was rarely found in the large tributary rivers (Merced, Tuolumne, and Stanislaus rivers) to the San Joaquin River. Brown (2000) hypothesized that the low, clear water conditions prevalent in the tributaries during the summer are favorable for predators, resulting in heavy predation on red shiners that moved upstream during the winter and spring. Thus, the distribution of red shiners is a balance of invasion and predation mortality processes.

Native and introduced species appear to be more closely associated during the summer than during the winter and spring, with the exception of riffle sculpin (Figure 16). Riffle sculpin were found in high percentages at the most upstream sites probably for two reasons. The gravel riffle habitat they were associated with is most abundant in the most upstream areas and water temperatures are coolest there. Temperature has been found to limit the downstream distribution of riffle sculpin in other Central Valley streams (Baltz and others 1982).

The other native species were closely associated with introduced species (Figure 16). This is unusual compared to the Merced and Stanislaus rivers. Multivariate analyses presented in Brown (2000) indicate a close association of native and introduced species in the Tuolumne River, but in the Merced and the Stanislaus rivers, the most upstream sites were clearly dominated by native species. This difference may be related to the summer flow regimes and water diversion practices in the two rivers. In the Merced River, the native species dominate the river upstream of a series of diversion dams, but introduced species dominate downstream of the diversions. Flows in the Stanislaus River are relatively high all summer because of upstream releases to control water quality in the San Joaquin River and native species are dominant at several upstream sites. In the Tuolumne River, the major diversions are made at La Grange Dam with summer releases being relatively small (particularly during the period of study), and introduced species were present throughout the system. These results are also consistent with the hypothesis described earlier that natural hydrologic patterns appear to favor the native species (Baltz and Moyle 1993; Moyle and Light 1996a, 1996b; Brown and Moyle 1997). The recent implementation of new minimum summer flow requirements (FERC 1996) may change the pattern to one more similar to that observed in the other tributaries.

The comparisons between early and late samples indicate that significant changes can occur in resident fish assemblages over the course of the summer (Figure 18). It is unclear what process is causing these changes. There may simply be random events due to immigration and emigration. Changes might also result from physical or biological processes such as temperature avoidance as the river warms during the summer or competition or predation among species as low summer flows concentrate fishes into limited depth and cover refugia. More detailed field and laboratory work is necessary to clarify such processes and their interactions.

Monitoring of the resident fish community provides useful data on the effects of flow conditions on the river ecosystem. Continuation of the documentation of resident fishes in the winter-spring seining will provide a long-term database unmatched in any other Central Valley stream. Resumption of annual monitoring of summer fish assemblages could provide useful data on the positive or negative effects of changes in water management activities on native species of interest. Though resident species often appear to be of little management interest in the short term, they can often become critically important when populations reach low levels and threatened or endangered status becomes a possibility. The splittail, recently listed as a federal threatened species, is a good example. Effective monitoring of all species seems a worthwhile investment to reduce future uncertainty in management concerns.

References

- Baltz DM, Moyle PB. 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. *Ecol Appl* 3:246-55.
- Baltz DM, Moyle PB, Knight NJ. 1982. Competitive interactions between benthic stream fishes, riffle sculpin, *Cottus gulosus*, and speckled dace, *Rhinichthys osculus*. *Can J Fish Aquat Sc* 39:1502-11.
- Brown LR. 1997. Aquatic biology of the San Joaquin-Tulare basins: analysis of available data through 1992. US Geological Survey Water-Supply Paper 2471. 89 p.
- Brown LR. 2000. Fish communities and their associations with environmental variables, lower San Joaquin River drainage, California. *Environ Biol Fish* 57:251-69.
- Brown LR, Moyle PB. 1993. Distribution, ecology, and status of the fishes of the San Joaquin River drainage, California. *California Fish and Game* 79:96-114.
- Brown LR, Moyle PB. 1997. Invading species in the Eel River, California: successes failures, and relationships with resident species. *Environ Biol Fish* 49:271-91.

- [EA] EA Engineering, Science, and Technology. 1991. Report of Turlock Irrigation District and Modesto Irrigation District pursuant to Article 39 of the license for the Don Pedro Project nr. 2299. Lafayette (CA): EA Engineering, Science, and Technology.
- [EA] EA Engineering, Science, and Technology. 1997. 1996 FERC report: lower Tuolumne River. Annual report to the Federal Energy Regulatory Commission, Washington, DC. Prepared for Turlock Irrigation District and Modesto Irrigation District, California.
- [FERC] Federal Energy Regulatory Commission. 1996. Projects nrs. 2299-024 and 2299-031: order amending license and dismissing rehearing requests. 15 p.
- Fry DH. 1961. King salmon spawning stocks of the California Central Valley, 1940-1959. *California Fish and Game* 47:55-71.
- Fry DH, Petrovich A. 1970. King salmon (*Oncorhynchus tshawytscha*) spawning stocks of the California Central Valley, 1953-1969. California Department of Fish and Game anadromous fisheries administrative report 70-11.
- Jennings MR, Saiki MK. 1990. Establishment of red shiner, *Notropis lutrensis*, in the San Joaquin Valley, California. *California Fish and Game* 76:46-57.
- Moyle PB. 1976. Inland fishes of California. Berkeley (CA): University of California Press.
- Moyle PB, Light T. 1996a. Fish invasions in California: do abiotic factors determine success? *Ecology* 77:1666-70.
- Moyle PB, Light T. 1996b. Biological invasions of fresh water: empirical rules and assembly theory. *Biol Conserv* 78:149-62.
- Moyle PB, Smith JJ, Daniels RA, Taylor TL, Price DG, Baltz DM. 1982. Distribution and ecology of stream fishes of the Sacramento-San Joaquin drainage system, California. *University of California Publications in Zoology* 115:1-256.
- Moyle PB, Yoshiyama RM, Williams JE, Wikramanayake ED. 1995. Fish species of special concern in California, 2nd ed. Final report for Contract Nr. 2128IF. Rancho Cordova (CA): California Department of Fish and Game.
- [NMFS] National Marine Fisheries Service. 1998. Endangered and threatened species: proposed endangered status for two chinook salmon ESUs and proposed threatened status for five chinook ESUs; proposed redefinition, threatened status, and revision of critical habitat for one chinook salmon ESU; proposed designation of chinook salmon critical habitat in California, Oregon, Washington, Idaho. *Federal Register* 63:11481-519.

- [NMFS] National Marine Fisheries Service. 1999. West coast salmon and endangered species act listing status: chinook. Available at <http://www.nwr.noaa.gov/1salmon/salmesa/pubs/1pgr.pdf>. Accessed on 12 December 2000.
- [NRC] National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Washington, DC: National Academy Press. 452 p.
- Saiki MK. 1984. Environmental conditions and fish faunas in low elevation rivers on the irrigated San Joaquin Valley floor. *California Fish and Game* 70:145-57.
- Sommer T, Baxter R, Herbold B. 1997. Resilience of splittail in the Sacramento-San Joaquin estuary. *Trans Am Fish Soc* 126:961-76.
- [TID and MID] Turlock Irrigation District and Modesto Irrigation District. 1998. 1997 FERC report: lower Tuolumne River. Second annual report to the Federal Energy Regulatory Commission as required by Section (F), amending Article 58, and Section (G) of the 31JUL96 FERC Order of Project License 2299 and by Section 15 of the 1995 Don Pedro Project FERC Settlement Agreement (FSA). Prepared by T. Ford, Turlock and Modesto Irrigation Districts and EA Engineering, Science, and Technology. Lafayette, California.
- [USFWS] US Fish and Wildlife Service. 1995. Sacramento-San Joaquin Delta native fishes recovery plan. Portland (OR): US Fish and Wildlife Service. 195 p.

Building Models and Gathering Data: Can We Do This Better?

Wim Kimmerer, Bill Mitchell, and Andy Hamilton

Abstract

We are constructing a “second generation” model of chinook salmon for the Sacramento Basin to help investigate factors affecting salmon populations and the effects of management actions. We chose to build a new model rather than modify an older one to apply recent developments in computer interfaces and individual-based modeling and to incorporate a more detailed and flexible geographic representation. We also expected that substantial new knowledge had been developed that would enable us better to characterize the life cycle and influences on survival of chinook salmon. These expectations have not been met, and despite some recent progress we still find gaps between the knowledge available and that needed for successful modeling. Key examples of gaps in our knowledge include sublethal temperature effects, abundance of young fish, factors triggering migration, factors limiting rearing habitat, and survival of young salmon, particularly fry rearing in the mainstem or Delta reaches and early survival in the ocean. We believe these gaps arise for several reasons: (1) a mismatch in perceptions of what data are needed; (2) a lack of institutional commitment to long-term, broad-scale programs to provide knowledge useful in modeling; and (3) the fundamental difficulty of gathering information about environmental influences on fish populations.

Introduction

Models are representations of real-world objects or systems. Simulation models are formal mathematical representations of dynamic systems developed to examine the time course of system response to selected inputs. These models can be used as research or management tools or, if the underlying mathematics and parameters are known well enough, for prediction. Models of ecological systems are rarely suitable for prediction. Simulation models can be useful in investigating properties of a complex system, but are also useful as a framework for organizing knowledge and identifying knowledge gaps.

We are in the second phase of development of a chinook salmon simulation model for the Sacramento Basin. In the first phase we developed a conceptual model which has been distributed for review. In the second phase we are receiving and discussing comments on the conceptual model, while developing the code for the simulation model with the initial goal of producing a working prototype.

In this paper we briefly describe the model and some of its potential uses. We then discuss the more significant gaps in knowledge that have been identified during model development. Some of these gaps have been known for many years, yet little progress has so far been made to close them. We discuss some possible reasons for this and potential remedies that could lead to more effective allocation of effort devoted to research and monitoring on salmon biology and better understanding of the effects of human actions on salmon life histories.

Background

The Central Valley Project Improvement Act (CVPIA), an ambitious effort to increase production of chinook salmon in the Central Valley, mandates the development of "ecosystem models" to support understanding of potential measures needed to restore anadromous fisheries. The model described here is an element of the ecosystem modeling effort designed to assist with analyses and comparison of various alternatives for water and fisheries management. It is intended to build on both current understanding of the ecology of salmon and experiences of previous modeling efforts for chinook salmon in the Central Valley. These efforts include the following:

1. A simple stock-recruit model used to investigate effects of Delta conditions (Kelley and others 1986)
2. CPOP, a cohort simulation model of Sacramento Basin fall-run or winter-run chinook salmon (Kimmerer and others 1989), written in Fortran.
3. EACH, a simulation model for the San Joaquin Basin with similar structure to CPOP, written in Stella (EA Engineering, Science, and Technology 1991).
4. Two statistical models of the effects of Delta conditions on San Joaquin Basin chinook salmon (Speed 1993; Rein 1994: <http://felix.vcu.edu/~srein/chinook.ASA/talk.html>).

5. An individual-based simulation model of chinook salmon smolt production in the Tuolumne River (Jager and others 1996).
6. Statistical models of mark-recapture experiments using salmon smolts in the Delta (Kjelson and others 1982; Baker and others 1995; Rice and Newman 1997).
7. The CRiSP model of chinook salmon smolt passage, originally developed for the Columbia River by the University of Washington, modified for the Sacramento River in a student paper (<http://www.cqs.washington.edu/papers/sacramento.html>).
8. A survival model of winter-run salmon (Botsford and Brittnacher 1996).

We refer to our model as a “second-generation” model, because it builds on the results of previous modeling efforts. This model differs from previous models: it applies to all races in the Sacramento Basin; uses an individual-based approach; takes input from a variety of data sources, including flow and temperature data or model output; is designed in modules to simplify analyses of selected stages of the life cycle; will have a modern user interface so users can spend their time learning about the model rather than the program; and is being programmed in an object-oriented language that will make future modifications relatively straightforward.

The model is essentially a large combination of conditional statements about the salmon population. It contains various mathematical descriptions of attributes of habitat and individual fish, which determine responses of salmon to their environment. Many of the mathematical descriptions and the parameters and input variables used to develop numerical values for responses are based on limited data or expert opinion. Thus, it is extremely unlikely that all of them are accurate, so output of the model is not reliable as a prediction of future salmon population trends. Rather, the model will be most useful in a comparison among alternative scenarios. Provision will be made for varying important parameters and selecting alternative mathematical descriptions of functional relationships to determine the sensitivity of the conclusions based on model runs to the assumptions contained in the model.

Model Description

The model is capable of simulating the entire life cycle of all four races of chinook salmon in the Sacramento Basin (Figure 1). Conceptually the model can be divided into the four modules shown in the figure. Individual modules, corresponding to stages of the life cycle, can be run independently to simplify the model run for particular purposes. This will be a useful feature for investigating particular aspects of the life cycle such as spawning or ocean life.

We have chosen to use an individual-based modeling approach (DeAngelis and Gross 1995). Individual-based models (IBMs), also known as agent-based or multi-agent models, are a relatively recent development in modeling made possible by substantial advances in computer memory and speed. In an IBM, populations are represented by some number of individual entities, rather than by cohorts or other aggregates. Models written at the cohort or higher levels of aggregation have many advantages, but they do not accurately portray the population response to environmental change when the individuals in a cohort undergo different trajectories of growth or movement. This can happen when, for example, physical habitat is occupied at a small scale so that different fish experience different environments. A cohort model also suffers from the disadvantage that any nonlinear response of the fish to their environment distorts the statistical distribution of properties within the cohort (e.g., mean weight). Finally, some environmental influences act on individuals over a long period relative to the simulated time step; resolving variable temporal influences can be very complicated in a cohort or similar model.

In an IBM, there is no difficulty resolving whatever level of spatial or temporal resolution is of interest, and heterogeneity at the selected level of resolution is incorporated explicitly in the model. Any environmental influence requiring a "memory" of past conditions (e.g., thermal or toxic stress, feeding history) is easily represented. Nonlinearities in responses do not result in distortion of distributions of properties. Events occurring at the individual level, such as movement, growth, or death, are summed to arrive at the population response.

There are significant advantages in the individual-based approach: clarity and consistency of logic; unambiguous "currency" of the model (i.e., individual fish); ease of tracking movements and adding new features (e.g., energetic and genetic effects, interactions); ease of accumulating effects of past conditions (e.g., toxic body burden and condition factor); and straightforward simulation of responses to a spatially and temporally heterogeneous environment.

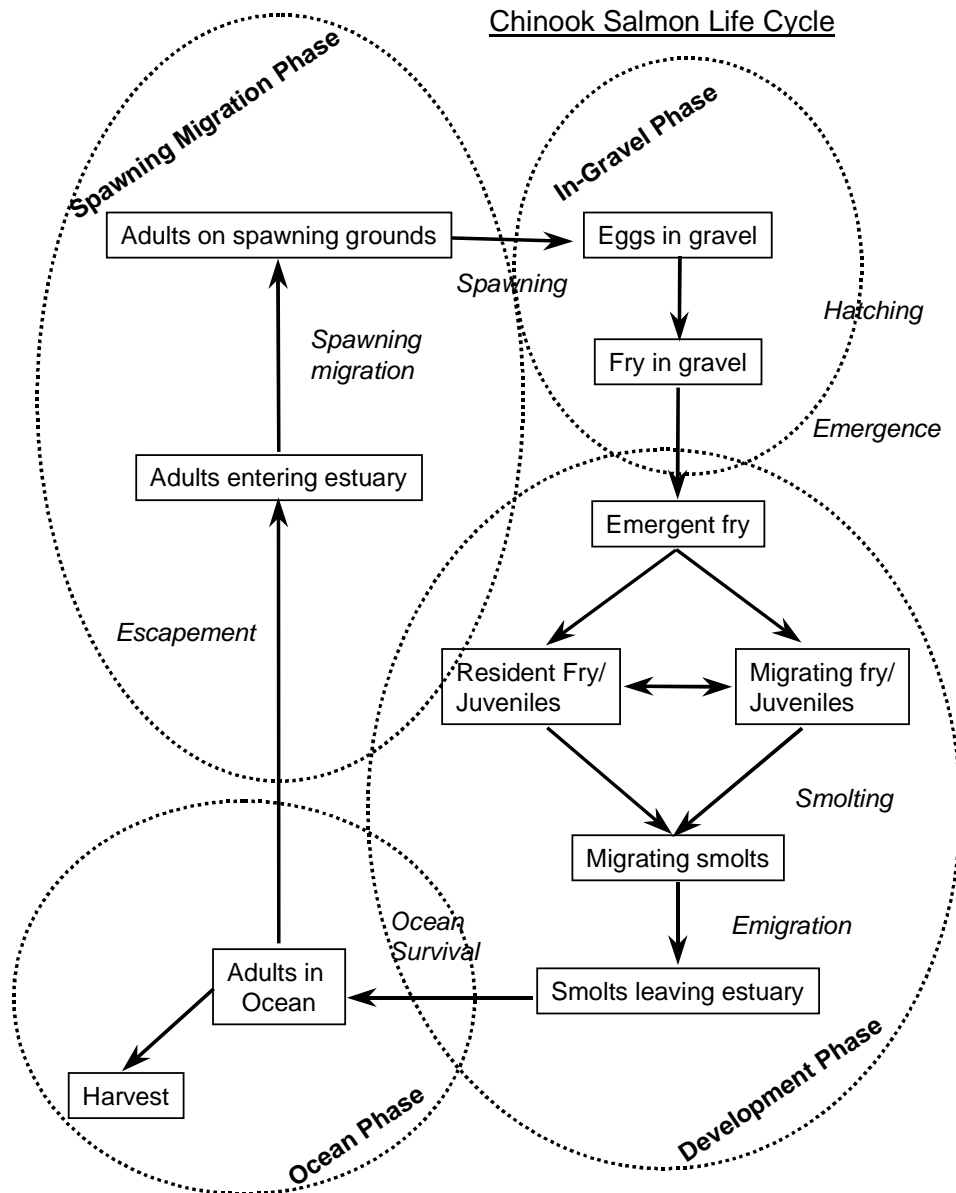


Figure 1 Key points in the life cycle of chinook salmon. The four oval areas represent the major life stages, represented by separate modules in the model. Arrows indicate a change of state of surviving salmon, with ocean harvest represented explicitly but other mortality not shown. Terms in italics indicate major life history events occurring in each stage.

The principal disadvantage of an IBM is that it is computationally intensive, and the computer power needed to run the model can be difficult to predict. Furthermore, simulating explicitly the hundreds of millions of fall-run juveniles in the Sacramento Basin would make the model unwieldy even with the fastest available computers. Therefore, the populations will be represented by a sample of the actual fish, and each model fish will be a "super-individual" representing some number of individuals (Scheffer and others 1995). This method, which is analogous to stratified sampling in opinion polls, should provide equivalent results to modeling every individual but at a manageable cost in computer time. It may be superior to the resampling method of Rose and others (1993), which can introduce bias if the number of model fish is too low (Scheffer and others 1995). It is also different from cohort modeling because sufficient numbers of sample fish are tracked to represent adequately the full range of variability in the population. The ratio of model to actual fish can be varied among life stages and races to keep the sample size large. Thus, abundant fall-run fry will be represented at a fairly small ratio of model to actual fish, while winter-run (and initially all) adults will be represented at a ratio of 1:1. Preliminary testing will ensure that the ratio selected does not bias the results. Clearly the selection of these ratios will represent a compromise between the speed at which the model runs and the amount of bias or error due to aggregation, and can change with type of model run and available computer power.

The individual-based approach lends itself directly to the use of object-oriented programming methods. In contrast to procedural languages (e.g., FORTRAN, C), an object-oriented language isolates elements of the program as "objects" which pass, receive, and respond to "messages." Objects may be any element of the program, but are most useful when they bear direct relationships to real objects, such as fish, river reaches, or computer windows. Thus, there is a direct correspondence between individuals in the model and objects in the program, making the transition from conceptual model to computer program as straightforward as possible. We have chosen to use the Swarm software package for multi-agent simulation of complex systems, developed by the Santa Fe Institute. This package comes with several ready-made objects and tools for input and analysis that will simplify coding and testing the model.

As noted previously, we have developed a draft conceptual model (Kimmerer and Jones & Stokes Associates 1998) and an annotated bibliography. We are proceeding on three parallel tracks in model development: (1) refining the conceptual model based on comments received, discussions with interested parties, and experience with submodels; (2) assessing the data available for model input; and (3) developing a model formulation in Swarm focusing initially on in-river life stages.

Principal Gaps in Knowledge

Significant advances have been made in understanding the biology of Sacramento Basin salmon since the previous population models were developed. However, our assessment of the available information gives little encouragement that the principal gaps have been filled. Although the model can be used to some degree to explore the consequences of different assumptions about these gaps, a lack of solid understanding may restrict use of the model for management purposes.

It is relatively easy to identify knowledge gaps, and several key ones are discussed below. However, a significant problem we have encountered in attempting to fill these gaps is that relatively few of the existing data are in the form of published reports or articles. Much of the information is either anecdotal, or has not yet been published or widely disseminated. Some data are presented in technical reports, but the data are not made available to the research community on a timely basis.

Thermal Effects Below Lethal Limits. When temperature exceeds lethal limits, mortality is expected to be rapid, but results of mark-recapture experiments in the Delta suggest effects at temperatures below these limits (Kjelson and Brandes 1989; Rice and Newman 1997). Although these effects could be artifacts from the use of hatchery smolts or other aspects of the experiments, it is also likely that similar effects apply to naturally-reared fish. If so, similar temperature effects should occur throughout the river system. They may arise through physiological changes that affect growth, disease resistance, predator avoidance, and smolting, through ecological effects such as increased predator activity or increased food requirement without an increase in supply, or through a combination of these effects. Since temperature in the system often varies within the range at which these effects seem to occur, these effects may be important influences on survival of young salmon. Available information on thermal effects, however, is largely confined to laboratory experiments on temperature above lethal limits, with abundant food (e.g., Brett 1952). The potential effects listed above remain virtually unexamined.

Abundance of Young Fish. There are reasonably good estimates of adult and redd abundance, although abundance of some adults has become more difficult to determine with the revised operation of the Red Bluff Diversion Dam, where dam gates are open during most of the upstream migration period. However, estimates of fry or smolt abundance in the rivers are uncommon, and although the data are available, estimates of abundance have not been made for the Delta. Many measurements of abundance in the river system provide only indices rather than actual abundance values. The problem is for many measures of abundance, no suitable method has been developed to calibrate

the measures to the actual number of fish passing a point or residing in an area. Although these indices are adequate for comparing abundance data among years and investigating effects of local restoration actions, they fall short of the data needed to develop a comprehensive view of the salmon population. In particular, mortality values, essential for assessing population status, require accurate abundance estimates.

Availability of Rearing Habitat. Recent data suggest that most of the young salmon in some of the rivers leave their natal streams shortly after emergence (Snider and others 1997). Furthermore, beach-seining data show large numbers of salmon fry in the lower Sacramento River and the Delta (Kjelson and Raquel 1981; Brandes and McLain, this volume). This implies the existence of two very different life histories, that is, fish that rear largely in the natal streams and those that rear mostly downstream. The relative contribution to recruitment by these life histories needs to be assessed, and some effort needs to be made to determine the factors that induce the young salmon to migrate as early fry instead of rearing in the natal streams. This may relate to the carrying capacity of different parts of the system for rearing salmon, which may be a key element in density dependence and therefore population regulation (for example, Elliott 1989). However, existing data are insufficient to assess the importance of rearing in the natal river compared with the mainstem Sacramento River and Delta, the factors influencing the availability of rearing habitat, or the factors that stimulate movement of pre-smolt salmon. The principal issue is where and under what conditions the extent or quality of physical habitat limits the abundance or survival of rearing salmon. Although the model may be useful in testing the outcome of alternative conceptual models about rearing habitat, the ultimate answer to its importance must be obtained through hypothesis-driven field research. The importance of rearing habitat has obvious, large implications for the success of alternative restoration actions.

Survival of Young Salmon. A related issue about which little is known is survival during early life. Survival through hatching and emergence is at least qualitatively understood to be high except in cases of extreme changes in flow or high temperature. However, survival during rearing, seaward migration, and early ocean life is unknown, except for survival indices for smolts passing through the Delta. The location of rearing may have a big effect on survival: for example, density-dependent migration out of the natal stream combined with lower, density-independent survival in the Delta would result in density-dependent survival. Little is known about the influence of food supply on survival, nor is there good information on the abundance and activity of predators. Finally, the occurrence and locus of density dependence, a crucial ecological feedback to any biological population, is unknown; previous studies have shown evidence of density dependence in young salmonids both in

streams (Neilson and Banford 1983; Elliott 1989) and in the ocean (Peterman 1984).

Filling these knowledge gaps will not be easy. Most of them would require a coordinated effort involving a variety of agencies and a long time frame. However, without this information the effects of restoration actions will be difficult to predict, and therefore the actions will be difficult to justify.

Filling the Knowledge Gaps

Why are these information gaps still present? We do not wish to understate the difficulty of gathering the kind of knowledge described above, nor to denigrate the efforts of the biologists investigating Central Valley salmon. Much of the difficulty lies with the complexity of the ecosystem and the populations to be investigated. Nevertheless, we believe there are some key impediments to filling these knowledge gaps, and removing or reducing these impediments may improve the rate at which the gaps are filled.

The first impediment is a mismatch in perception among modelers, fish biologists, and managers about what data are needed and how to use a model. Modelers tend to focus on the “big picture,” with less attention to details and a tendency for excessive generalization. Fish biologists tend to have a deeper understanding of certain topics, but a narrower view, often constrained by their experience to certain aspects of geography or life history. Understandably, many fish biologists tend to view data needs in terms of their own research experience. Many managers prefer not to hear about uncertainty and tend to rely heavily on expert opinion or on well-presented (usually conceptual or statistical) models. Although managers often support status and trends monitoring, they may see little need for research aimed at fundamental questions, which can be expensive and risky. The perspectives of these three groups do not lend themselves to a coordinated attack on the key problems, because each group sees the key issues differently.

The second impediment is what we see as a lack of institutional commitment to resolving system-level uncertainties. Much of the work being done by fish biologists and other scientists in the system is focused on particular exigencies, mostly related to endangered-species protection. Thus, little time is available for consideration of larger issues. There is no agency whose mission is solely to investigate and understand the biology of salmon and the influences on it. Each of the resource agencies has significant other duties, particularly environmental or endangered-species protection, that may actually impede progress toward understanding at a system level. This impediment has been evident in the resistance of some agency biologists to adaptive management experiments designed to determine the effects of certain management actions

on salmon populations when the experimental actions were seen as potentially (but not demonstrably) harmful.

There also seems to be a strong degree of territoriality in the Central Valley salmon biology field. Although the situation is improving (for example, with this Symposium), there is still a remarkable lack of collaboration among researchers. This situation is particularly alarming given the amount of work being done at public expense and the importance of salmon to the Central Valley's ecosystems and economy.

Several potential approaches may help to resolve these issues. The most direct is individual commitment by fish biologists to consider the "big picture" in what they do on a daily basis and to continually re-evaluate their contribution. Although such a commitment would seem consistent with the role and activities of scientists, it would be naive to expect individual scientists to deviate much from their immediate interests to the common good, at least without added incentive.

This indicates a need for institutional commitment to working toward answering large-scale questions. This commitment could be underwritten by one of the larger organizations (e.g., CALFED Bay-Delta Program, Comprehensive Monitoring, Assessment and Research Program, Interagency Ecological Program), but the individual agencies would still have to support the contributions of their own fish biologists to the larger view. This may be seen as contrary to the mission of resource agencies, which have immediate responsibilities for endangered-species protection and other activities that may preclude devoting adequate attention to large-scale issues. One mechanism for enlarging the view of agency biologists is to make publication in peer-reviewed journals a criterion for promotion. The process of preparing a paper and getting it through the review process is an excellent way of helping a researcher to put his or her work in a larger context.

An alternative method for filling gaps is to establish a small, dynamic research team whose sole mission would be to gather, analyze, and publish data specifically related to population-level issues. This team could be given the mandate to collect data from other researchers, and to initiate field research projects into areas outside of the interests of other agencies. Mechanisms would have to be established to ensure cooperation by agency biologists, and reciprocally to ensure partnerships between members of this team and agency biologists.

An additional aid to filling in knowledge gaps is to make data freely available. Although data are routinely published in annual and other reports, these data are not readily available to other researchers. Identifying and obtaining data has been one of the most time-consuming and frustrating activities in our modeling work. These data have been collected by public agencies with public

funds, and the maximum possible use should be made of them. The prerogative of the investigators to publish their results can be upheld through a delay time of no more than one year from the date of collection to the date at which the data are made available on an Internet site. The salmon monitoring and research community would do well to follow the lead of the Interagency Ecological Program in terms of data dissemination and availability.

Regardless of the mechanism used, we urge managers and biologists to consider seriously the need for better use of the available information, better mechanisms for determining what information is gathered, and research targeted at a more comprehensive view of the biology and population dynamics of salmon.

In our model development to date, we have found it easy to identify significant gaps in the knowledge about salmon, as discussed above. No model runs were necessary to convince us that the gaps are serious impediments to understanding the complete life cycle of chinook salmon. As the simulation model is developed, we anticipate using sensitivity analysis to further delineate where significant gaps occur, and possibly to develop methods for filling the gaps. We hope that as this work progresses some of the impediments to knowledge discussed above can be removed, and progress can be made toward filling the gaps.

References

- Baker PF, Speed TP, Ligon FK. 1995. Estimating the influence of temperature on the survival of chinook salmon smolts (*Oncorhynchus tshawytscha*) migrating through the Sacramento-San Joaquin River Delta of California. *Can J Fish Aquat Sci* 52:855-63.
- Botsford LW, Brittnacher JG. 1996. Viability of a Pacific salmon population: the Sacramento River winter run chinook. Unpublished draft manuscript. Center for Population Biology, University of California, Davis.
- Brandes P, McLain J. 2001. Juvenile chinook salmon abundance, distribution, and survival in the Sacramento-San Joaquin Estuary. In: Brown RL, editor. *Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 2.* Sacramento (CA): California Department of Fish and Game.
- Brett JR. 1952. Temperature tolerance of young Pacific salmon, genus *Oncorhynchus*. *J Fish Res Board Can* 9:265-309.
- DeAngelis DL, Gross LJ, editors. 1995. *Individual-based models and approaches in ecology.* New York: Chapman.

- EA Engineering, Science, and Technology. 1991. San Joaquin River system chinook salmon population model documentation. Prepared for Turlock and Modesto Irrigation Districts, California.
- Elliott JM. 1989. Mechanisms responsible for population regulation in young migratory trout, *Salmo trutta*. I. The critical time for survival. *Journal of Animal Ecology* 58:987-1001.
- Jager HI, Cardwell HE, Sale MJ, Bevelhimer MS, Coutant CC. 1996. Simulating the effects of instream flows on fall chinook salmon. Unpublished report. Oak Ridge (TN): Environmental Sciences Division, Oak Ridge National Laboratory.
- Kimmerer W, Jones & Stokes Associates Inc. 1998. Conceptual framework for the Sacramento River chinook salmon individual-based model. Draft report prepared for the US Fish and Wildlife Service. Sacramento, California.
- Kimmerer W, Hagar JM, Garcia J, Williams T. 1989. Chinook salmon population model for the Sacramento River basin, version CPOP-2. Tiburon (CA): Biosystems Analysis, Inc.
- Kjelson MA, Raquel PF. 1981. The life history of fall run juvenile chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento-San Joaquin Estuary of California. *Estuaries* 4:285.
- Kjelson MA, Raquel PF, Fisher FW. 1982. Life history of fall-run juvenile chinook salmon, *Oncorhynchus tshawytscha*, in the Sacramento-San Joaquin estuary, California. In: Kennedy VS, editor. *Estuarine comparisons*. New York: Academic Press. p 393-411.
- Kjelson MA, Brandes P. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento-San Joaquin Rivers, California. In: Levings C, Holtby L, Henderson M, editors. *Proceedings of the National Workshop on Effects of Habitat Alteration on Salmonid Stocks*. *Can Spec Publ Fish Aquat Sci* 105:100-15.
- Neilson JD, Banford CE. 1983. Chinook salmon (*Oncorhynchus tshawytscha*) spawner characteristics in relation to redd physical features. *Can J Zool* 61:1524-31.
- Peterman RM. 1984. Density-dependent growth in early ocean life of sockeye salmon (*Oncorhynchus nerka*). *Can J Fish Aquat Sci* 41:1825-9.
- Rice J, Newman K. 1997. Statistical model for survival of chinook salmon smolts outmigrating through the lower Sacramento-San Joaquin system. Interagency Ecological Program Technical Report 59. Sacramento (CA): California Department of Water Resources.
- Rose KA, Christensen SW, DeAngelis DL. 1993. Individual-based modeling of populations with high mortality – a new method based on following a fixed number of model individuals. *Ecological Modelling* 68:273-92.

- Scheffer M, Baveco JM, DeAngelis DL, Rose KA, van Nes EH. 1995. Super-individuals, a simple solution for modelling large populations on an individual basis. *Ecological Modelling* 80:161-70.
- Snider B, Titus RG, Payne BA. 1997. Lower American River Emigration Survey, October 1995 - September 1996. California Department of Fish and Game, Environmental Services Division, Stream Evaluation Program.
- Speed T. 1993. Modelling and managing a salmon population. In: Barnett V, Turkman KF, editors. *Statistics for the environment*. New York: J Wiley & Sons. p 268-90.

Exploring the Role of Captive Broodstock Programs in Salmon Restoration

Kristen D. Arkush and Paul A. Siri

Abstract

Severe population declines have occurred in many Pacific salmon stocks. Stock declines have been attributed to both anthropogenic and natural environmental causes. These declines have been so dramatic that resource agencies have not had the time or means to quantitatively describe stocks and develop rapid, reliable methods of conserving rare genes. One method to prevent extinction is gene banking by means of rearing broodstock in captivity for use in supplementing rare and endangered stocks. With varying degrees of success, several captive breeding programs have been initiated to provide "insurance" against genetic loss of imperiled stocks. Captive breeding is expensive, requiring long-term intensive fish husbandry. It is not an alternative to habitat restoration. In certain situations, such as small runs (20 to 100 spawning adults) combined with habitat undergoing restoration, captive breeding may be a desirable supplementation strategy. It is certainly a beneficial option for any stock on the edge of extinction. There are several salmon captive broodstock programs on the west coast of North America, each employing different approaches and technologies. Captive breeding techniques are evolved to a point where the progeny of wild fish can be reared with a high degree of success. However, this kind of intervention is costly and must be weighed against other factors that will determine stock recovery. It is incumbent upon managers and scientists to define the uncertainty, or risk, of captive breeding. Risk assessment is an essential component of any captive breeding program. Emerging captive breeding programs can benefit from the range of experience and technological development that has evolved over the past decade. Molecular genetics, captive broodstock technology, conservation biology, and fisheries supplementation risk assessment have matured to a stage where salmonid captive breeding can be planned as an intervention with a measured effect.

Captive Breeding as a Response to Declining Salmon Stocks

During the last four hundred years, approximately 490 described animal species are known to have become extinct (Magin and others 1994). Approximately 24,600 species of fish (in 482 families) exist worldwide, although this number may reach 28,500 as more species are described (Nelson 1994). The International Union for the Conservation of Nature (IUCN) has compiled a list of threatened or extinct fish species, documenting the downward trend in aquatic biodiversity (IUCN 1996). Moyle and Leidy (1992) estimated that 20% of the freshwater fishes of the world is at risk of extinction, yet this figure is likely very conservative (Leidy and Moyle 1998).

Anadromous salmonids, including many stocks of Pacific salmon along the west coast of North America, have experienced severe population declines. The Northwest Power Planning Council (1987) reported that annual returns of anadromous salmon and trout decreased from an estimated 12 to 16 million in the 1880s to 2.5 million fish in the 1980s. At least 106 major populations of salmon and steelhead have been extirpated from the West Coast (Nehlsen and others 1991). Nehlsen and others (1991) identified 214 stocks of Pacific salmonids from California, Oregon, Idaho, and Washington that face a high or moderate risk of extinction. Stock declines have been attributed to both anthropogenic and natural causes including land-use practices such as urbanization and logging, reduction of genetic diversity in native stocks and introduction of disease through hatchery production, overharvest, and flood and drought events (Nehlsen and others 1991; Pearcy 1992; NRC 1996).

The role of hatcheries in the conservation of wild salmon populations depends upon a keen appreciation of the reproductive interactions among and between hatchery and wild salmon (Fleming 1994). True "gene banking" efforts based on sperm cryopreservation to avoid the loss of valuable genotypes have been initiated for Snake River sockeye salmon (*Oncorhynchus nerka*) and chinook salmon (*O. tshawytscha*) in the Columbia River of the northwestern United States (Thorgaard and others 1998). Captive breeding can be considered a form of gene banking in that it relies on the captive rearing of the living genetic resource. Unlike conventional salmon hatcheries that rear animals to fry or smolts in single cohorts, captive breeding requires the maintenance of multiple age classes, in numerous family groups, to maturation. As such, captive breeding programs are costly and labor intensive.

Captive propagation is becoming accepted as one component of species enhancement (Gipps 1991; Johnson and Jensen 1991; Olney and others 1994). For example, the U.S. Fish and Wildlife Service uses captive propagation to enhance populations of nearly 30% of the non-anadromous North American fish species listed under the federal Endangered Species Act (USFWS 1990;

Johnson and Jensen 1991). With varying degrees of success, several captive breeding programs have been initiated to provide "insurance" against genetic loss of imperiled stocks. While captive breeding may be less cost-effective in the long-term than *in situ* preservation, it may provide the only mechanism to prevent extirpation of a stock, especially before or during the early implementation of an environmental recovery program. Indeed, the National Research Council (1996) now recognizes that long-term sustainability requires conservation of both wild populations and their natural habitats. Ecosystem-wide approaches are beginning to be recognized and adopted on both the theoretical and practical levels.

One aspect of the ecosystem approach to salmon restoration that is gaining attention is the role of salmon in the regeneration of forest-stream systems (Bilby and others 1996, National Research Council 1996). It is possible, given the multiple pathways salmon create for marine-derived nutrients to enter watersheds, that there is a critical abundance threshold necessary to stabilize runs. The precipitous stock declines witnessed during the past twenty years are likely some combination of ecosystem and population effects. If this is the case then supplementation becomes a more important part of the restoration equation.

Captive breeding may entail *in situ* gene banking ("insurance" only) or it may include a supplementation to the watershed. In the case of salmon and anadromous trout, captive breeding typically involves the propagation and early life stage rearing of a stock with subsequent release at the fry, parr, or smolt stage. Snyder and others (1996) described several limitations of captive breeding in endangered species recovery and asserted that it should be viewed as a last resort to avoid species extinction instead of a prophylactic or long-term solution. Artificial propagation in itself is not the remedy to stock declines. On the contrary, it may even contribute to the decline of native populations (Goodman 1990), risking further loss of genetic resources (Waples 1991). Case-specific economic, biological, and conservation-related variables must be considered in determining the appropriateness of captive propagation for a particular species (Balmford and others 1995; Snyder and others 1996). For example, *ex situ* conservation for the purpose of supplementing wild stocks depends on successful reintroduction, which in turn depends on the availability of suitable habitat (Griffith and others 1989; Wilson and Stanley Price 1994). For threatened and endangered species, artificial propagation and release may not assist in their recovery, particularly in instances where population declines are the result of altered or unsuitable habitat for self-sustaining reproduction. In the case of natural salmon populations, supplementation is appropriate in two scenarios: (1) when short-term extinction risk for the population is high, and (2) in re-seeding vacant habitat that is unlikely to be colonized naturally within a reasonable time frame (Robin S. Waples, personal communication, see "Notes").

Surprisingly, Balmford and others (1996) found that existing captive breeding efforts in zoos for mammals failed to focus on species subject to potentially reversible pressures such as overexploitation or small-scale habitat deterioration. Captive breeding efforts for fish have received similar criticism. For Pacific salmon, the use of hatchery techniques in conservation has been criticized as being a "halfway technology" since supplementation of wild stocks with hatchery produced fish addresses a symptom (declining fish stocks) but not the causes (Meffe 1992). The World Conservation Union's Conservation Breeding Specialist Group (CBSG) has developed a series of Conservation Assessment and Management Plans (CAMPs) calling for long-term captive breeding of numerous taxa (Seal and others 1994). In 1993, Tear and others reported that of the current 314 approved recovery plans for U.S. endangered and threatened wildlife, 64% recommended captive breeding. In the case of salmonids, the Forest Ecosystem Management Assessment Team (FEMAT) identified 314 native stocks as being threatened with extinction (FEMAT 1993). Yet with only limited resources for conservation and recovery measures, Allendorf and others (1997) asserted that priorities should be established for stocks which are candidates for preservation. Limited resources dictate that only a few stocks can be identified for intervention potential. Given the uncertainty in predicting extinction rate using measures of cohort replacement rate and population growth rate for Pacific salmon (Botsford and Brittnacher 1998), this task is indeed daunting.

Benefits and Risks of Captive Breeding

Captive breeding programs can serve multiple objectives in salmon restoration. The Sacramento River Winter-Run Chinook Salmon Captive Broodstock (WRCCB) project was developed with multiple goals. WRCCB's primary objective is to maintain broodstock in captivity as an insurance program in the event the remaining wild population is further reduced or is extirpated. In this situation captive broodstock could serve as a gene bank to assist in rebuilding the stock. Alternatively, this propagation program can provide gametes for supplemental breeding. The supplementation strategy is based on the premise that an appropriate genetics program, developed in parallel with the broodstock technology, could guide the spawning of wild caught broodstock in tandem with captive broodstock. In this manner captive reared spawning candidates could expand the spawning options of the supplementation program, which can be limited if dependent solely on wild trapped fish.

Captive breeding differs significantly from conventional hatchery practice. Sound captive breeding should be based on rules of conservation biology that recognize the potential effect of creating a population of captive progeny that, if released, will influence the genetic variation of the remaining wild stock it is intended to enhance. Models of effective population size described by Ryman

and Laikre (1991) provide a means characterizing the interaction of two or more populations of salmon (in this case wild versus captive) at various production levels if the genetic variation is known. These models are essential if a captive broodstock program is going to operate as a true supplementation mechanism that enhances the genetic resource and contributes to species' recovery. Due to the high fecundity of salmon the risk of disproportionately supplementing the captively bred population can be serious and jeopardize the wild population. However, precise measures of genetic variation require sophisticated and expensive techniques such as molecular genetic analysis. This expense will limit application of these preferred methods of monitoring and evaluation. Without these techniques and proper evaluation captive breeding programs can easily introduce unacceptable risk to salmon recovery efforts aimed at assisting threatened and endangered populations. However, it should be recognized that integrating supplementation in a captive breeding program with interannual variation of the wild salmon counterpart links a captive breeding intervention with ecosystem function. This is a desirable model for the evolution of all hatchery practice.

If implemented as a basic element of stock recovery, captive breeding warrants assessment and evaluation to minimize risk posed to the stock it is addressing. Some of the ways risk can be manifested in captive breeding programs can be subtle. A major difference between conventional hatchery operation and captive breeding is that the gene banking aspect of captive rearing often includes rearing multiple cohorts of salmon from embryo to sexual maturation. This long-term husbandry increases the opportunity for artifacts of the captive setting to create differential mortality in the captive population or among captive family groups. Such artifacts lend themselves to various genetic sinks and are a cause for concern (Waples 1991). Allendorf and Waples (1996) have described genetic risks associated with supplementation programs including effects of broodstock collection on wild populations, reduction of fitness, and changes in reproductive potential in naturally spawning fish as a result of lack of control in restocking efforts.

In the last few years a few salmonid captive breeding projects have attempted to share information and develop methods based on sound science. A major obstacle of captive breeding is that by the time a population warrants such a serious intervention, the population is likely so reduced that true experimental approaches cannot proceed due to the limited number of fish available. And, for threatened and endangered species the protective nature of the federal Endangered Species Act (ESA) usually precludes invasive techniques such as tissue or serological assays and other conventional laboratory analyses of animal health and reproductive physiology. Given these unusual limitations captive breeding programs have been slow to evolve new techniques aimed at the special conditions of captively rearing and spawning undomesti-

cated fish. However, new technologies have emerged that set captive breeding programs apart from conventional hatcheries.

The Sacramento River winter-run chinook was the first anadromous salmonid population to be protected under the ESA. In November, 1990, the National Marine Fisheries Service (NMFS) issued a final listing of the Sacramento River winter-run chinook salmon as a threatened species (54 Federal Register {FR} 32085), and in February 1994 the stock was listed as endangered (59 FR 440). The WRCCB Project, now in its ninth year, has made substantial progress in both fish survival and gamete production (Arkush and others 1995). Application of advanced technologies in systems design such as computer controlled salinity systems that create seawater environments for smoltification have increased fish survivorship and simplified maintenance. Veterinary techniques such as the use of ultrasonography to assess maturation and even predict spawning time have been developed in concert with this project (Petervary and others, forthcoming). Moreover, the project has enabled significant advances in the areas of fish health and genetics, particularly with the development of molecular markers for genetic discrimination among stocks that have wide application in fisheries management (Banks and others 2000).

All of these developments demonstrate a divergence from conventional hatchery practices and set the stage for new possibilities in salmon restoration. In this way sound captive broodstock conduct creates the potential for changes in future hatchery practice. Scientifically-based captive broodstock programs have the ability to serve as research hatcheries, which have been proposed as one of several requirements for salmon restoration (Moyle 1993). Research hatcheries, based on sound conservation biology and captive breeding advances, can balance the need to continue salmon supplementation while identifying the changes required to move towards a larger conservation strategy (Hilborn 1992).

Integration with Habitat Recovery Plans

Threatened and endangered species restoration requires implementation of a carefully designed and comprehensive recovery plan as the ultimate goal. Artificial propagation programs can play a pivotal role in preventing extirpation of stocks. If such an intervention is warranted, it is critical that implementation is initiated before, and during, the early phases of recovery plan action. However, restoring naturally sustaining populations is the only way to address ecosystem-wide concerns; supplementation provides no equivalent. In accordance with Section 4(f) of the ESA, a recovery plan must be developed for species listed as endangered or threatened, and this plan must be implemented unless it is found not to promote conservation of the species. A recovery plan must include: (1) a description of site-specific management actions

necessary for recovery, (2) objective, measurable criteria, which when met, allow delisting of the species, and (3) estimates of the time and cost to carry out the recommended recovery measures.

The National Marine Fisheries Service (NMFS) identified several factors as major causes of the decline of the winter-run chinook salmon, such as elevated water temperatures in the upper Sacramento River and impediments to upstream and downstream migration at the Red Bluff Diversion Dam (Hedrick and others 1995; Botsford and Brittnacher 1998). However, there is a wide range of factors that affect winter-run chinook salmon survival, and all factors must be addressed to assist in its recovery. Hence, NMFS has concluded that no single action will suffice, and a comprehensive plan will require the participation of federal agencies, state and local governments, private industry, conservation organizations, and the public. Moreover, while the ESA is designed to recover individual species, the recovery plan for the winter-run chinook salmon must consider ecosystem restoration. Concurrent with the winter-run chinook salmon decline is the reduction of other native species of plants and animals in the Sacramento River ecosystem. Moyle and Williams (1990) described 46% of the native fish stocks of the Sacramento River drainage as extinct, endangered, or in need of special protection. The loss of native fish genetic resources is further complicated by the invasion of non-native species that increases the level of complexity in ecosystem restoration. Moyle and Light (1996) describe how invasive species and invaded systems interact in idiosyncratic ways that are difficult to predict. Further, the degree of integration of an invasive species will depend on the level and degree of human and natural disturbance to the aquatic system (Vermeij 1996). One hundred State and federal candidate, proposed, and listed plants and animals, and California Department of Fish and Game species of special concern occur in the present habitat range of the Sacramento winter-run chinook salmon (NMFS 1997). Clearly, recovery plans must incorporate some form of adaptive management plan to protect the endangered or threatened stocks as well as other flora and fauna identified as species of special concern during implementation. And, recovery plans need to be "plastic" so as to allow the inclusion of newly identified components of the ecosystem during the monitoring phase.

Conclusions

Captive breeding is an expensive and labor intensive effort. Programs such as the Winter-run Chinook Salmon Captive Broodstock Project have made significant contributions to the evolution of hatchery management practice while functioning as stop gap measures in the decline of natural stocks. Captive breeding programs that are defined by the rules of conservation biology can calibrate supplementation to increase abundance without loss of the genetic

variation they are intending to preserve. Captive breeding programs that operate as conservation hatcheries can be a template for future hatchery practice.

References

- Allendorf FW, Bayles D, Bottom DL, Currens KP, Frissell CA, Hankin D, Lichatowich JA, Nehlsen W, Trotter PC, Williams TH. 1997. Prioritizing Pacific salmon stocks for conservation. *Conserv Biol* 11(1):140-52.
- Allendorf FW, Waples RS. 1996. Conservation and genetics of salmonid fishes. In: Avise JC, Hamrick JL, editors. *Conservation genetics: case histories from nature*. xix+512 p. New York (NY): Chapman and Hall.
- Arkush KD, Banks MA, Hedgecock D, Siri PA, Hamelberg S. 1995. Winter-run chinook salmon captive broodstock program: progress report through April 1996. Interagency Ecological Program for the San Francisco Bay-Delta Estuary Technical report 49. 42 p. Sacramento (CA): California Department of Water Resources.
- Balmford A, Leader-Williams N, Green MJB. 1995. Parks or arks: where to conserve large threatened mammals? *Biodiversity and Conservation* 4:595-607.
- Balmford A, Mace GM, Leader-Williams N. 1996. Designing the ark: setting priorities for captive breeding. *Conserv Biol* 10(3):719-27.
- Banks MA, Rashbrook VK, Calavetta MJ, Dean CA, Hedgecock D. 2000. Analysis of microsatellite DNA resolves genetic structure and diversity of chinook salmon in California's Central Valley. *Can J Fish Aquat Sci* 57:915-27.
- Bilby RE, Fransen BR, Bisson PA. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. *Can J Fish Aquat Sci* 53:164-73.
- Botsford LW, Brittnacher JG. 1998. Viability of Sacramento River winter-run chinook salmon. *Conserv Biol* 12(1):65-79.
- [FEMAT] Forest Ecosystem Management Assessment Team. 1993. *Forest ecosystem management: an ecological, economic, and social assessment*. US Forest Service, National Marine Fisheries Service, Bureau of Land Management, Fish and Wildlife Service, National Park Service, and Environmental Protection Agency, Portland and Washington, D.C.
- Fleming IA. 1994. Captive breeding and the conservation of wild salmon populations. *Conserv Biol* 8(3):886-8.
- Gipps JHW, editor. 1991. *Beyond captive breeding: reintroducing endangered species through captive breeding*. Zool Soc London Symp 62. 284 p.

- Goodman ML. 1990. Preserving the genetic diversity of salmonid stocks: a call for federal regulation of hatchery programs. *Environmental Law* 20:111-66.
- Griffith B, Scott JM, Carpenter JW, Reed C. 1989. Translocation as a species conservation tool: status and strategy. *Science* 245:477-80.
- Hedrick PW, Hedgecock D, Hamelberg S. 1995. Effective population size in winter-run chinook salmon. *Conserv Biol* 9:615-24.
- Hilborn R. 1992. Hatcheries and the future of salmon in the Northwest. *Fisheries* 17(1):5-17.
- [IUCN] International Union for the Conservation of Nature. 1996. Red list of threatened animals. Cambridge (UK): World Conservation Monitoring Centre.
- Johnson JE, Jensen BL. 1991. Hatcheries for endangered freshwater fish. In: Minckley WL, Deacon JE, editors. *Battle against extinction*. Tucson (AZ): University of Arizona Press. p 199-217.
- Leidy RA, Moyle PB. 1998. Conservation status of the world's fish fauna: An overview. In: Fiedler PL, Kareiva PM, editors. *Conservation biology for the coming decade*. p 187-227.
- Magin CD, Johnson TH, Groombridge B, Jenkins M, Smith H. 1994. Species extinctions, endangerment and captive breeding. In: Olney PJS, Mace GM, Feistner ATC, editors. *Creative conservation: interactive management of wild and captive animals*. London (UK): Chapman and Hall. p 3-30.
- Meffe GK. 1992. Techno-arrogance and halfway technologies: salmon hatcheries on the Pacific coast of North America. *Conserv Biol* 6(3):350-4.
- Moyle PB. 1993. Saving California's salmon: the legacy of Ishi. *TROUT, The Journal of the Coldwater Fisheries Foundation*. Summer:14-7.
- Moyle PB, Leidy RA. 1992. Loss of biodiversity in aquatic ecosystems: Evidence from fish faunas. In: Fiedler PL, Jain SK, editors. *Conservation biology: the theory and practice of nature conservation, preservation, and management*. New York (NY): Chapman & Hall. p 127-70.
- Moyle PB, Light T. 1996. Biological invasions of fresh water: empirical rules and assembly theory. *Biological Conservation* 78:149-61.
- Moyle PB, Williams JE. 1990. Biodiversity loss in the temperate zone: decline of the native fish fauna of California. *Conservation Biology* 4:275-84.
- Nehlsen W, Williams JE, Lichatowich JA. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* 16(2):4-21.

- Nelson JS. 1994. Fishes of the world. New York (NY): J Wiley & Sons.
- [NMFS] National Marine Fisheries Service. 1990. Endangered and threatened species; Sacramento winter-run chinook salmon. Federal Register 55:46515-23.
- [NMFS] National Marine Fisheries Service. 1997. Proposed recovery plan for the Sacramento River winter-run chinook salmon. 241 p.
- [NRC] National Research Council. 1996. Upstream: Salmon and society in the Pacific Northwest. Washington, DC: National Academy Press.
- Northwest Power Planning Council. 1986. Compilation of information on salmon and steelhead losses in the Columbia River basin. Appendix D of the 1987 Columbia River basin fish and wildlife program. Portland (OR): Northwest Power Planning Council.
- Olney PJS, Mace GM, Feistner ATC. 1994. Creative conservation: interactive management of wild and captive animals. London (UK): Chapman & Hall. 571 p.
- Pearcy WG. 1992. Ocean ecology of North Pacific salmonids. Seattle (WA): University of Washington Press.
- Petervary NA, Willits NH, Arkush KD. The use of ultrasonography to monitor sexual maturation and predict time to spawning in winter-run chinook salmon *Oncorhynchus tshawytscha*. Forthcoming.
- Ryman N, Laikre L. 1991. Effects of supportive breeding on the genetically effective population size. Conserv Biol 5:325-9.
- Seal US, Foote TJ, Ellis S. 1994. Conservation assessment and management plans (CAMPs) and global captive action plans (GCAPs). In: Olney PJS, Mace GM, Feistner ATC, editors. Creative conservation: interactive management of wild and captive populations. London (UK): Chapman & Hall. p 312-25.
- Snyder NFR, Derrickson SR, Beissinger SR, Wiley JW, Smith TB, Toone WD, Miller B. 1996. Limitations of captive breeding in endangered species recovery. Conserv Biol 10(2):338-48.
- Tear TH, Scott JM, Hayward PH, Griffith B. 1993. Status and prospects for success of the Endangered Species Act: a look at recovery plans. Science 262:976-7.
- Thorgaard GH, Wheeler PA, Cloud JG. 1998. Status and potential value of sperm banking for Snake River salmon. In: Brannon EL, Kinsel WC, editors. Proceedings of the Columbia River Anadromous Salmonid Rehabilitation and Passage Symposium. Aquaculture Research Institute, University of Idaho. p 51-6.
- [USFWS] US Fish and Wildlife Service. 1990. Report to Congress: endangered and threatened species recovery programs. Washington, DC: Department of Interior, US Fish and Wildlife Service.

- Vermeij GJ. 1996. An agenda for invasion biology. *Conserv Biol* 78:3-9.
- Waples RS. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. *Can J Fish Aquat Sci* 48(Suppl. 1):124-33.
- Wilson AC, Stanley Price MR. 1994. Reintroduction as a reason for captive breeding. In: Olney PJS, Mace GM, Feistner ATC, editors. *Creative conservation: interactive management of wild and captive populations*. London (UK): Chapman & Hall. p 243-64.

Notes

- Waples, Robin S. (National Marine Fisheries Service). Personal communication via e-mail on 2 November 2000.

Are Juvenile Chinook Salmon Entrained at Unscreened Diversions in Direct Proportion to the Volume of Water Diverted?

Charles H. Hanson

Abstract

Mark-recapture experiments were used to test the null hypothesis that juvenile chinook salmon smolts emigrating from the Sacramento River are entrained at unscreened water diversions in direct proportion to the water volume diverted. The experiments were conducted at the RD1004 Princeton Pumping Plant during June 1995, with a similar set of mark-recapture experiments conducted at the RD108 Wilkins Slough diversion. Results of four tests conducted at the RD1004 Princeton Pumping Plant showed an average of 0.05% of the marked salmon being entrained, compared to 1.03% of the Sacramento River flow diverted. Overall results at the RD108 Wilkins Slough diversion showed a similar pattern, with 0.08% of the marked salmon being recaptured compared to 1.1% of the Sacramento River flow being diverted. Based upon results of these tests the null hypothesis was rejected. The percentage of juvenile chinook salmon entrained was more than ten times lower than the corresponding percentage of Sacramento River flow diverted. Results of these tests have implications in the assessment of entrainment mortality of juvenile chinook salmon at unscreened diversions and the calculation of costs and biological benefits for intake screening projects. These study results are limited, however, due to the relatively low percentage of Sacramento River flow diverted during these 1995 tests, the assumption that hatchery-reared, spray-dyed salmon released a relatively short distance upstream of an unscreened diversion are representative of the behavioral patterns and distribution of wild salmon within the Sacramento River, and the size and configuration of water diversions tested.

Introduction

A large number of water diversions exist on the Sacramento and San Joaquin rivers and throughout the Delta (Herren and Kawasaki, this volume). The majority of these water diversions is unscreened. Concern has been expressed by resource agencies and other interested parties regarding the incremental increase in mortality to juvenile chinook salmon (*Oncorhynchus tshawytscha*), and other aquatic species, resulting from entrainment losses at these diversions. Data are not available, however, to quantify entrainment losses of juvenile chinook salmon at a majority of these sites. As part of the assessment evaluating diversion effects on juvenile chinook salmon, and benefits associated with positive barrier fish screens, an assumption has been made that fish entrainment is proportional to the volume of unscreened water diverted. To date few experimental tests have been performed within the Sacramento-San Joaquin system to verify or refute this fundamental assumption. Furthermore, no studies have been identified from the scientific literature that document the relationship between entrainment losses for juvenile salmon and steelhead in relationship to the volume of water diverted at unscreened intake structures located on west coast tributaries.

To test the null hypothesis that juvenile chinook salmon are entrained at unscreened diversions in direct proportion to flow diverted mark-recapture studies were performed in 1995 at an unscreened water diversion. The experiment was performed at the Reclamation District 1004 (RD1004) Princeton Pumping Plant. These tests were conducted as part of a more comprehensive investigation of the potential application of alternative fish protection devices (for example, acoustic barriers) in reducing juvenile chinook salmon entrainment losses at water diversions (Hanson 1996a).

Princeton Pumping Plant

The Princeton Pumping Plant is located on the east bank of the Sacramento River just north of the town of Princeton at river mile 164.4 (Figure 1). The pumping plant diverts water from the Sacramento River into Drumheller Slough, which serves as part of the RD1004 conveyance and distribution system. RD1004 provides water to approximately 15,000 acres of agricultural land and 10,000 acres of migratory waterfowl wetland habitat within the Butte Basin in Glenn and Colusa counties.

The Princeton Pumping Plant has been in operation since 1912, but was extensively rebuilt in 1981. The facility consists of four 150 hp, 36-inch diameter, vertical mix-flow pumps. The fifth pump is a 30-inch diameter, 100 hp, vertical mix-flow pump located on a separate platform. Each of the pumps has a

separate 36-inch diameter flap-gate and steel discharge line entering Drumheller Slough. At the time of the 1995 investigations the pumping plant diversion was unscreened.

Peak seasonal diversions at the Princeton Pumping Plant occur during the spring irrigation of rice fields and other agricultural lands and during the fall flooding of seasonal managed wetlands. During the remainder of the irrigation season, the pumping plant provides water for agricultural operations. The spring peak typically occurs from April 15 to May 30, which coincides with the primary seasonal period of fall-run chinook salmon smolt emigration from the Sacramento River. The fall and early winter peak pumping typically occurs between October and mid-January, a time when juvenile winter-run chinook may be emigrating.

Peak diversion capacity at the Princeton Pumping Plant is approximately 290 cfs. During maintenance flow two to three pumps are typically in operation (120 to 180 total cfs), depending on water demand within the service area. Diversions occur both by active pumping and, when Sacramento River elevation is high, by gravity flow.

Methods

The experimental design of the field investigations was based on the release of spray-dyed marked juvenile chinook salmon into the Sacramento River upstream of the unscreened Princeton Pumping Plant diversion and subsequently monitoring the number of marked salmon recaptured at the water diversion over a 48-hour period. Results of more comprehensive fish investigations at two unscreened diversion sites (Hanson 1996a, 1996b) documented that a 48-hour sampling duration was appropriate for these mark-recapture tests.

Using release and recapture data, an estimate was calculated of the percentage of the marked salmon entrained at the unscreened diversion. Monitoring the volume of water diverted and the corresponding flow within the Sacramento River allowed calculation of the percentage of the Sacramento River flow diverted. The null hypothesis that juvenile chinook salmon are diverted in direct proportion to flow diversion could then be tested by comparing the estimated percentage of juvenile chinook salmon entrained with the corresponding estimate of the percentage of Sacramento River flow diverted during each test period.

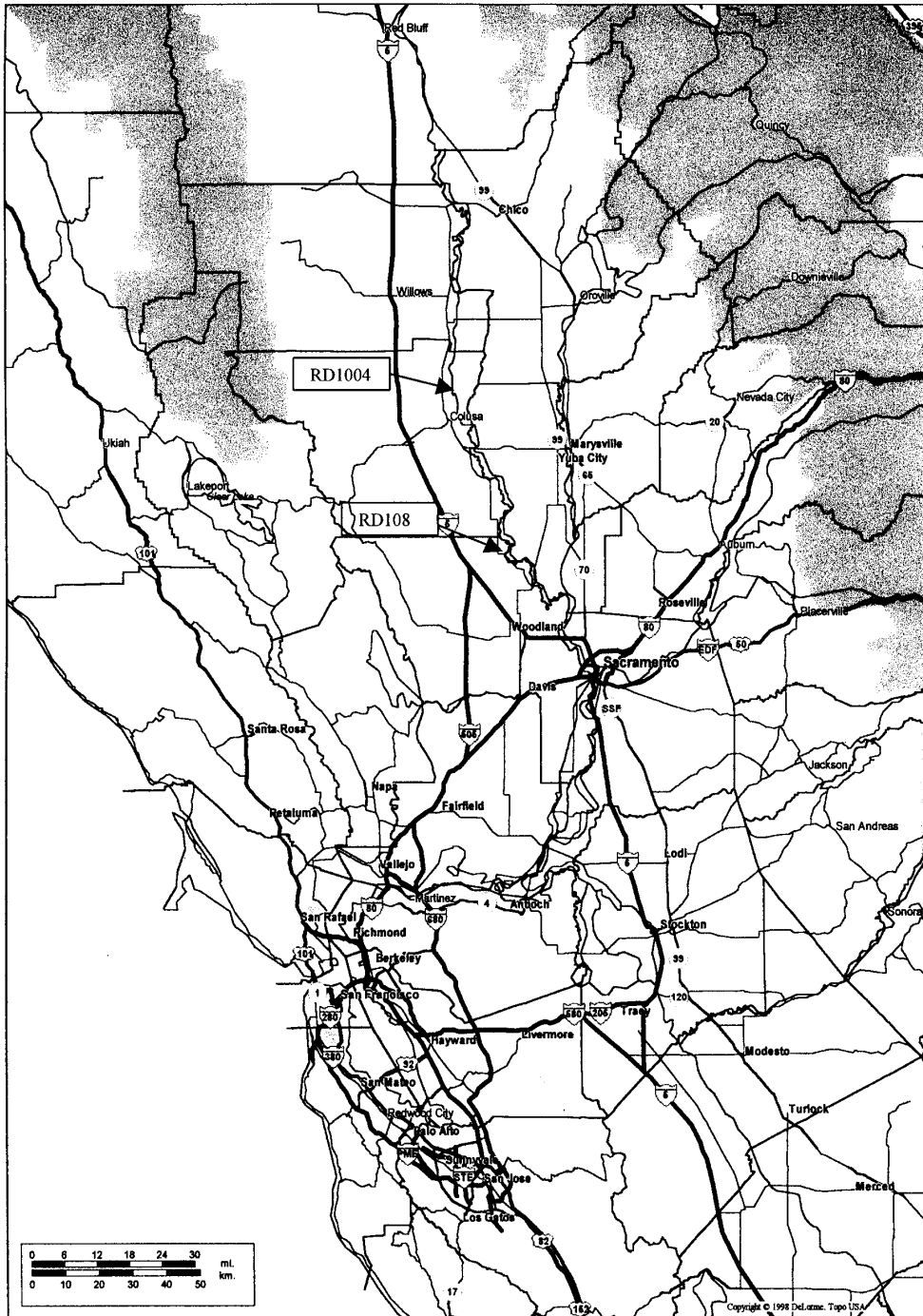


Figure 1 Location of the RD 1004 Princeton Pumping Plant and RD 108 Wilkins Slough diversion on the Sacramento River

Juvenile Salmon Spray-Dye Marking and Release

Juvenile chinook salmon used in these tests were obtained from the California Department of Fish and Game's (DFG) Feather River Hatchery. Juvenile salmon were marked using spray-dye (Scientific Marking Materials) at the hatchery. The number of fish marked was determined by weighing a sub-sample (number of fish per pound) and subsequently by weighing all marked fish within a test group. Juvenile salmon were marked without anesthesia and were retained in the Feather River Hatchery for a minimum of 72 hours after marking to recover from handling stress.

A sub-sample of approximately 100 marked fish from each release group was obtained from the transport truck and held on-site for a period of 48 hours, corresponding to the duration of the recapture collections for each test, to determine post-release survival. Fish held for post-release survival observations were inspected for dye retention as part of the quality assurance program.

Approximately 25,000 juvenile chinook salmon were marked for use in each release group. Mortalities occurring during and after marking were documented for each release group. After the hatchery recovery period, the marked group was loaded into a commercial hatchery truck for transport to the release location. Before release, fish within the transport truck were examined to determine the number of mortalities and the overall condition of the release group. Transport mortality ranged from 0.1% to 0.3%, while survival of a sub-sample from each release group 48-hours after release ranged from 98% to 100%. Inspection of the sub-sample of juvenile salmon held on-site from each release group confirmed 100% spray-dye retention and detection.

Dissolved oxygen and temperature were measured within the transport truck and Sacramento River at the time of release. Water temperature within the hatchery transport truck and Sacramento River at the release site were within 0 to 1.7 °C (0 to 3 °F), thereby avoiding significant temperature changes and thermal shock for fish at the time of release.

Marked fish were released at a location on the east side of the Sacramento River approximately 0.55 miles upstream of the RD1004 Princeton diversion. The release location selected for use in these tests was based upon access to a location sufficiently far upstream to provide the juvenile salmon an opportunity to disperse within the Sacramento River before encountering the unscreened diversion, yet sufficiently far downstream of identified sources of mortality, including other unscreened diversion locations.

Juvenile Salmon Entrainment Monitoring Using Fyke Nets

Monitoring the number of juvenile chinook salmon and other fish species entrained was performed using fyke nets approximately 35 feet long, mounted over the discharge of each pump. The fyke nets sampled 100% of the flow diverted from the Sacramento River. Fyke nets were constructed using 1/8-inch mesh equipped with a live box at the cod end. Collections were made from each live box to remove both fish and debris without the necessity of removing the entire net. Each live box was accessed from a floating dock located within the discharge canal of the Princeton Pumping Plant.

Fyke nets were processed to remove entrained fish and debris a minimum of twice per day (morning and afternoon), although more frequent processing was also performed as part of diel distribution studies. Although rips and tears in the fyke nets were uncommon, the nets were removed and inspected approximately every four to six days.

Direct release studies were performed to determine collection efficiency of the fyke nets. Collection efficiency studies were performed by releasing a known number of marked juvenile chinook salmon into the intake of diversion pump number one, and subsequently documenting the number of marked fish retained in the fyke net at the completion of the sampling cycle. Sampling cycles varied from 2 to 24 hours after release of marked fish into the diversion pump to determine the effects of sampling duration on net retention. Typically 40 juvenile chinook salmon were used in each collection efficiency test. Juvenile chinook salmon used in these tests ranged from 76 to 142 mm FL (mean length 102 mm). Salmon were alive at the time of release into the diversion pump. Fyke net collection efficiency studies had an overall recapture efficiency of 80%, with a range of 65% to 100%.

Data collected in association with each fyke net sample included identification and enumeration of all fish species collected. All salmon collected were examined using ultraviolet lights to determine the number and color of marked fish recaptured. Fork-length was measured for juvenile chinook salmon. Length measurements were made for a sub-sample of other fish species. Data were recorded for each collection identifying the individual fyke net where the collection was made, the start and end times of the sampling interval, and the water volume sampled. Mortality and damage to fish collected was also documented. After processing, live fish were released approximately 0.25 miles downstream of the diversion.

Sacramento River Flow and Diversion Operations

Data on daily Sacramento River flows in the vicinity of the Princeton diversion (Colusa Bridge) were obtained from the California Department of Water Resources (DWR) California Data Exchange Center Database (CDEC). Daily average Sacramento River flow during the study ranged from approximately 13,300 to 14,100 cfs.

The volume of water diverted from the Sacramento River by individual pumps at the Princeton facility was documented coincident with each fish collection. To the extent possible, diversion pump operations were held constant throughout each test to reduce effects attributable to variation in diversion operations. The diversion rate (cfs) and total volume diverted (acre-foot) were monitored for each individual diversion pump using a Sparling Inline flowmeter. Diversion rates for individual pumps typically ranged from 50 to 70 cfs. Diversion pump number five was not operational during the June 1995 study period. Diversion pump number three experienced operational problems and was removed from service in mid-June. Diversion pumps one, two, and four operated on a relatively consistent basis throughout the study period.

Results

Four mark-recapture tests were performed, which provided information on the percentage of juvenile chinook salmon entrained at the unscreened Princeton Pumping Plant. During the four mark-recapture tests included in this analysis (Table 1), a total of 124,394 salmon was released into the Sacramento River.

Spray-dyed chinook salmon were recaptured in low numbers in the RD1004 Princeton Pumping Plant fyke nets (see Table 1). The percentage of marked fish recaptured ranged from 0% to 0.1%, with an overall average for the four tests of 0.05%. The corresponding estimate of the percentage of Sacramento River flow diverted during each of these test periods ranged from 0.9% to 1.2% (see Table 1), with an overall average of 1.03%.

Table 1 Summary of juvenile chinook salmon mark-recapture test results used to determine the percentage of entrainment at the RD1004 unscreened Princeton Pumping Plant diversion in June 1995

| <i>Date</i> | <i>Number released</i> | <i>Number recaptured</i> | <i>Expanded number recaptured^a</i> | <i>Sacramento River flow (cfs)</i> | <i>Percentage of salmon entrainment</i> | <i>Percent Sacramento River flow diverted</i> |
|------------------|------------------------|--------------------------|---|------------------------------------|---|---|
| 7–9 June | 24,865 | 21 | 26 | 14,068 | 0.10 | 1.0 |
| 17–19 June | 24,850 | 0 | 0 | 14,139 | 0 | 0.9 |
| 21–23 June | 24,869 | 0 | 0 | 13,286 | 0 | 1.0 |
| 28–30 June | 49,810 | 28 | 35 | 13,772 | 0.07 | 1.2 |
| Total or Average | 124,394 | 49 | 61 | | 0.05 | 1.03 |

^a Recaptures were expanded based on 80% fyke net collection efficiency (see text).

Discussion

The numbers of marked salmon entrained and recaptured at the RD1004 unscreened diversion was substantially and consistently lower than the percentage of Sacramento River flow diverted (Figure 2). The overall percentage of juvenile salmon recaptured was 0.05% (adjusted for net collection efficiency), compared with an average of 1.03% of the Sacramento River flow diverted during the period of these studies. The substantially lower percentage of fish diverted in these tests demonstrates that marked hatchery-reared juvenile chinook salmon are not entrained in direct proportion with the water volume diverted at the RD1004 intake and, the results suggest juvenile salmon are substantially less vulnerable to entrainment losses than would be expected based purely on a volumetric relationship. Factors such as the location of the diversion with respect to major flow patterns, topographic characteristics of the Sacramento River channel, the location of the diversion pump inlet within the water column, and the behavioral response of chinook salmon smolts to turbulence and velocity differences associated with operation of the intake may contribute to a reduction in the susceptibility of juvenile salmon to entrainment. In addition, the juvenile salmon used in these mark-recapture tests were hatchery reared and released a relatively short distance upstream of the diversion (0.55 miles) and may, therefore, not be representative of the behavioral patterns or distribution of wild salmon within the Sacramento River.

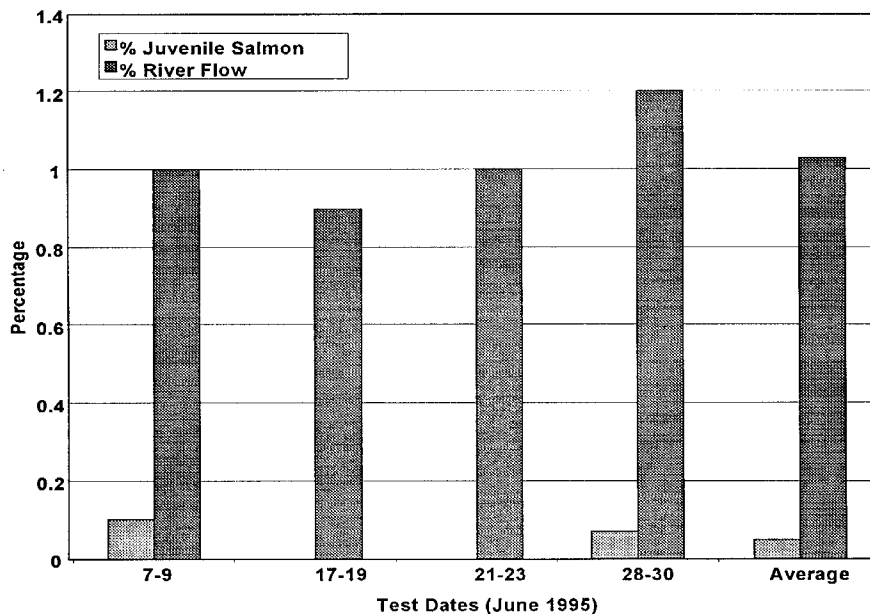


Figure 2 Comparison of the percentage of marked juvenile chinook salmon entrained and Sacramento River flow diverted at the unscreened RD 1004 Princeton Pumping Plant in June 1995

Results of the mark-recapture studies conducted at the RD1004 Princeton Pumping Plant are consistent with results of a similar mark-recapture investigation conducted in 1995 on the Sacramento River at the RD108 Wilkins Slough diversion (Hanson 1996b). Reclamation District No. 108 operates the Wilkins Slough Pumping Plant, located on the west bank of the Sacramento River at river mile 117.8, which was unscreened during 1995. A mark-recapture experiment was used at RD108 to evaluate entrainment of juvenile chinook salmon during four experiments conducted during June 1995. Spray-dyed salmon were released along the west bank of the Sacramento River at locations 0.45 to 0.65 miles upstream of the Wilkins Slough diversion. Marked salmon were subsequently recaptured within the Wilkins Slough diversion using fyke nets and processed in a manner similar to that described for the RD1004 investigation. During this study average daily Sacramento River flow ranged from approximately 13,000 to 14,500 cfs, while average daily diversion rates ranged from 118 to 221 cfs. Additional information regarding the four mark-recapture experiments conducted in 1995 at the RD108 Wilkins Slough diversion is documented in Hanson (1996b). Results of the RD108 mark-recapture tests are summarized below and compared to results from the RD1004 experiments.

| <i>Diversión location</i> | <i>Number of marked salmon released</i> | <i>Expanded number recaptured^a</i> | <i>Percentage of salmon entrainment</i> | <i>Percentage of Sacramento River flow diverted</i> |
|---------------------------------------|---|---|---|---|
| Princeton Pumping Plant ^b | 124,394 | 61 | 0.05 | 1.03 |
| Wilkins Slough Diversion ^c | 99,419 | 75 | 0.08 | 1.1 |

^a Fyke net collections were expanded assuming a collection and retention efficiency of 80%.

^b Source: this study.

^c Source: Hanson 1996b.

Results of the 1995 studies were consistent in demonstrating the low susceptibility of hatchery-reared juvenile chinook salmon to entrainment losses, and the fact that marked juvenile salmon were not entrained in direct proportion to the volume of Sacramento River water flow diverted by either the RD1004 Princeton Pumping Plant or the RD108 Wilkins Slough diversion. Results of these experiments provide useful insight into the vulnerability of juvenile chinook salmon to entrainment losses and can be used as part of the basis for assessing the risk of adverse impacts resulting from unscreened water diversion operations. Additional studies will be required, however, to provide data on the relationship between the vulnerability of hatchery-reared, marked salmon released a relatively short distance upstream from the diversion to entrainment losses and the vulnerability of wild salmon to entrainment losses at these unscreened diversion locations. The percentage of juvenile salmon entrained during mark-recapture studies should also be viewed in context with the flow occurring in the Sacramento River, diversion operations, and the percentage of Sacramento River flow diverted during these tests. Results of the 1995 tests may or may not be representative of the relationship between unscreened diversion operations and the susceptibility of juvenile chinook salmon to entrainment losses under other environmental conditions in which the Sacramento River flow may be reduced, and the percentage of river flow diverted may be higher than that observed during the 1995 tests.

Acknowledgements

Funding for this study was provided by Reclamation Districts 108 and 1004 as part of investigations to evaluate juvenile chinook salmon entrainment losses and the effectiveness of alternative behavioral barrier technologies in reducing entrainment mortality. The California Department of Fish and Game provided juvenile chinook salmon from the Feather River Fish Hatchery for use in mark-recapture tests. Field data collection and analysis was performed by the staff of Hanson Environmental, Inc. The author is grateful to Pete Rhoads, Joe Merz, and Nina Kogut for providing constructive comments on an earlier draft of this manuscript.

References

- Hanson CH. 1996a. Guidance efficiency of an acoustic low-frequency sound (barrier) in reducing juvenile chinook salmon entrainment at the Reclamation District 1004 Princeton Slough diversion: 1995 field studies and evaluation. Prepared for Reclamation District 1004 by Hanson Environmental, Inc. June 1996.
- Hanson CH. 1996b. Guidance efficiency of a flow distribution system - electrical barrier in reducing chinook salmon entrainment at the Reclamation District 108 Wilkins Slough diversion: 1995 field studies and evaluation. Prepared for Reclamation District 108 by Hanson Environmental, Inc. June 1996.
- Herren J, Kawasaki S. 2001. Inventory of water diversions in four geographic areas in California. In: Brown RL, editor. Fish Bulletin 179: Contributions to the biology of Central Valley salmonids. Volume 2. Sacramento (CA): California Department of Fish and Game.

Inventory of Water Diversions in Four Geographic Areas in California's Central Valley

Janna R. Herren and Spencer S. Kawasaki

Abstract

Water diversions in California, used primarily for agricultural, municipal, and industrial applications, have been considered a possible culprit in the decline of many California fishes. In 1991, the California Department of Fish and Game (DFG) initiated a study using the Global Positioning System (GPS) to inventory water diversions. The initial focus was on the Sacramento-San Joaquin Delta (Delta) and the Suisun Marsh, then continued to the Sacramento River and the San Joaquin River Basin. The inventory was to find, quantify, describe, and categorize diversions along waterways where California fish may be affected by water diversions. As of April 1997, 3,356 diversions have been located and mapped in a Geographical Information System (GIS). Approximately 98.5% of the diversions identified were either unscreened or screened insufficiently to prevent fish entrainment. The GPS data were post-processed to provide a horizontal accuracy of ± 5 meters. The information was primarily collected by visual inspection of diversions on the stream bank. Information is maintained in a Microsoft Access database.

Introduction

California's Central Valley waterways support a rich diversity of fish species that are ecologically, economically, and recreationally important. Much of the water necessary for the survival of these species, however, is diverted out of the streams primarily for agriculture, but also for industry and municipalities.

A few researchers have attempted to estimate the number of Central Valley water diversions. Hallock and Van Woert (1959) estimated that there were 900 water diversions on the San Joaquin and Sacramento rivers above the Delta, which are used by anadromous fishes. Of the 900 diversions, only a small portion were specifically identified and described. Brown (1982) estimated 1,850 water diversions in the Delta based on an inventory conducted by the U.S. Bureau of Reclamation (USBR) in 1963-1964 and limited field observations.

These previous inventories were based on estimates and did not accurately assess the true number of diversions, nor did they maintain a database to monitor diversion modifications or relocations. In fact, water diversion inventories were not the objective of past studies, rather the objectives were to estimate water export volumes from geographic regions or fish losses due to entrainment. They did not identify all diversions in the area and map each diversion.

Past studies often located water diversions by visual observation while driving levee roads (Brown 1982). The corresponding odometer reading was then compared with river miles and river banks on maps to determine the locations of individual diversions (Hallock and Van Woert 1959; USBR 1963, 1964; Brown 1982). Another source of water diversion location and information in the Automated Water Rights Information Management System (AWRIMS) managed by the State of California Water Resources Control Board. AWRIMS gives locations of water diversion using the Public Land System, providing accuracies within 40 acres.

Comparisons of these earlier data did not correspond to GPS locations. DFG determined that a standardized and accurate database of water diversions was necessary before the magnitude of diversion-related fish losses could be recognized and addressed.

The GPS is a satellite-based positioning system maintained and operated by the U.S. Department of Defense (DOD). The use of GPS by the scientific community is growing due to its ease of use and high degree of accuracy. Examples of such uses include radiotelemetry studies of moose populations under various types of canopies (Moen and others 1996) and mapping and counting ponds used by breeding waterfowl (Strong and Cowardin 1995). With differential correction, the accuracy of GPS is usually within two meters of the true location 50% of the time, and within five meters 95% of the time (Trimble Navigation Ltd. 1992).

The objectives of our study were to find existing Central Valley water diversions, map them using GPS and GIS, and to identify and categorize them as screened or unscreened. The database of water diversions created by this program can easily be updated with future surveys to identify changes to location, size, and other features. Future objectives of the program will include prioritizing fish screen projects. GPS was selected as the survey method because of its ease of use, superior accuracy, application to various mapping programs and GIS compatibility.

Methods and Materials

Our study began with four regions established based on watershed drainages and similar geographic features (Figure 1). The initial focus was on the Sacramento-San Joaquin Delta (defined in California Water Code, Section 1220) and Suisun Marsh (defined in California Water Code, Sections 29101 and 29002–29003) since many ecologically, commercially, and recreationally popular fish species either reside in these areas or pass through them during some stage of life. These species include the chinook salmon (*Oncorhynchus tshawytscha*), striped bass (*Morone saxatilis*), white sturgeon (*Acipenser transmontanus*), delta smelt (*Hypomesus transpacificus*), Sacramento splittail (*Pogonichthys macrolepidotus*), and steelhead (*Oncorhynchus mykiss*). The survey for water diversions then continued to the San Joaquin River Basin (San Joaquin River mile 72.4 to the confluence with the Merced River, as well as the Stanislaus, Tuolumne and Merced rivers) and the Sacramento River (river mile 59.4 to Keswick Dam).

Field

A physical search to locate water diversions was made by boat, driving levee roads, or by walking the banks of waterways. A Pathfinder Basic Plus and a GeoExplorer, two portable GPS receivers manufactured by Trimble Navigation Limited, were used to geographically locate the position of water diversions. Topographical and navigational maps were used to systematically survey waterways, eliminating the possibility of data duplication.

Upon visual discovery of a water diversion, collection of data points was initiated using a GPS receiver. Data points were received via radio signals sent from 24 NAVSTAR satellites operated and maintained by the DOD (Trimble Navigation Ltd. 1982). Collection of points was made at, or as close to, the point of diversion as possible. Between 180 and 200 data points were collected at each site and stored in the receiver as individual rover files with unique file numbers. A location consisting of more than four diversions were treated as a single point of diversion.

Along with the GPS data, other attributes and a physical description of the diversion were recorded including type of diversion, intake size (outside diameter to the nearest inch, as measured with a logger's diameter tape), type of discharge, bank location, screen type (when present), river system or waterway, and likely primary use of the diverted water. Photographs were taken of each diversion or intake structure. Discharge outfalls or structures were only photographed if unique or uncommon to the region.

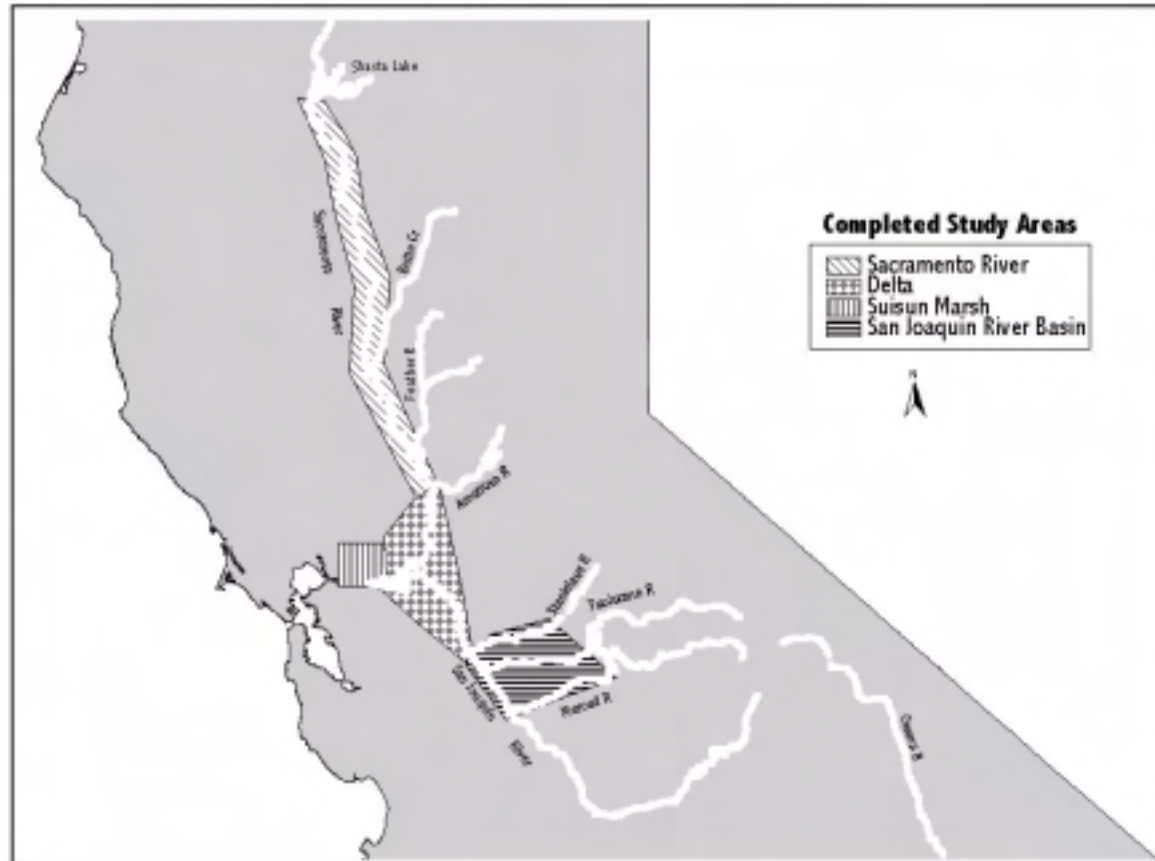


Figure 1 The water diversion study area showing the four geographic areas surveyed: mainstem Sacramento River, Sacramento-San Joaquin Delta, Suisun Marsh, and San Joaquin River basin watershed

Office

At the completion of each field day the rover files were uploaded to a personal computer. These files were then differentially corrected using the post-processing software, pFinder. Differential correction is the process of comparing the raw GPS positions (rover), to a known location (base station). Base station files were downloaded from various locations: USFWS offices in cities (including Sacramento, Susanville, Porterville, and Eureka); Trimble Navigation Ltd.; and other companies that operate base stations throughout the State. After post-processing, GPS data and associated attributes were entered, stored, and maintained in a Microsoft Access database. This information has been used to create a GIS layer output to a North American Datum 27 (NAD-27) Teale-Albers projection to be compatible with DFG's Arcview GIS system.

Each diversion is stored in the database as an individual record where it is assigned a unique identification number. Associated with the identification numbers are the map coordinates of the diversions, as well as its attributes and owner identification number. The owner identification relates to another Microsoft Access database containing the names and addresses of diversion owners. Determination of ownership is attempted through the research of water rights applications in AWRIMS, signs on the diversions, or through personal communication with the owners themselves.

Results

As of April 1997, 3,356 diversions have been located and mapped using GPS (Figure 2). Of these, 424 diversions were along the Sacramento River above the I Street Bridge in Sacramento (Figure 3), 298 diversions were found within the San Joaquin River Basin (Figure 4), 2,209 diversions were within the Delta, and 366 diversions were in the Suisun Marsh (Figure 5). Individual diversion sites containing a group of more than four diversions account for 31 points in our database. These points, if counted individually, add 144 diversions to the total number. These results have been placed on a layer of DFG's GIS as coverage files of 1:250,000 scale United States Geological Survey (USGS) topographic maps using ArcView (version 3.0).

Along with the locations of each diversion, we identified their attributes including the type of diversion and type of fish screen (if present) (Table 1). According to our data, a regional preference is evident for each diversion type. Floodgates are almost exclusively used in Suisun Marsh, while siphons are the preferred method of diversion in the Delta. Pumps are necessary in the Sacramento River and the San Joaquin River Basin because the land elevation is higher relative to water elevation. Furthermore, the Sacramento River study area contained the highest percentage of fish screens that are designed to meet

current DFG criteria – almost 6%. The Delta, which had the highest density of water diversions, had fish screens on only 0.7% of the intakes.

The intake size of the diversions also varied based on region. Ninety percent of the diversion intake sizes in the Delta measured between 12 and 24 inches, whereas the Suisun Marsh was composed of 90% floodgates, with intake sizes between 36 and 48 inches. Fifty-four percent of the San Joaquin River diversions measured between 9 and 16 inches. Greater variability of diversion intake diameters for the Sacramento River and San Joaquin River Basin regions may be due to the higher horsepower pumps that are necessary to move water out of streams where more head differential exists. The largest water diversion in our database, to date, occur in the Delta where water is transported through large pumping plants into the California Aqueduct (State Water Project) and the Delta-Mendota Canal (Central Valley Project).

Discussion

Water diversions have been suggested as a significant cause of the loss and decline of many resident and migratory fish species. Most water diversions are unscreened, and to date, very little information has been reported on the entrainment losses of fish due to unscreened water diversions. Species such as the chinook salmon, steelhead, striped bass, white sturgeon, delta smelt, and Sacramento splittail, are valuable resources to California because of their ecological, commercial, and recreational importance or because they contribute to the rich biological diversity in California. Winter-run chinook salmon, delta smelt, Sacramento splittail, and steelhead are currently listed as endangered or threatened. Most small diversions do not entrain many young salmon and steelhead, however, collectively considerable numbers may be taken (Hallock and Van Woert 1959).

Other west coast states including Washington, Oregon, and Idaho, have undertaken similar inventories on water diversions (John Easterbrooks, personal communication), but on a smaller scale. Their surveys are mainly on watersheds where migrating anadromous fish may be adversely affected by water diversions. The data being collected are neither post-processed nor applied to a GIS. Our inventory of California water diversions is of much greater magnitude and accuracy than other west coast states.

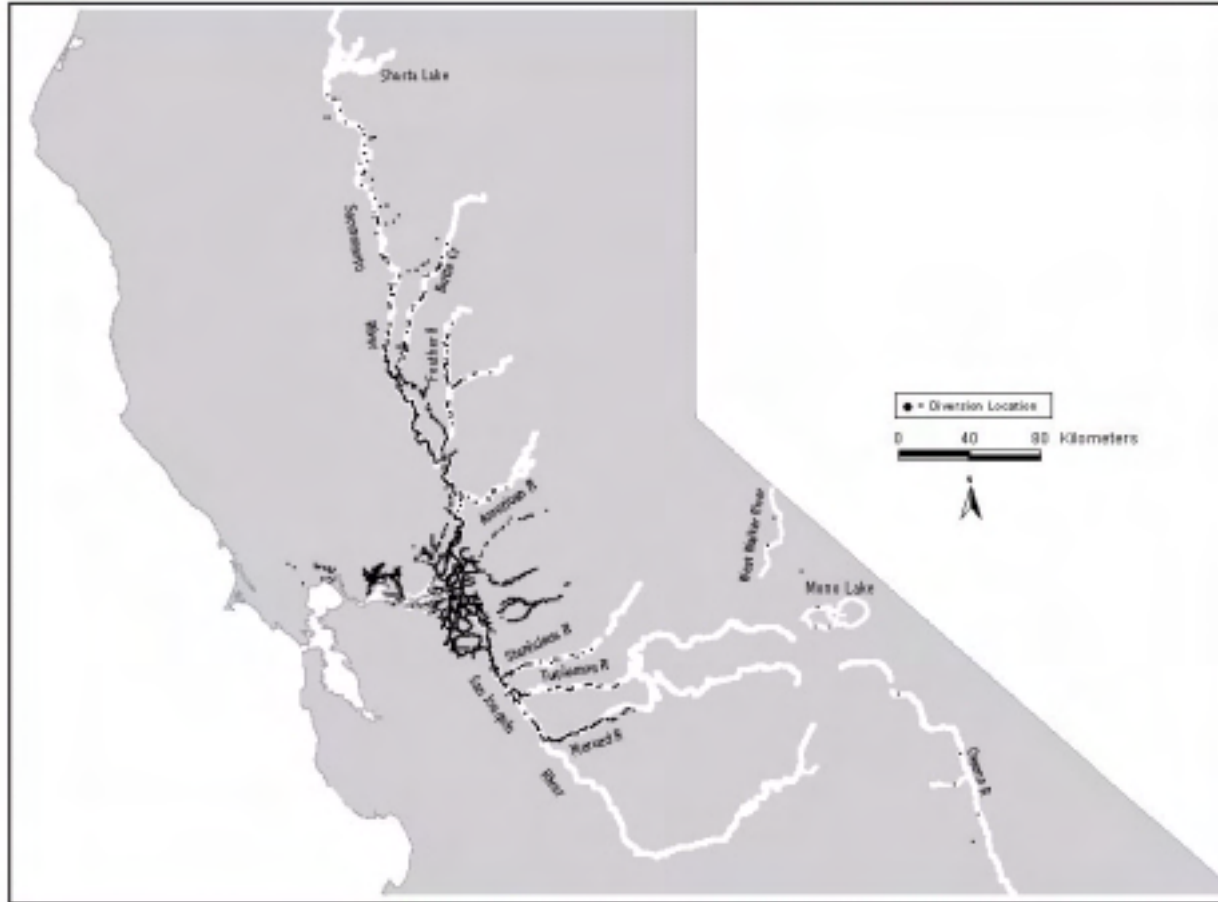


Figure 2 The Global Positioning System has been used to locate and map 3,356 water diversions in California as of April 1997

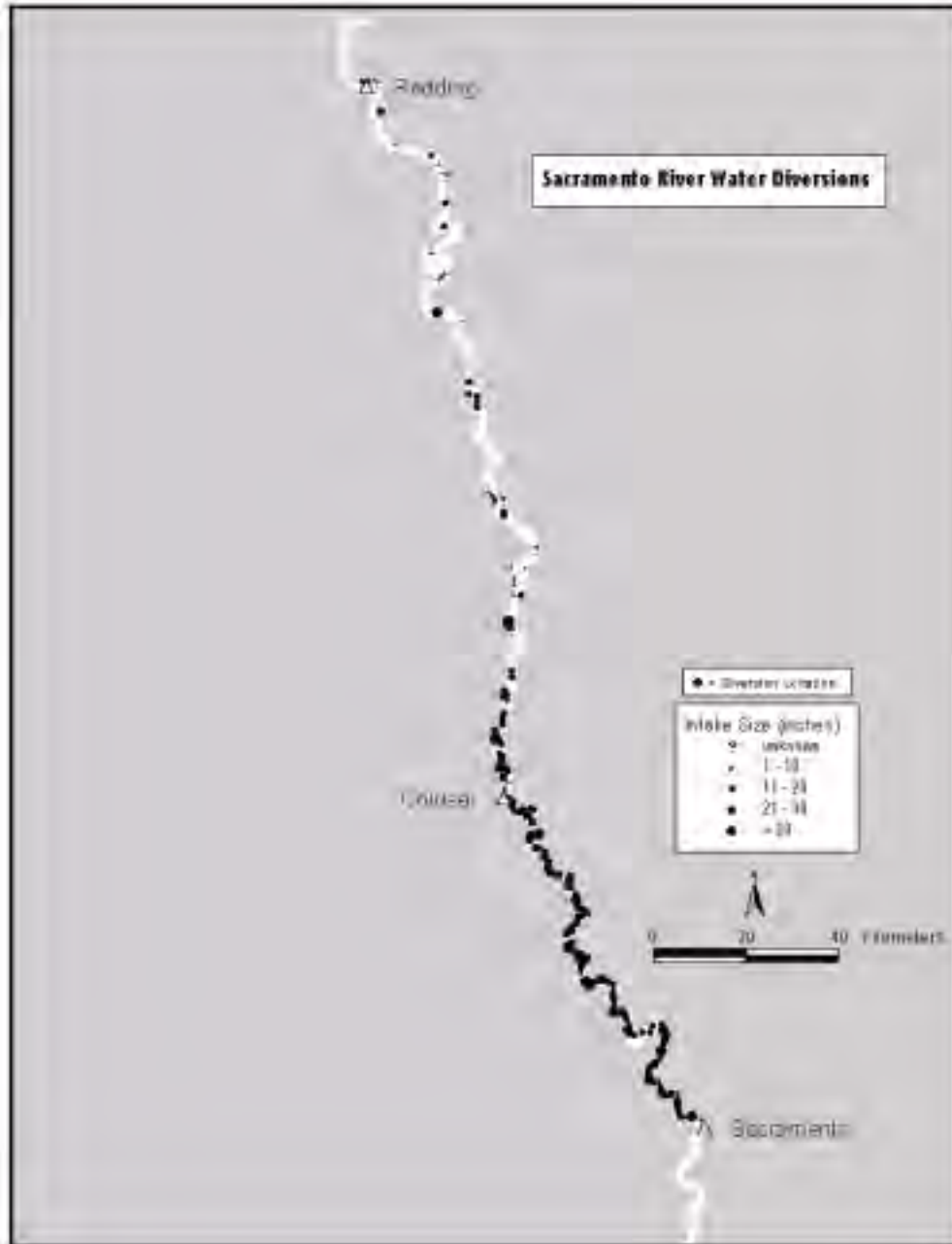


Figure 3 Four hundred and twenty-four water diversions have been identified on the Sacramento River between Keswick Dam and Sacramento at the I Street Bridge as of April 1997

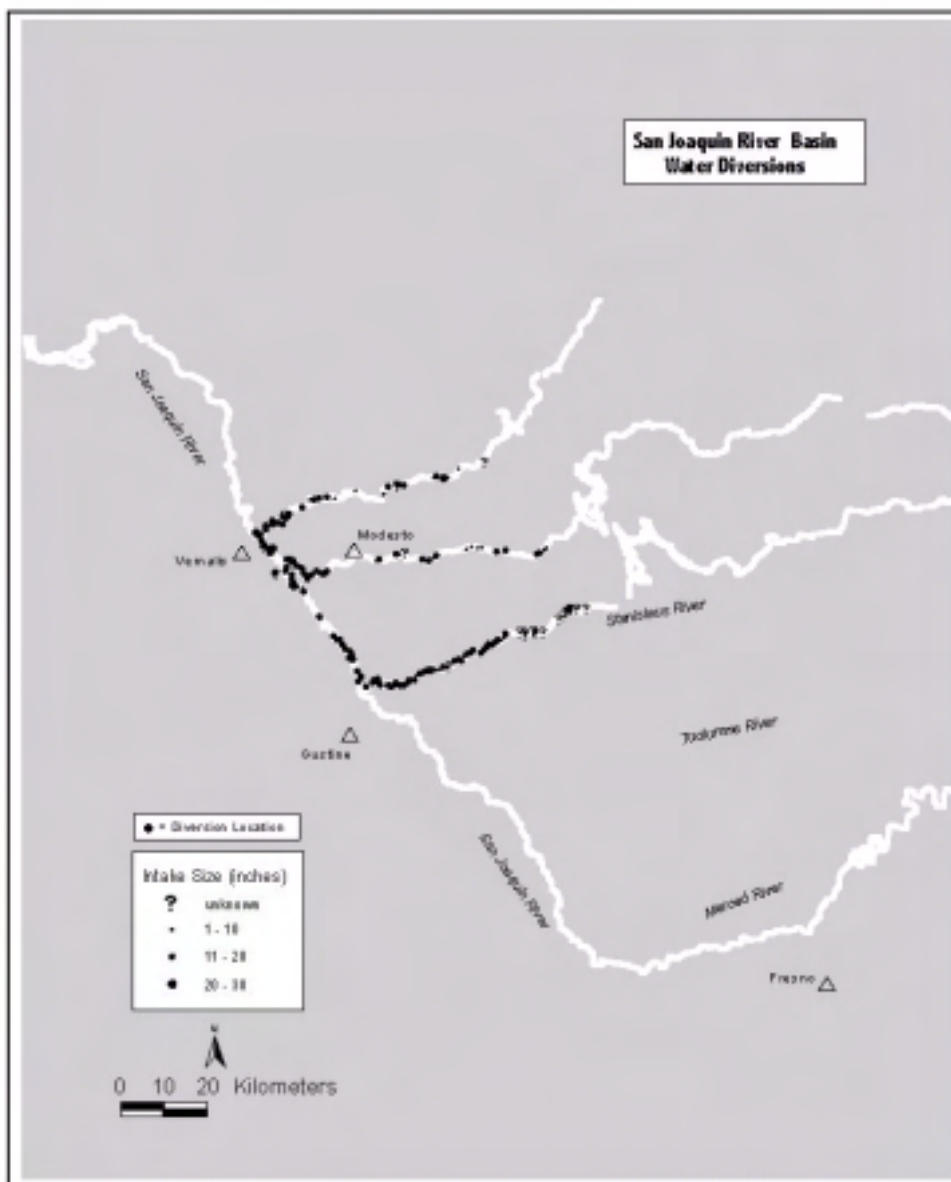


Figure 4 Two hundred and ninety-eight water diversions have been identified on the San Joaquin River between the lower boundary of the Sacramento-San Joaquin Delta and the mouth of the Merced River including the major tributaries as of April 1997

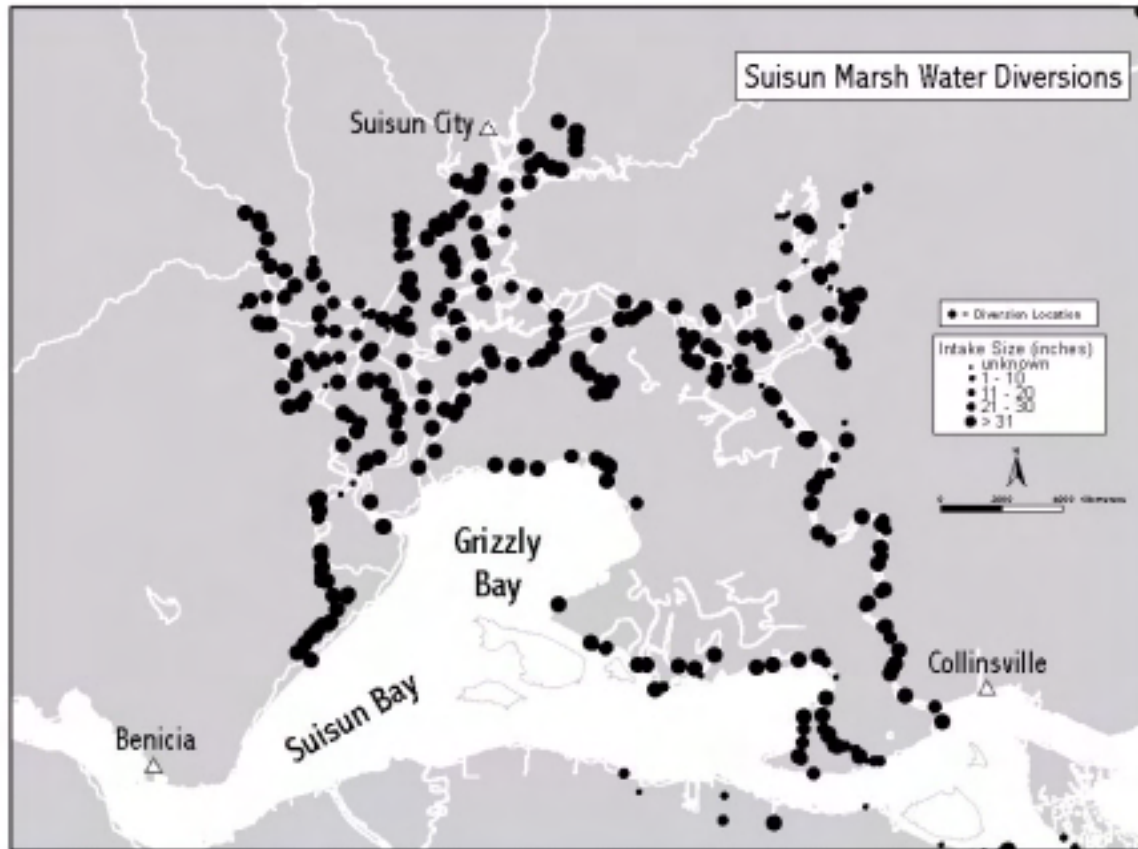


Figure 5 In the Suisun Marsh and the Sacramento-San Joaquin Delta, 366 and 2,209 water diversions, respectively, were identified and mapped using the Global Positioning System as of April 1997

Table 1 Percent and number of diversion types found in each of the four geographic study areas

| | <i>Delta</i> | | <i>Sacramento River</i> | | <i>San Joaquin River Basin</i> | | <i>Suisun Marsh</i> | |
|----------------------|--------------|------|-------------------------|-----|--------------------------------|-----|---------------------|-----|
| | % | No. | % | No. | % | No. | % | No. |
| Vertical pump | 19.1 | 423 | 27 | 114 | 48 | 143 | 3 | 11 |
| Slant pump | 7.3 | 161 | 41 | 173 | 9 | 27 | --- | --- |
| Centrifugal pump | 17 | 375 | 19 | 80 | 34 | 100 | <1 | 2 |
| Siphon | 45 | 994 | <1 | 1 | <1 | 1 | --- | --- |
| Floodgate | 3.6 | 79 | --- | --- | --- | --- | 79 | 328 |
| Unknown ^a | 1.3 | 28 | 5 | 21 | 3 | 8 | 1 | 4 |
| Misc. ^b | 6.7 | 149 | 8 | 35 | 6 | 19 | 17 | 69 |
| Total | | 2209 | | 424 | | 298 | | 414 |
| Screened | 1% | 17 | 6% | 25 | 1% | 2 | 2% | 8 |

^a Diversions are classified as unknown when they cannot be definitively identified due to their location (private property or concealed by brush), missing parts, or hybridized pumps.

^b Miscellaneous diversions are other devices used to move water. These include submersible pumps, Archimedes screw pumps, weirs, portable pumps, channels, culverts, and variable speed pumps.

We compared data from previous studies on water diversions conducted by the USBR (1963–1964) and Brown (1982) with our data for five selected Delta islands and noted several differences (Table 2). Approximately 21% of the diversions on the islands identified in the 1982 report had changed location. Some differences can be attributed to alternate methods, diversion relocation, or the consolidation of several small diversions into a centrally located large diversion. Since locations and sizes of water diversions could become an important source of information for issues including water pollution cases and fish screen planning, these discrepancies support the need for a comprehensive and standardized database. Water diversion GIS data should be kept in a format that is acceptable and easily accessible by various agencies and private individuals.

Table 2 A summary of changes in agricultural diversions on five islands between the DWR water diversion survey (Brown 1986–1987) and GPS data collected by DFG through April 1997

| <i>Island</i> | <i>Total # of diversions in 1993–1994</i> | <i>Deletions since 1987</i> | <i>Additions since 1987</i> | <i>Intakes increased in size</i> | <i>Intakes decreased in size</i> |
|---------------|---|-----------------------------|-----------------------------|----------------------------------|----------------------------------|
| Bacon | 30 | 14 | 7 | 8 | 2 |
| Bouldin | 38 | 11 | 11 | 11 | --- |
| McDonald | 36 | 5 | 9 | 8 | 2 |
| Twitchell | 22 | 2 | 2 | 8 | 1 |
| Venice | 24 | --- | 2 | --- | 1 |
| Total | 150 | 32 | 31 | 35 | 6 |

Currently, along with the four geographic regions already surveyed, the American River and parts of the Mono Lake Basin have been surveyed (Figure 2). The study is ongoing to complete the San Joaquin River, the major tributaries to the Sacramento River, the coastal rivers and streams, and all watersheds containing migratory or resident fish populations that might be affected by water diversions.

Acknowledgements

This study was funded by the Sport Fish Restoration Program and the California Striped Bass Stamp Fund, and supported by the California Department of Fish and Game. We are grateful to I. Oshima for all the countless hours of computer software and technical assistance. We thank W. Harrell, California Department of Water Resources, S. DeLeón, California Department of Fish and Game, and scientific aids F. Muegge, J. Nordstrom, C. Bailey, and M. Volkoff for their help in data collection and data entry. We also thank D. Odenweller and P. Raquel for contributing their expertise and for editing this report.

References

- Brown RL. 1982. Screening agricultural diversions in the Sacramento-San Joaquin Delta. Sacramento (CA): California Department of Water Resources. 42 p.
- Hallock RJ, Van Woert WF. 1959. A survey of fish losses in irrigation diversions from the Sacramento and San Joaquin rivers. *California Fish and Game* 45(4):227-95.
- Moen R, Pastor J, Cohen Y, Schwartz CC. 1996. Effects of moose movement and habitat use on GPS collar performance. *J Wildl Manage* 59:543-51.
- Strong LL, Cowardin LM. 1995. Improving prairie pond counts with aerial video and global positioning systems. *J Wildl Manage* 59:708-19.
- Trimble Navigation Ltd. 1992. GPS Pathfinder System General Reference. Sunnyvale (CA): Trimble Navigation.
- [USBR] US Bureau of Reclamation. 1963. Delta uplands Service Area Investigations Report, Area DU-13, Yolo Bypass. 26 p.
- [USBR] US Bureau of Reclamation. 1964. Delta Lowlands Service Area Investigations Report, Area DL-5, Walnut Grove to Isleton and Vicinity. 34 p.

