STATE OF CALIFORNIA
THE RESOURCES AGENCY
**DEPARTMENT OF WATER RESOURCES**
NORTHERN DISTRICT

# SACRAMENTO RIVER SPAWNING GRAVEL STUDIES

## EXECUTIVE SUMMARY

JUNE 1985

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| **Gordon K. Van Vleck**<br>**Secretary for Resources**<br>**The Resources Agency** | **George Deukmejian**<br>**Governor**<br>**State of California** | **David N. Kennedy**<br>**Director**<br>**Department of Water Resources** |

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# Foreword

The Sacramento River is the most important chinook salmon stream in California. With the construction of Shasta and Keswick Dams, the river reach between Keswick and Red Bluff Diversion Dams became the premier spawning area. Since the 1950s, however, spawning populations in this upper reach have shrunk to about 13 percent of former runs. This decline has been attributed in part to fish passage problems at the Red Bluff Diversion Dam and the loss of spawning gravel in the area below Shasta and Keswick Dams. During this same period, however, the population in the middle Sacramento River between Red Bluff and Chico Landing has increased. More than 50 percent of the salmon spawning the main channel of the river above the confluence with the Feather River now spawn in this middle reach.

This report is an executive summary of two spawning gravel studies: the "Upper Sacramento River Spawning Gravel Study," completed in 1980, and the "Middle Sacramento River Spawning Gravel Study," completed in 1984. The two studies were done under contract with the Department of Fish and Game to collect data on the sources, condition, and distribution of spawning gravel. The reports discuss geology, hydrology, geomorphology, location of spawning areas, gravel characteristics, and a gravel budget. Also included are recent hydrologic, geomorphic and environmental changes, including dams and diversions, bank protection, levees, urbanization, stream-gravel removal, hydraulic mining, agriculture, and land-use changes in tributary watersheds. Both studies include a salmon-spawning gravel atlas (Appendix A, published separately) and management plans with specific action alternatives for preserving this vital salmon-spawning habitat.

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The Resources Agency
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# Abstract

Spawning escapement of chinook salmon, Oncorhynchus tshawytscha, in the Sacramento River has declined dramatically over the last century. Today, fewer than 10 percent of the historical salmon-spawning areas in the Central Valley remain. In 1979, the U. S. Fish and Wildlife Service reported that 95 percent of stream miles of salmon and steelhead habitat in the State was lost statewide from 1940 to 1970, steelhead were down 80 percent, silver salmon 65 percent, and chinook salmon 64 percent. Declines in California fisheries are due, in part, to the development of more than 1,000 dams, logging, mining, commercial and sport fishing, grazing, farming, urbanization, gravel extraction, stream alteration, and wastewater discharge.

In the upper Sacramento River below Keswick and Shasta Dams, many historic salmon-spawning riffles are now armored by cobbles too large for salmon to move. Before the dams, an estimated 60 percent of the spawning gravel recruitment came from areas above the dams, and the remainder came from tributaries in the study reach. At present, gravel from above is trapped in Shasta Reservoir, and tributary contributions are much reduced by gravel mining.

While the spawning population in this upper reach has shrunk to about 13 percent of former runs, the number in the middle Sacramento River between the Red Bluff Diversion Dam and Chico Landing has increased. More than 50 percent of the salmon spawning in the main channel above the confluence with the Feather River now spawn in this middle reach. The Department of Fish and Game and the U. S. Fish and Wildlife Service have concluded that one of the main reasons for this is that the dam is a partial barrier to upstream migrants and contributes to the mortality of downstream migrants (DFG 1978).

Spawning gravel quality and quantity in the middle Sacramento River also are excellent. Most spawning occurs at the upstream end of point bars and in multiple channel areas where bank erosion and meandering processes are active. About 85 percent of the spawning gravel comes from bank erosion; the rest comes from tributaries and the main river above Red Bluff.

# Introduction

The Sacramento River is the largest and most important river system in California. The basin represents about 17 percent of California's land area, yet yields 35 percent of the water supply. The river is the State's most important salmon stream. The Sacramento River king, or chinook, salmon is the origin of 90 percent of the San Francisco-to-Monterey commercial catch, 40 percent of the North Coast, and 5 percent of the Oregon catch (DFG 1978). In 1964 the Department of Fish and Game (1965) estimated that an average of 421,000 salmon return to the Sacramento River system each year to spawn.

Above its confluence with the Feather River, the reach of the main river between Keswick Dam (River Mile 302) and Chico Landing (RM 194) is the primary spawning ground for Sacramento River salmon. This reach is the subject of two reports, one covering the area between Keswick Dam and Red Bluff (DWR 1980), and one the area between Red Bluff and Chico Landing (DWR 1984). For the sake of continuity and ease of presentation, some of the data in the latter report extend to Colusa (RM 143) (Figure 1).

Since the advent of European man, the study reach has undergone a number of hydrologic, geomorphic, and environmental changes, most of which have been detrimental to salmon. These changes include dams and diversions, urbanization, stream gravel removal, hydraulic mining, agriculture, and logging. Many of these changes have had long-reaching effects, including changes in streamflow and sediment distribution. Alteration of river characteristics, such as depth, width, gradient, sinuosity, and temperature, has affected hydrologic diversity, food sources, and spawning gravel quantity and quality. In addition, spawning stocks have been subjected to over 100 years of commercial fishing.

In the 1950s, the Department of Fish and Game (DFG) estimated the fall-run spawning population between Keswick Dam and the Balls Ferry area to be in excess of 190,000. Between 1960 and 1969, the average dropped to about 130,000, even though the counts were extended to Red Bluff. Between 1970-79 the average dropped sharply to 48,000. The first four years of the decade can only be described as disastrous, with an average count of only 24,000 fish passing the Red Bluff Diversion Dam. This represents about 13 percent of the estimated 1950 population.

The Sacramento River and its numerous tributaries drain parts of the Coast Ranges, Klamath Mountains, Cascade Range, Sierra Nevada, and Great Valley geomorphic provinces. From its headwaters in the Klamath Mountains, the Sacramento River is a cool, clear and sparkling mountain stream. As it flows southward, it is joined by numerous small tributaries draining the metamorphic rocks of the Klamath Mountains on the west and the volcanic Cascade Range on the east.

About 12 miles north of Redding, Shasta Dam and Reservoir impound the combined flow of Squaw Creek and the Sacramento, McCloud, and Pit Rivers. Finished in 1943, the dam is a 487-foot-high concrete gravity structure with a reservoir storage capacity of 4.5 million acre-feet. The dam is used for flood control, water supply, power and recreation. Keswick Dam is an afterbay below Shasta, into which an average of 1.20 million acre-feet of water a year is diverted from the Trinity River Basin.

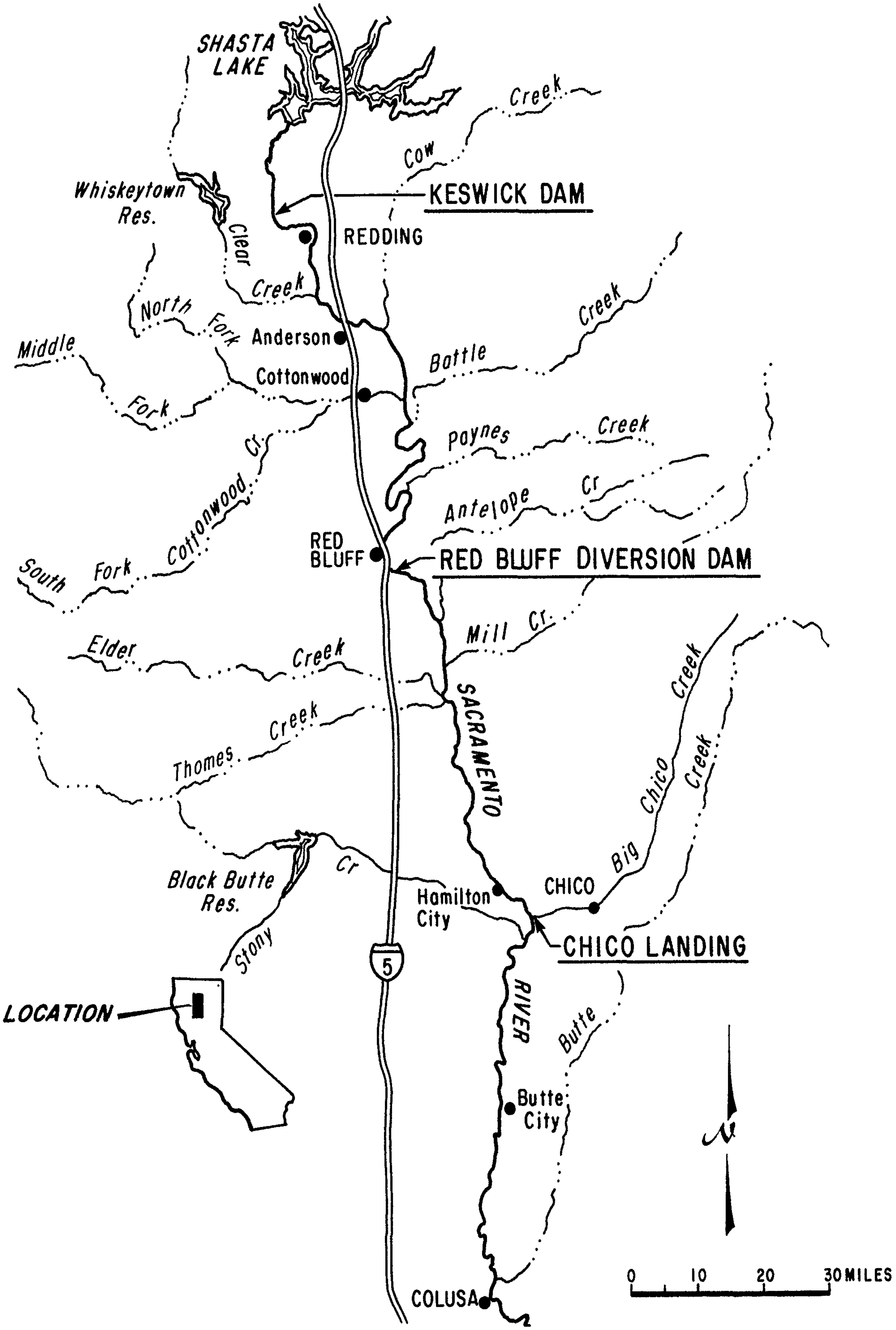

Figure 1. Location map showing the Sacramento River between Keswick Dam and Colusa in Northern California. The upper Sacramento River is the reach between Keswick Dam and the Red Bluff Diversion Dam. The middle Sacramento River extends to Colusa.

The study reach begins at Keswick Dam. About four miles below Keswick Dam, the river widens to about 500 feet. Near Redding the river is broader and slower, but below Jellys Ferry it enters Iron Canyon and forms a series of rapids before entering the alluvial plains of the Sacramento Valley near Red Bluff.

Here the river changes character. Above, it is mostly a bedrock stream controlled by the underlying geology. Below, it is an alluvial stream controlled by its own water and sediment discharge.

The Sacramento Valley here is 20 to 30 miles wide with relief ranging from 170 feet above mean sea level near Hamilton City, 390 feet near Red Bluff, to 600 feet near Redding. The river lies in a region of agricultural bottom lands and low, flat-topped ridges generally covered with grass, brush and trees.

The climate is mild with moderate, wet winters and hot, dry summers. Eighty-five percent of the precipitation occurs between November and April. The mean seasonal precipitation is 36 inches at Redding, 22 inches at Red Bluff, and 19 inches near Colusa.

On the east side, the valley merges with the Cascades, a range of volcanic breccias, volcanic cones and basalt plateaus, rugged foothills, and deep stream-cut valleys. This area contains a large portion of Lassen Volcanic National Park. The lower foothills consist of erosion-resistant volcanic mudflows and stream-deposited fanglomerates. Blue oaks and grassland predominate here. Between elevations of 1,500 to 2,000 feet, blue oak and digger pines become more dense and gradually merge with coniferous forests of pine, fir, and cedar. Eastside tributaries of the Sacramento River that drain this area include Ash, Bear, Cow, Battle, Inks, Paynes, Mill, Antelope, and Deer Creeks. Mean seasonal precipitation at the headwaters approaches 90 inches. Some of the precipitation occurs as snowfall, particularly in Mill and Battle Creeks, and does not appear as runoff until late spring.

Westside streams, including Clear, Cottonwood, Red Bank, Elder, Thomes Creeks, and some eastside streams, such as Churn and Stillwater Creeks, drain the valley and parts of the Coast Ranges and Klamath Mountains. For the most part, the metamorphic rocks of the Klamath Mountains are resistant to erosion and do not produce much gravel. The Coast Ranges are also metamorphic rocks, but in contrast, produce large amounts of both suspended sediment and gravel. Great Valley rocks, mostly shales, occur mostly along the west side of the valley. Shales produce suspended sediment and very little gravel. The valley floor is underlain by more recent sedimentary rocks of clay, silt, sand and gravel. These semi-consolidated sediments are erodible and can provide large quantities of sand and gravel to the westside streams.

Mean seasonal precipitation in the headwater region of westside streams is about 60 inches. Most of the precipitation occurs as rain, with only minor snowmelt to augment spring flows. Most of the westside streams are dry during summer and fall.

## Salmon in the Sacramento River

The Sacramento River supports a wide variety of fish species. The lower river below Colusa is mainly a warmwater fishery. Above Colusa it is mainly a coldwater fishery. Chinook salmon, steelhead trout, striped bass, shad, and sturgeon are anadromous fish, which use the river to spawn. The chinook salmon, the focus of this report, is the only species using the study reach to spawn that also supports a commercial fishery.

About half of the Great Central Valley chinook population originates from the Sacramento River system above Colusa. DFG (1981) estimates that the combined averaged yearly economic value of the commercial and sport fishery in this reach is about $30 million in 1980 dollars.

Four different "runs" or "races" of chinook salmon are recognized in the Central Valley (DFG 1979). These are:

1. The late-fall run. These fish are largely confined to the upper part of the Sacramento's main stem and are usually larger than fish of either the fall or winter runs. Most spawn from January through March.

2. The winter run. Most spawn in the Sacramento main stem above Red Bluff Dam from April into July.

3. The spring run. Spring-run salmon were once widespread in the valley but have disappeared from many of the streams they once utilized. Most spawn in September or early October.

4. The fall run. These are the most numerous and widely distributed salmon in the valley. Most Central Valley streams that have regular salmon runs of any type have an annual fall run. Most fall-run fish spawn from the middle of October through December.

Before settlement of the Sacramento Valley by white man, the Sacramento River was free flowing. Late summer flows were low, averaging 3,000 cubic feet per second (cfs), and in dry years dropping as low as 1,000 cfs.

During the low-flow period, the water temperature in the Keswick-to-Colusa reach was often too high for salmon spawning and contributed to low egg survival when fish did spawn. The river, however, would fluctuate widely in response to winter rains and spring snowmelt. Periodically, it would overflow its banks and flood large areas of the valley floor. These areas were covered by dense forests of riparian vegetation adapted to the periodic flooding.

Below Red Bluff, bank erosion and lateral migration across the flood plain were natural processes. Large floods would uproot streamside vegetation, causing bank erosion and lateral migration. Sediment derived from tributaries and from bank erosion was deposited where vegetation slowed water velocities.

Over a period of years, erosion and deposition were roughly in balance, so that the valley floor neither aggraded or degraded. The riparian forests played a doubly important role here, first by reducing bank erosion and second, by inducing deposition on the flood plain.

A large number of chinook salmon migrated up the river. Two runs predominated, the largest in the fall and a somewhat smaller one in the spring. A minor winter run was also reported (USFWS 1940). Partial counts between 1937-39 showed that the run past the present site of Shasta Dam exceeded 27,000 salmon yearly. Historically, the number was probably considerably higher. Most of the spring-run salmon and some of the fall-run salmon migrated past this point to spawn in the upper Sacramento, Pit, and McCloud Rivers. Above Shasta Dam, the Sacramento was a typical mountain stream, with innumerable pools, rapids, and gravel beds, forming ideal spawning places for salmon. The Pit was a much larger stream than the Sacramento. Salmon spawned in the main stem and in tributaries up to the Pit River Falls, which, until a fishway was blasted, were impassable for salmon. The McCloud River, draining the south side of Mt. Shasta, and Battle Creek, draining the northwest part of Mt. Lassen, were probably the two most important salmon streams in terms of numbers of spawners. The McCloud was accessible to salmon for 46 miles to Lower Falls (USFWS 1940).

A large number of fall-run salmon also used the main Sacramento River below Redding.

In a salmon-spawning survey, the U. S. Fish and Wildlife Service (USFWS) (1940) reported that in 1939 there were "many short stretches of riffle area suitable for spawning which are used by the salmon in years of low water such as the fall of 1939, and the estimated potential utilization in terms of female salmon for the 50 miles surveyed between the Shasta Dam site and Bend Bridge was 25,822." According to Rutter (1903):

> "In ordinary years when the river is in its normal low-water condition the principal spawning beds of the fall salmon are in this portion of the main river, notably in the vicinity of Red Bluff and Tehama. In November 1900, the river was examined carefully between the mouth of Battle Creek and Tehama. Few salmon were seen until within a few miles of Red Bluff, but from that point on every riffle was covered with spawning beds and dead salmon were everywhere abundant in their vicinity."

Cottonwood, Thomes, and Stony Creeks probably supported runs in years with early fall rains. Other smaller westside streams probably never have supported a salmon fishery because of low spring and fall flows and high temperatures. On the east side, Antelope, Mill, and Deer Creeks were important spawning areas, supporting sizable runs of both fall and spring salmon.

Table 1 shows some of the more important events affecting Sacramento River salmon. Some of the first impacts on the river were related to forestry, mining, ranching, and agriculture. Timber harvesting and the grazing of sheep and cattle in western tributary watersheds were major industries in the late 1800s and early 1900s (DWR 1983). Overgrazing, timber conversion, and large fires deliberately set to improve grazing periodically removed the native vegetation and resulted in a large influx of sediment to the stream system. Timber harvesting is still a major industry, and erosion and landsliding (primarily from logging roads and land conversion) are presently providing above-normal sediment down westside tributaries, such as Cottonwood, Elder, and Thomes Creeks.

Table 1. Events Affecting Sacramento River Salmon.

| TIME LINE | | EVENT | EFFECT |
|---|---|---|---|
| Decade | Year | | |
| | 1849 - | Gold rush began | Large increase in human population |
| 1850s | 1852-85 | Dredger and hydraulic mining in tributaries and in the river above Redding | A large influx of debris into spawning riffles and the lower river |
| | 1852- | Hard-rock mining above Redding | Acid mine drainage caused fish kills during low flows |
| 1860s | 1864 | First commercial salmon fishery and canning on the Sacramento River | Gill nets capture a large number of chinooks returning to spawn |
| | 1868 | Sale of State land along river for agriculture | Construction of levees and removal of riparian vegetation |
| 1870s | 1872 | Founding of the Baird Hatchery on the McCloud River | First artificial propagation of salmon |
| 1880s | 1882 | Peak production for salmon canning | 12 million pounds of salmon taken from the Sacramento River |
| | 1884-87 | Railroad construction along river above Redding | Temporary destruction of salmon spawning |
| | 1885 | End of hydraulic mining | Debris still affected river into the 1940s |
| 1890s | 1897 | First Battle Creek Hatchery | Egg-taking station; artificial propagation of salmon |
| 1900s | 1902 | Mill Creek Hatchery | Egg-taking station; artificial propagation of salmon |
| 1910s | 1910 | Rapid increase in number of agricultural diversions | Loss of fry from unscreened diversions, fish blockages in tributaries |
| | 1917 | Construction of ACID Diversion Dam near Redding | Blocked spring run from spawning in areas above dam |
| | 1917 | Flood Control Act of 1917 | Authorized construction of levees and bypasses in lower river |

Table 1. (Continued)

| TIME LINE | | EVENT | EFFECT |
|---|---|---|---|
| Decade | Year | | |
| 1920s | 1927 | Fish ladder built over ACID Dam | Allowed fish passage, but fry still diverted into farmers' fields |
| | 1927 | Finish construction of Pit River No. 4 Dam below Burney | Blocked spawning above dam |
| 1930s | 1937 | Fish counts began | |
| 1940s | 1940 | Closure of Sacramento River above Redding for construction of Shasta Dam | Eliminated spawning in Pit, McCloud, and Sacramento River above dam |
| | 1943 | New hatchery on Battle Creek<br>Shasta Dam completed | Partial mitigation for Shasta Dam. Construction required 7 million cubic yards of gravel from river; changed river hydrology |
| | 1944 | Flood Control Act of 1944 | Levees and bank protection authorized for tributaries |
| | 1950 | Flood Control Act of 1950 | Levees and bank protection on tributaries |
| 1950s | 1957 | Acid mine drainage spills from Spring Creek | Massive fish kills in Sacramento River |
| | 1957 | Commercial river fishing banned in river | Increased number of returning spawners |
| | 1958 | Flood Control Act of 1958 | Levees and bank protection, Chico Landing to Red Bluff |
| 1960s | 1963 | Complete Whiskeytown Dam on Clear Creek | Blocked Clear Creek to upstream spawners, diverted water to Keswick |
| | 1963 | Diversion of 1.2 million acre-feet Trinity River water to Keswick | Increase year-round flow in Sacramento River |
| | 1966 | Complete Red Bluff Diversion Dam | Partial fish blockage, affects survival of downstream migrants |
| | 1967 | Complete Spring Creek Debris Dam | Partial control of acid mine drainage from mines |
| 1970s | 1973 | Spawning in artificial spawning channel of Tehama-Colusa Canal | 2,491 salmon diverted from Sacramento River, 4.7 million fry released |

Hydraulic mining in the period 1850 to 1885 was the chief cause of large, unnatural sediment loads in the river channels until about 1940. During this time, nearly 1.4 billion cubic yards of silt, sand, and gravel were washed into the Sacramento River. While most of the debris affected the Sacramento below the confluence with the Feather River, some dredging and hydraulicking occurred in the upper watershed.

More directly, abandoned gold, copper and silver mines near Redding have leached, and are leaching, high concentrations of copper, zinc, and cadmium into the Sacramento River. During low flows in the Sacramento River, mine drainage historically caused massive fish kills. The Spring Creek Debris Dam was constructed by the U. S. Bureau of Reclamation (USBR) in 1967 to control the outflow of pollutants into the main stream. However, pollution still presents a formidable problem during droughts such as those in 1977 and 1978.

Urbanization, primarily in Redding, Anderson, Cottonwood, and Red Bluff, has caused additional problems in the study reach. Gravel extraction for highways, housing, and other projects averages more than 1.3 million cubic yards per year in Shasta County and 0.5 million in Tehama County. Effluent from factories and sewage plants may have had, or still have, an effect on the salmon.

Along with the rapid expansion of the mining industry, California agriculture also grew. First to be converted to agriculture were the fertile rimlands. Rimlands are higher than the surrounding tule lands, are closer to water transportation, and are less often flooded. Flood control had its inception in the low levees constructed on the rimlands by farmers protecting their crops.

Next to be developed were the tule, or swamp and overflow, lands. Through a series of legislative acts passed between 1855 and 1868, the State sold these lands to farmers, who were obliged to reclaim them individually or through the formation of reclamation districts. Within a period of three years following the last act, nearly all of such lands had passed into private ownership (Jones 1967).

Over a number of years, flood control problems in these low-lying areas led to the Sacramento River Flood Control Project. This project now consists of over 440 miles of river, canal, and stream channels; 1,000 miles of levees; five major weirs; two sets of outfall gates; three major drainage pumping plants; 95 miles of bypasses; five low-water check dams; 50 miles of drainage canals and seepage ditches; and numerous smaller structures, including minor weirs and control structures, bridges, and gaging stations (Jones 1967).

The use of Sacramento River water for irrigation has caused numerous problems for anadromous fish. During late spring and early summer, tens of millions of downstream migrants have been, and in some cases still are, trapped in improperly or unscreened irrigation diversions and pumping facilities on both the Sacramento River and its tributaries. USBR has estimated (1972) that prior to screening of the Glenn-Colusa Canal pumps, 10 million fry a year died at this facility. During the fall, tributaries that still have water in them have irrigation and/or power diversions that dry up portions of the streams and preclude migration past the diversion structures.

Dams and diversions have had a major impact on the fishery. Early dams and diversions built by miners and farmers obstructed miles of habitat without allowance for fish passage or mitigation measures. By the 1920s, at least 80 percent of the Central Valley spawning grounds had been cut off by obstructions (USBR 1972).

More recently, major water development projects, such as Shasta and Keswick Dams and the Trinity River Diversion, have affected the fishery. Shasta Dam required 7.1 million cubic yards per year of gravel from the Redding area for construction. Shasta and Keswick Dams eliminated 40 percent of the pre-Shasta spawning area north of the Feather River (USFWS 1940). This loss is partially offset by the Coleman National Fish Hatchery and by increased spawning below the dam. Spawning below the dam was enhanced by decreased fall water temperatures and increased flows.

However, gravel movement from areas above the dam has been halted, and high releases have scoured and armored the channel to at least Stillwater Creek (DWR 1980). The effect of the Trinity River diversion on the salmon is unknown, but probably slight.

The Federal Central Valley Project and the State Water Project pumps in the Delta affect the downstream migrants mostly by reversing flow directions, thereby delaying or completely blocking some downstream migrants.

Channelization and bank protection between Red Bluff and the Delta eliminates and degrades habitat by increasing the depth and/or velocity of flow and by reducing the hydrologic diversity. Bank protection also reduces the amount of fresh gravel available through bank erosion. DFG (1981) also found that salmon densities at three paired riprap and eroding bank sites indicated an average of only one-third the number of fry in the riprap vs. cutbank areas.

One of the larger human impacts that affected the salmon directly was commercial fishing. In the late part of the 1800s (1873-1910), as many as 21 canneries were processing 5 million pounds of salmon a year from the Sacramento-San Joaquin River system. In 1882 the commercial catch from the Sacramento River alone was 12 million lbs, representing over one-half million fish. This commercial catch is more than the 421,000 salmon estimated in 1964 as the average annual spawning escapement of the Sacramento River system (DFG 1965). From 1912 to 1957, when commercial fishing was banned in the river, the commercial catch had declined some 60 percent. The reduction and end of commercial fishing on the river led to a concomitant rise in the ocean fishery. In the last decade, it is estimated that Sacramento River stocks contributed about 4.5 million pounds yearly, with a dockside value of about $10 million, to the commercial fishery. Sport fishing takes a small, but significant, part of the total catch.

Predation also takes its toll of salmon downstream migrants. Squawfish, steelhead trout, striped bass, herons, mergansers, largemouth bass, and American shad feed extensively on salmon fry. Some of these are introduced exotic species. American shad was introduced in 1871 and striped bass in 1879. These species have thrived in the Sacramento, to the general detriment of salmon.

Predation below the Red Bluff Diversion Dam is known to have a significant effect. Water released from the bottom of the dam causes turbulence and reverse surface flow. This is believed to cause juvenile fish to become confused and disoriented, making them easy prey for a large concentration of predators that exist immediately below the dam. A program is presently under way to solve this problem (USFWS 1984). Predation losses may be increased by water projects as well. Large dams reduce the number of turbid floodflows during the outmigration period. Lower flows greatly increase the amount of time the fry spend in the river, and less turbidity increases predation.

The present salmon spawning escapement in the Sacramento River has declined significantly. Table 2 shows the spawning stock estimates for the fall run between 1937 and 1983. Fall-run counts are more accurate, are available for a longer period, and are easier to estimate than the other runs or the total run. No actual counts are available before 1937; counts between 1937 and 1943 are incomplete counts at Redding; 1943 to 1966 are based on tag recoveries and spawning area surveys and 1967 to present include counts from the Red Bluff Diversion Dam. Before Shasta Dam, it was estimated that over 27,000 salmon spawned above Keswick Dam; an unknown number spawned below. Incomplete counts between Keswick Dam and Battle Creek indicated a spawning population in excess of 50,000. Counts between 1950-59 averaged 190,000, with a high of 408,000 in 1953 to a low of 68,000 in 1957. The Department of Fish and Game believes the 190,000 to be a more accurate estimate of the spawning population in this reach. Between 1960 and 1969 the average dropped to 130,000 even though the counts extended to Red Bluff. Between 1970-79 the average count dropped sharply to 48,000. The first four years of the decade can only be described as disastrous for the fall run, with an average count of only 24,000. It is normal for salmon escapement to vary from year to year. However, it is clear that the spawning population of the Sacramento River main stem above Red Bluff has shrunk to about 13 percent of the 1950s population.

The rate of decline above the dam increased significantly after the diversion dam began operation (Frank Fisher, personal comm.). In contrast, the number of spawners below the diversion dam has shown a gradual increase since the dam began operation in 1967. Counts are available from 1956 to present. From 1956-59 the average was about 12,000 fish. From 1960-69 the average dropped to 9,000; from 1970-79 the number of spawners increased to an average of 33,000. This average number has been maintained through the first four years of this decade. The DFG and USFWS have concluded that the dam is a partial barrier to upstream migrants and contributes to the mortality of downstream migrants (DFG, 1978).

Table 2. Chinook Salmon-Spawning Estimates (in thousands)

| Date | Sacramento River Above Red Bluff | Tributaries Above Red Bluff | Sacramento River System Above Red Bluff | Sacramento River Below Red Bluff | Tributaries Below Red Bluff | Total Below Red Bluff |
|---|---|---|---|---|---|---|
| 1937 | 8* | - | 8* | - | - | - |
| 1938 | 14* | - | 14* | - | - | - |
| 1939 | 16* | - | 16* | - | - | - |
| 1940 | 29* | 4 | 33* | - | - | - |
| 1941 | 30* | 3 | 33* | - | - | - |
| 1942 | 4* | 3 | 7* | - | - | - |
| 1943 | 36* | 2 | 38* | - | - | - |
| 1944 | 73* | 3 | 76* | - | - | - |
| 1945 | 52* | 3 | 55* | - | - | - |
| 1946 | 49 | 17 | 66 | - | - | - |
| 1947 | 75 | 16 | 91 | - | 10 | - |
| 1948 | 40 | 4 | 44 | - | 5 | - |
| 1949 | 50 | 8 | 58 | - | 2 | - |
| 1950 | 111 | 4 | 115 | - | 2 | - |
| 1951 | 73 | 14 | 87 | - | 12 | - |
| 1952 | 267 | 15 | 282 | - | 28 | - |
| 1953 | 408 | 24 | 432 | - | 18 | - |
| 1954 | 276 | 21 | 297 | - | 11 | - |
| 1955 | 231 | 28 | 259 | - | 4 | - |
| 1956 | 87 | 29 | 116 | 6 | 1 | 7 |
| 1957 | 55 | 7 | 62 | 12 | 8 | 20 |
| 1958 | 107 | 35 | 142 | 21 | 6 | 27 |
| 1959 | 257 | 36 | 293 | 9 | 1 | 10 |
| 1960 | 219 | 26 | 245 | 14 | 2 | 16 |
| 1961 | 140 | 21 | 161 | 9 | 2 | 11 |
| 1962 | 130 | 26 | 156 | 9 | 6 | 15 |
| 1963 | 139 | 31 | 170 | 7 | 3 | 10 |
| 1964 | 143 | 23 | 166 | 5 | 1 | 6 |
| 1965 | 105 | 14 | 119 | 2 | 0 | 2 |
| 1966 | 112 | 15 | 127 | 3 | 1 | 4 |
| 1967 | 78 | 7 | 85 | 9 | 1 | 10 |
| 1968 | 98 | 24 | 122 | 12 | 1 | 13 |
| 1969 | 135 | 19 | 154 | 18 | 3 | 21 |
| 1970 | 65 | 12 | 77 | 6 | 5 | 11 |
| 1971 | 59 | 5 | 64 | 23 | 2 | 25 |
| 1972 | 36 | 5 | 41 | 16 | 1 | 17 |
| 1973 | 44 | 8 | 52 | 18 | 2 | 20 |
| 1974 | 49 | 4 | 53 | 28 | 2 | 30 |
| 1975 | 52 | 5 | 57 | 36 | 2 | 38 |
| 1976 | 48 | 9 | 57 | 37 | 1 | 38 |
| 1977 | 39 | 3 | 42 | 46 | 2 | 48 |
| 1978 | 34 | 5 | 39 | 48 | 0 | 48 |
| 1979 | 48 | 13 | 61 | 67 | 2 | 69 |
| 1980 | 22 | 14 | 36 | 30 | 1 | 31 |
| 1981 | 26 | 27 | 53 | 43 | 3 | 46 |
| 1982 | 19 | 28 | 47 | 24 | 2 | 26 |
| 1983 | 27 | 15 | 42 | 33 | 1 | 34 |

Source: "King Salmon Spawning Stocks of California's Central Valley" CDFG annual reports and unpublished data from Frank Fisher, CDFG, Red Bluff.

* Incomplete counts
\- No counts

## Historic Hydrologic Changes

Recent hydrologic changes that affect conditions in the study reach are caused mostly by dams and diversions. These include changes in mean monthly discharge, flow duration, flood peaks, flood frequency, water depth, velocity, and temperature. Numerous of these structures were constructed above and in the study area, but until the completion of Shasta Dam in 1943 they had little effect on the hydrology.

Today, Shasta Dam, its afterbay Keswick Dam, the Red Bluff Diversion Dam, and the Trinity Project control, divert, and regulate flows in the Sacramento River.

Shasta Dam stores 4.5 million acre feet and, to a large extent, regulates flows of the Pit, McCloud, and Sacramento Rivers. Keswick Dam, 9 miles downstream from Shasta, and at the northern end of the study reach, has a storage capacity of 23,800 acre-feet. Besides water regulation and power generation, Keswick Dam acts as a fish-trapping facility. Salmon and steelhead are trapped at the dam and transported to downstream fish hatcheries.

Since December 1963, water has been diverted from the Trinity River Basin through the Clear Creek Tunnel and Judge Francis Carr Powerhouse to Whiskeytown Lake. The Spring Creek Tunnel then diverts Trinity water and most of Clear Creek water through another power plant into Keswick Lake. An average of 1.20 million acre-feet of Trinity River water is thus diverted into the Sacramento River Basin each year, primarily during the summer (DWR 1980).

Between 1963 and 1975, under normal conditions about 90 percent of the normal flow releases from Clair Engle Lake (Trinity Reservoir) were diverted into the Sacramento River system. This affected the flows of both the Sacramento and Trinity Rivers. The Trinity River near Burnt Ranch experienced a 42-percent decrease, and the Sacramento River above Bend Bridge a 16-percent increase in mean annual discharge. Since 1975, Trinity River flows have been increased so that now only about 75 percent is being diverted to the Sacramento River.

Table 3 lists the known diversions and dams on the Sacramento River and tributaries between Shasta Dam and Chico Landing. Some of the more notable structures are the Anderson-Cottonwood Irrigation District Diversion Dam on the Sacramento River, McCormick-Saeltzer and Whiskeytown on Clear Creek, numerous power and irrigation developments on Battle, Mill, Thomes, and Deer Creeks, the Glenn-Colusa Irrigation District pumps and the Red Bluff Diversion Dam on the Sacramento.

Changes in mean monthly flow, flow duration, and flood frequency were analyzed for the U.S. Geological Survey stream gaging station above Bend Bridge near Red Bluff (#11377100).

The data are divided into three hydrologic periods. These are pre-Shasta (before October 1943), post-Shasta; pre-Whiskeytown Lake (October 1943-September 1963), and post Whiskeytown Lake (October 1963-present).

Table 3. Dams and Diversions in the Study Reach.

| Station | Sacramento River Mile | USGS Gaging Station Number | Comments |
|---|---|---|---|
| Sacramento River at Keswick Dam | 298.4 | 11370500 | Flow regulated by Shasta and Keswick Dam. |
| Judge Francis Carr Powerhouse | - | 11525430 | Diversion from Trinity River to Whiskeytown Lake. |
| Spring Creek Powerhouse | - | 11371600 | Diverts Clear Creek and Trinity River to Keswick Dam. |
| Clear Creek | 289.2 | 11372000 | As above. Diversion at McCormick-Saeltzer Dam. |
| Cow Creek | 280.1 | 11374000 | Numerous small diversions. |
| Cottonwood Creek | 273.5 | 11376000 | Numerous small diversions. |
| Battle Creek | 271.4 | 11376550 | Four small power plants; diversions for Coleman Hatchery and irrigation. |
| Sacramento River at Red Bluff | 260.5 | 11377100 | Flow regulated by Shasta Dam and augmented by Trinity Diversion. Numerous small diversions. |
| Red Bank Creek | 243.2 | 11378800 | Some ponds and diversions. |
| Antelope Creek | 234.7 | 11379000 | Numerous small diversions. |
| Elder Creek | 230.4 | 11380500 | Small diversions. |
| Mill Creek | 230.0 | 11381500 | Few small diversions. |
| Thomes Creek | 225.2 | 11382000 | Numerous small diversions. |
| Deer Creek | 219.5 | 11383500 | Few small diversions. |
| Sacramento River at Hamilton City | 199.3 | 11383800 | Major diversion at the Red Bluff Diversion Dam. One million acre-feet diverted. |

Figure 2 shows the average mean monthly discharge for the three hydrologic periods at the Bend gaging station. The effect of Shasta was to reduce mean winter discharge to 80 percent of the pre-Shasta flows. However, since the Trinity diversion, the December discharge has increased to 150 percent of normal, and January and February flows are near normal. The most striking changes, however, have been in summer and fall flows. Post-Shasta, pre-Trinity diversion mean flows are approximately 300 percent of pre-Shasta flows, and post-Trinity flows are more than 400 percent over pre-Shasta flows.

Flow-duration curves show the percentage of time a specified discharge is equalled or exceeded. Figure 3 shows the flow duration curve for the Sacramento River at Bend for the three hydrologic periods. The graph shows that post-Whiskeytown flows exceed 66,000 cfs 1 percent of the time, 11,000 cfs 50 percent of the time, and 4,000 cfs 99 percent of the time. The one-percent exceedence flow was 80,000 cfs before Shasta, 60,000 after Shasta, and 66,000 after Whiskeytown.

The effect of Shasta Dam on the natural flow duration curve has been to:

1. Decrease the minimum discharge and increase the number of very low discharges. This occurs when the powerhouse is closed for repairs.

2. Increase the number of moderate discharges.

3. Reduce the number and the volume of very high flows.

The effect of the Trinity River diversion on post-Shasta flows has been to increase the discharge for any particular exceedence frequency. For example, the discharge with a 50-percent exceedence frequency has been increased from 6,600 cfs to 9,100 cfs, a 38-percent increase.

In the few years prior to Shasta Dam, great floods (Table 4) occurred in 1937, 1940, 1941, and 1942. The storms of December 1937 were, to that date, the most destructive in the history of Northern California, and the Sacramento River reached its highest level in 42 years. Many cattle and sheep were lost, and massive amounts of debris from upstream lodged in the study reach. The greatest natural Sacramento River flow of record occurred in 1940, and severe flooding again occurred in the study area. According to the February 29, 1940 edition of the Red Bluff Daily News, floodwater was 2-1/2 feet over the deck of Bend Bridge, and "The Jelly District was under several feet of water as the river there yesterday reached an all-time high of 47 feet, nearly three feet higher than the 1937 flood."

Floods that occurred before Shasta Dam are essentially of historical interest only. However, flow conditions and the pattern of inundation during the 1940 flood would be very similar to the flow and the overflow pattern expected during a 100-year flood with Shasta Dam in operation (USCE 1977).

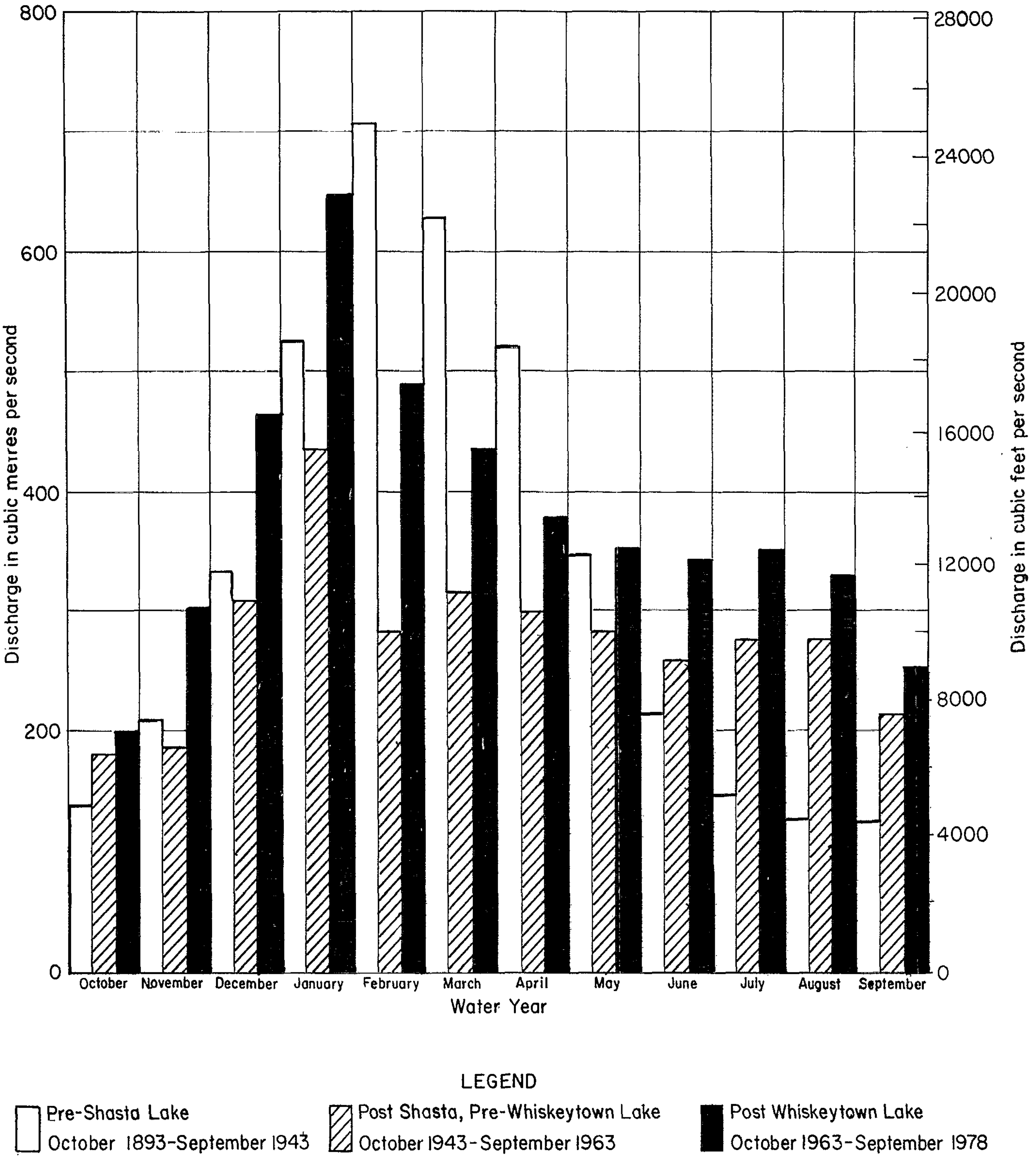

Figure 2. The graph shows the changes in the average mean monthly discharge at the "Sacramento River near Red Bluff" stream gage (11377100).

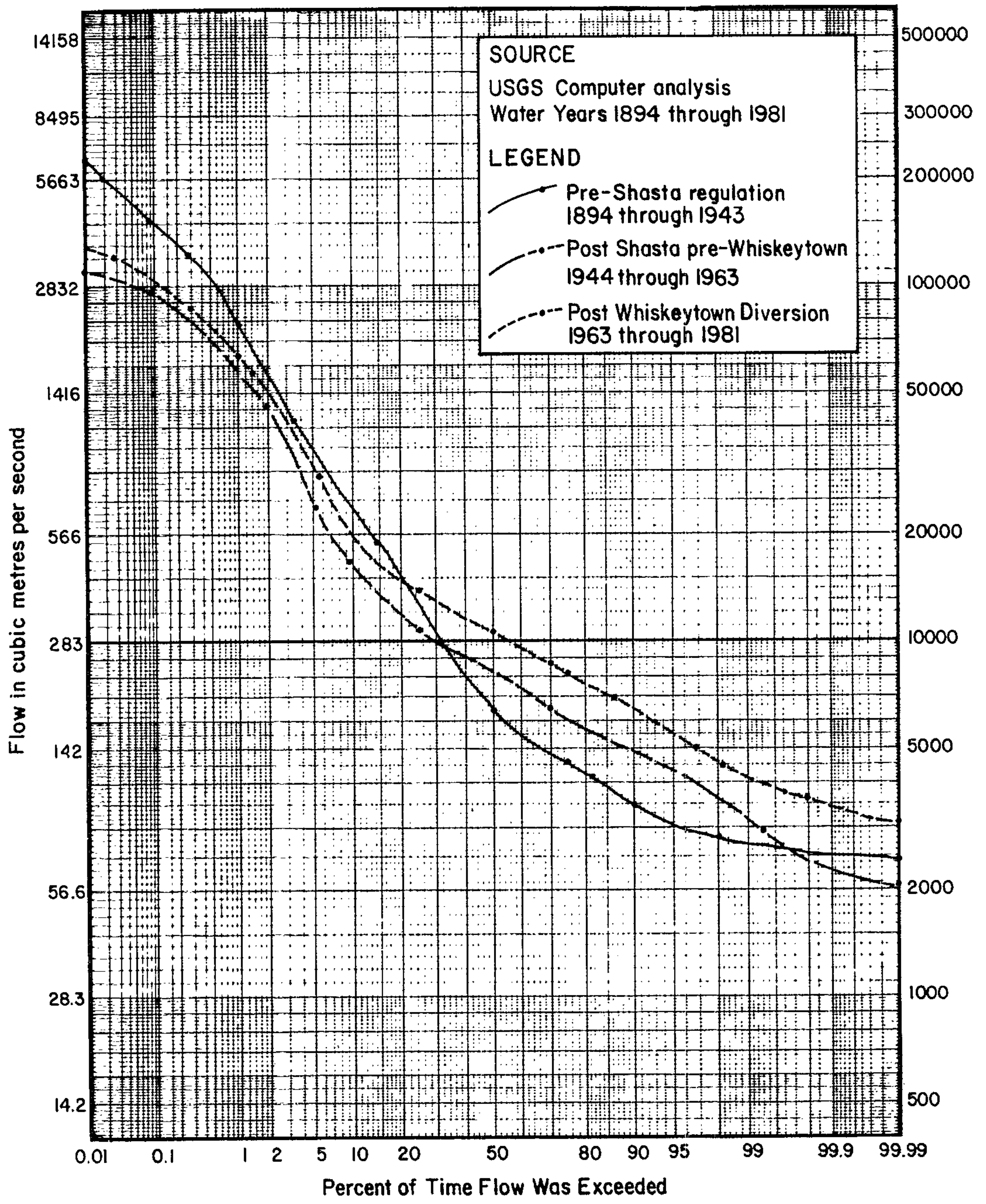

Figure 3. The graph shows flow duration curves for the three hydrologic periods at the "Sacramento River near Red Bluff" stream gage.

Table 4. Peak Flows of Historical Floods (in $ft^3/s$ x 1000).

| | 12/37 | 2/40 | 4/41 | 2/42 | 12/51 | 1/56 | 2/58 | 12/64 | 1/69 | 1/70 | 1/74 | 1/78 | 2/80 | 3/83 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Battle Creek (11376550) | 35 | - | 11.1 | 12.8 | 6.0 | 8.5 | 8.4 | 9.9 | 12.1 | 24.3 | 15 | 5.5 | 5.4 | 11.9 |
| Cottonwood Creek (11376000) | - | - | 52.3 | 42.6 | 32.6 | 49 | 48 | 60 | 23.5 | 58.5 | 70 | 39.1 | 36.3 | 86 |
| Sacramento River at Bend Bridge (11377100) | 262 | 291 | 157 | 203 | 137 | 115 | 139 | 156 | 92 | 157 | 133 | 106 | 104 | 152 |
| Red Bank Creek (11378800) | - | - | - | - | - | 5.6 | - | 9.7 | 9.2 | 8.7 | 6.7 | 9.3 | 8.4 | 10.5 |
| Antelope Creek (11379000) | - | - | 7.9 | 10.4 | 6.5 | 4.1 | 2.5 | 9.0 | 9.4 | 17.2 | 8.4 | 3.0 | 6.1 | - |
| Elder Creek (11380500) | 10.7 | 13.1 | 14.1 | - | 4.7 | 2.5 | 11.3 | 10.3 | 3.8 | 7.2 | 8.9 | 5.0 | 6.7 | 5.9 |
| Mill Creek (11381500) | 36.4 | 11.4 | 7.3 | 11 | 5.3 | 4.8 | 2.2 | 16 | 12.4 | 17.1 | 10.1 | 3.3 | 6.7 | 7.8 |
| Thomes Creek (11382000) | 16.5 | 17 | 5.6 | 8.1 | 5.7 | 10.9 | 11.4 | 37.8 | 9.3 | 18 | 29.4 | 7.3 | 6.7 | 7.1 |
| Sacramento River at Vina (11383730) | - | - | - | - | 146 | 135 | - | 163 | 139 | 171 | 159 | 121 | 132 | 174 |
| Deer Creek (11383500) | 23.8 | 18.4 | 8.0 | 11 | 6.7 | 6.6 | 8.7 | 18.8 | 15 | 21.1 | 10.3 | 4.3 | 9.0 | 11.3 |
| Sacramento River at Hamilton City (11383800) | - | 350 | - | - | - | - | - | 151 | 126 | 156 | 158 | 123 | - | 176 |

## Changes in River Geomorphology

Rivers naturally change with time due to changes in climate, hydrology, geology, and geography. Changes may occur over long periods of time. For example, the major climatic changes during the last few million years of earth's history have triggered changes in runoff and sediment loads with corresponding channel alteration. As a result, slow river changes have occurred. Rivers may also change rapidly because of droughts and floods, or by man's modification of the hydrologic regime. All these are interrelated in such a way that any change in one factor is likely to change another until the stream system is again in balance. This is the concept of a "graded" stream. A graded stream is in quasi-equilibrium, showing a balance between its transporting capacity and the amount of material supplied to it, and thus between degradation and aggradation in the stream channel. A graded stream is one in which over a period of years, slope and other channel parameters are adjusted to provide, with available discharge, just the velocity required for the transportation of the load supplied from the watershed. The graded stream concept is useful when using the energy and hydraulic balance equations and determining cause-effect relationships between human causes, hydrologic changes, and stream geomorphology.

Streams and stream reaches may be classified as either alluvial or bedrock streams. Bedrock streams flow through and are controlled by bedrock. Alluvial streams, on the other hand, flow through their own alluvial deposits. These streams are graded and occupy a broad flood plain belt, over which the depth of alluvium deposited by the river equals or exceeds the depth to which scour takes place. Between Redding and Red Bluff, the Sacramento River is mainly a bedrock stream; downstream of Red Bluff, it is an alluvial stream.

Streams may be further subdivided by channel pattern. There are numerous channel patterns that have been recognized (Leopold et al 1964, USGS 1977). Of these, the braided, anabranching, sinuous, meandering, and straight designations are the most applicable to the Sacramento.

The term "braided" is restricted to channels that are divided mainly by unvegetated bars, and the term "anabranching" is applied here to channels that are divided mainly by large vegetated islands. Most anabranching streams have gravel beds, and the islands that divide them are more stable than the smaller unvegetated bars of braided streams.

Meandering streams have some arbitrary degree of sinuosity, which is the ratio of reach length as measured along the channel centerline to reach length as measured along the valley centerline. Streams having a numerical value of sinuosity greater than 1.5 are regarded as meandering.

Some bedrock streams have "entrenched" meanders; that is, the stream is highly sinuous but stable. The meanders were formed when the stream was an alluvial river, but rapid uplift allowed the meanders to entrench into bedrock. This is the case for river reach 4 (Table 5) in Iron Canyon above Red Bluff.

Alluvial rivers and streams are also classified according to the size of the channel bed material. Sand-bed and gravel-bed streams are the most common. Most of the study reach is considered a gravel-bed stream. The average size of the gravel, however, changes, depending on such things as gradient and tributary inputs (see gravel budget section).

The Sacramento River from Keswick to Colusa may be divided into a number of geomorphic reaches.

Using such channel characteristics as gradient, geometry, underlying rock types, and gravel distribution, it is possible to divide the study reach into seven distinct and unique reaches. Many characteristics, such as the lessening of the river gradient in downriver reaches, are predictable under certain hydrologic laws. Other characteristics are unique, the result of many variables.

Table 5 summarizes some of the geomorphic characteristics of the seven reaches.

## Changes in Bank Erosion

A river erodes both its banks and bed. Bed erosion leads to degradation and grading of the stream profile. In a bedrock stream this process is generally slow, except during periods of geologically rapid rejuvenation and uplift. Bed erosion also occurs in alluvial streams, but the erosion is generally balanced by deposition over a period of years.

Bank erosion is the erosion of the river's banks, and is generally of much more interest and concern to people. Bank erosion is dependent on channel shape, bed and bank material, and the hydraulic characteristics of the river flow. Because of the generally stable banks of the Sacramento River between Keswick and Red Bluff, bank erosion is in most places insignificant. Between Red Bluff and Colusa, significant bank erosion occurs. Downstream of Colusa, flows and associated velocities are greatly reduced by overflow occurring upstream (both natural overbank flow and that taking place at the Moulton and Colusa overflow weirs of the Sacramento River Flood Control Project system). In addition, the flatter slopes of the channel bed downstream minimize the erosion potential.

In alluvial river systems, it is the rule rather than the exception that banks will erode, sediments will be deposited, and flood plains, islands, and side channels will undergo modification with time.

Bank erosion generally occurs on the outside of meander bends. Here, banks are susceptible to erosion because high flow velocities impinge directly onto banks, and turbulent motion along the channel thalweg undercuts the banks. Eroding banks may be either high terrace or low terrace. High-terrace banks are higher, and normally have a deep soil profile containing mostly loamy sand and silt. Below this is a point bar deposit of sand and gravel. Low-terrace banks consist of mostly sand and gravel with a thin soil profile on top.

Table 5. Geomorphic Characteristics of the Sacramento River in 1976 from Keswick to Colusa

| River Reach | River Miles | River Distance in mi | Slope | Bank Erosion | Meander Belt Width in ft | Sinuosity | Channel Shape | Combined Spawning 1964 and 1983 |
|---|---|---|---|---|---|---|---|---|
| 1 | 302.1-300 | 2.1 | .0015 | None | --- | 1.05 | Straight, narrow bedrock gage | Low |
| 2 | 300-280.1 | 19.9 | .0012 | Low | --- | 1.3 | Entrenched, anabranching and sinuous | High |
| 3 | 280.1-273.5 | 6.6 | .0009 | Low | --- | 1.2 | Short, straight, and narrow | High |
| 4 | 273.5-249.5 | 24 | .0006 | None | --- | 2.2 | Highly sinuous, entrenched non-meandering reach | Low |
| 5 | 249.5-243 | 6.5 | .0005 | Low | --- | 1.2 | Valley floor and channel widens | Low |
| 6 | 243-193 | 48.1 | .00054 | | | | | |
| 6A | 243-238.5 | 4.5 | .00050 | Low | 1200 | | Straight, with gravel bars | High |
| 6B | 238.5-231 | 7.4 | .00076 | High | 1400-5400 | 1.4 | Sinuous, anabranching | High |
| 6C | 231-228.5 | 2.5 | .00056 | Low | 700 | 1.05 | Straight | Low |
| 6D | 228.5-218.5 | 9.8 | .00054 | High | 700-5000 | 1.3 | Sinuous with gravel bars | High |
| 6E | 218.5-216 | 2.5 | .00030 | Low | 900 | 1.05 | Straight | None |
| 6F | 216-201 | 13.4 | .00054 | High | 900-5100 | 1.5 | Meandering, anabranching | Moderate |
| 6G | 201-198.5 | 2.5 | .00033 | Low | 800 | 1.05 | Straight | None |
| 6H | 198.5-193 | 5.5 | .00052 | High | 1300-6600 | 1.5 | Meandering | None |
| 7 | 193-143.5 | 49.4 | .00026 | | | | | |
| 7A | 193-178 | 17.2 | .00037 | High | 1200-4600 | 1.5 | Meandering, sand and gravel bars; oxbows in flood plain | None |
| 7B | 178-176 | 2.0 | .00025 | Low | 600 | 1.0 | Straight, channelized | None |
| 7C | 176-155 | 20.0 | .00028 | High | 500-8000 | 1.3 | Sinuous, oxbows in flood plain | None |
| 7D | 155-151.5 | 3.4 | .00019 | Low | 600 | 1.2 | Sinuous, channelized | None |
| 7E | 151.5-143.5 | 6.8 | .00021 | High | 400-2200 | 1.7 | Meandering, sand and gravel bars | None |

The fish, wildlife, and riparian vegetation are adjusted to the cycle of erosion, deposition, and changing channel pattern. In fact, the very health and productivity of this system is based on this periodic rejuvenation.

Salmon prefer to spawn in fresh gravels that have recently moved. Wide areas with multiple channels or chute cutoffs are preferred because of reduced floodflow velocities and greater hydrologic diversity. Gravel in the subsoil horizons of an eroding bank provides fresh gravel to spawning beds. Most of the sand and silt from the bank are deposited in the riparian forests below. Abandoned channel oxbows become homes for warmwater fish, such as perch and bass.

Bank erosion is also the driving force for riparian plant succession. On the outside of bends, high-terrace banks with a mature forest consisting of valley oak, box elder, and black walnut are eroded. On the opposite side is a point bar consisting of sand and gravel. Willows and cottonwood become established here. The rapid invasion of riparian vegetation slows floodflow velocities and allows sands and silts to deposit. With time, a succession of different plant species occurs as the point bar becomes higher and further away from the river.

Various birds and other wildlife use different riparian stages for feeding, nesting, and reproduction. The climax valley oak forests are relatively sterile compared to the younger riparian stages. Therefore, bank erosion and riparian rejuvenation are necessary to maintain a healthy and productive ecosystem.

Sediment deposition is the driving force of bank erosion. Without deposition, the channel would simply widen until it was so large that erosion would terminate. However, the coarser material eroded from the bank is deposited on point bars downstream. The point bars constrict the bend and enable erosion to continue.

DWR (1979) observed bank erosion over a 2-1/2-year period at six sites in the Red Bluff-to-Colusa Reach. This investigation has been expanded and is presently continuing. Bank erosion was divided into summer or low-flow erosion, and winter or high-flow erosion. Only two of the six sites showed any erosion during the summer. Erosion between April and October was 11.4 and 2.2 feet, respectively.

In contrast, high flows were far more conducive to erosion. A major storm occurred in January 1978. Erosion was greatest during the period that included this storm, with erosion ranging from 30 to 50 feet of bank recession. During the storm itself, Woodson Bridge State Recreation Area lost over 40 feet in a single 24-hour period.

DWR (1979), U. S. Corps of Engineers (USCE) (1981), and the U. S. Geological Survey (USGS) (1977) have compared pre- and post-Shasta erosion rates. All three investigations concluded that there has been a significant reduction of about 25 percent in bank erosion between the period 1896-1946 and 1946-1980. The differences in rates can be attributed in part to a reduction in the frequency and magnitude of peak flows resulting from regulation by Shasta Dam, since bank erosion increases exponentially with discharge. Therefore any reduction in the occurrence of high flows will impact the amount of bank erosion.

Figure 3 (in the Hydrology section) showed the flow duration curve for the Sacramento River above Bend Bridge. Bankfull discharges are considered to be the flows most responsible for bank erosion. On the graph, bankfull discharges are equalled or exceeded about one day every 1,000 days (.1 percent of the time). The post-Shasta and post-Whiskeytown diversion flow of this exceedence frequency is 100,000 ft $^3$/sec. Before the dams, this flow was exceeded 6 days every 1,000 days (.6 percent).

There are a number of conclusions that can be reached about bank erosion rates:

- Pre-Shasta Dam erosion rates are higher than post-Shasta rates. For the period 1896-1946 (USCE 1981), the rate averaged about 2 ac/yr/mi between Red Bluff and Colusa. For the period 1946-1980, USCE calculated a rate of about 1.5 ac/yr/mi for a 25-percent reduction over pre-Shasta conditions.

- By far the largest majority of bank erosion occurs during high winter flows, although substantial erosion may occur locally (i.e., the Princeton Erosion Site, as monitored by DWR) during low flows. Discharges at which bank erosion begins differ in various reaches, but in most cases the threshold is well above summer flow releases.

Between Red Bluff and Chico Landing about 83,000 feet of riverbank has been riprapped. This represents about 15 percent of the total length. Bank protection, when effective, stops bank erosion and lateral migration. It prevents loss of valuable agricultural lands, transportation facilities and structures.

Bank protection, particularly if it is along the entire length of the river, will cause some long-range geomorphic changes. First, it will have a stabilizing effect on length and sinuosity. Second, it will prevent the re-entrainment through bank erosion of gravel deposited on point bars. This will have some long-range effects on the amount of available spawning gravel. Third, over a period of time it will tend to narrow the channel, increase the depth of flow, and reduce the hydrologic diversity. Sloughs, tributary channels, and oxbow lakes will fill with sediment and no new ones will be created.

### Changes in Meandering

Meandering is defined as a characteristic habit of a mature river where it winds freely on a broad flood plain. The curves are formed by the bank erosion-point bar deposition process. Erosion is greatest across the channel from the point bar. As the point bars build out from the downstream sides of the bar, the bend gradually migrates down the valley. As the meander moves laterally and longitudinally, the loops move at unequal rates, resulting in meander cutoffs, oxbow lakes, and irregularities in the channel. On the Sacramento, however, most loops are bypassed by bend cutoffs.

According to the Corps (1981), bend cutoffs have recently occurred at river miles 235 to 234, 215 to 212, and 197 to 196. In each case, rock revetment (constructed under the Chico Landing to Red Bluff Project authority) was bypassed by the new flow channels. In March of 1983, Todd Island (RM 238 to 236) was cut in half by another bend cutoff channel.

The cutoffs at river miles 215 to 212 and 197 to 196 may have significant impacts on bank erosion rates. Not only were increases in local velocities created, but flows immediately downstream of the cutoffs are directed at nearly right angles to the opposite river banks (USCE 1981). Salmon, however, seem to prefer chute cutoffs for spawning. The increased gradient, fresh gravel and multiple channels improve spawning conditions considerably over the main channel. The bend cutoffs have not been blamed on Shasta Dam. USGS (1977) states:

> "Riparian vegetation on the inside of a loop serves to inhibit the downstream migration of the loop and to prevent cut-offs. Vegetation can be more easily established and protected there than on the outside of loops and it should not be cleared.
>
> ". . .but decrease in plant cover is probably a major factor in the decrease in sinuosity during the past 100 years."

Lateral migration rates are highly variable. A river may change little in many years, yet experience rapid movement in one flood season. A compilation of data by Leopold and Wolman (1957) shows that rates of lateral migration for the Kosi River of India approach 2,500 ft/yr. Rates of lateral migration for two major rivers in the United States are less dramatic, for example: Colorado River near Needles, California, 10 to 150 ft/yr; Mississippi River near Rosedale, Mississippi, 158 to 630 ft/yr. Between 1949-74, the Sacramento River has averaged about 10 ft/yr. Rates for various reaches between Chico Landing and Colusa are shown in Table 6.

Table 6. Lateral Migration Rates from Chico Landing to Colusa1/.

| | Area of Centerline Shift (in acres) | | | | | Rate of Centerline Shift (in acres/year/mile) | |
|---|---|---|---|---|---|---|---|
| River Mile | 1896-1908 | 1900-1920 | 1921-1948 | 1949-1974 | 1896-1974 | 1896-1948 | 1949-1974 |
| 193 -185 | 447 | 445 | 429 | 488 | 1,809 | 2.74 | 2.11 |
| 185 -178 | 374 | 248 | 359 | 327 | 1,308 | 2.75 | 1.91 |
| 178 -171.5 | 131 | 268 | 132 | 224 | 755 | 2.16 | 1.37 |
| 171.5-164.5 | 192 | 268 | 337 | 313 | 1,110 | 2.44 | 1.99 |
| 164.5-160 | 251 | 151 | 87 | 19 | 508 | 2.06 | .17 |
| 160 -153 | 183 | 237 | 272 | 122 | 814 | 1.84 | .67 |
| 153 -143.5 | 158 | 148 | 342 | 205 | 853 | 1.40 | .92 |
| 143.5-193 | 1,736 | 1,765 | 1,958 | 1,698 | 7,157 | 2.11 | 1.37 |

---

1/ Data from USGS (1977)

Figure 4 shows the variation in meander belt width from Keswick to Colusa. The width is determined from the sum of all the meander lines from 1896 to 1981 plotted in the atlases ("Upper Sacramento River Spawning Gravel Atlas", DWR 1980, and the "Middle Sacramento River Spawning Gravel Atlas", DWR 1984). There are a number of observations that can be made. First, the width, and hence bank erosion, is highly variable, ranging from less than 1,000 feet to 7,000 feet. Second, certain short reaches of river appear to be stable and do not move much. Third, there appears to be a certain periodicity in the spacing of unstable areas. Between Red Bluff and Chico Landing, the wavelength averages 8 miles. Between Chico Landing and Moulton Weir, the wavelength is consistently about 4 miles. Although it is not clear as to the reason for the periodicity, it may reflect an older meander pattern, some underlying geologic structure, or a systematic variation in grain size of the bank material.

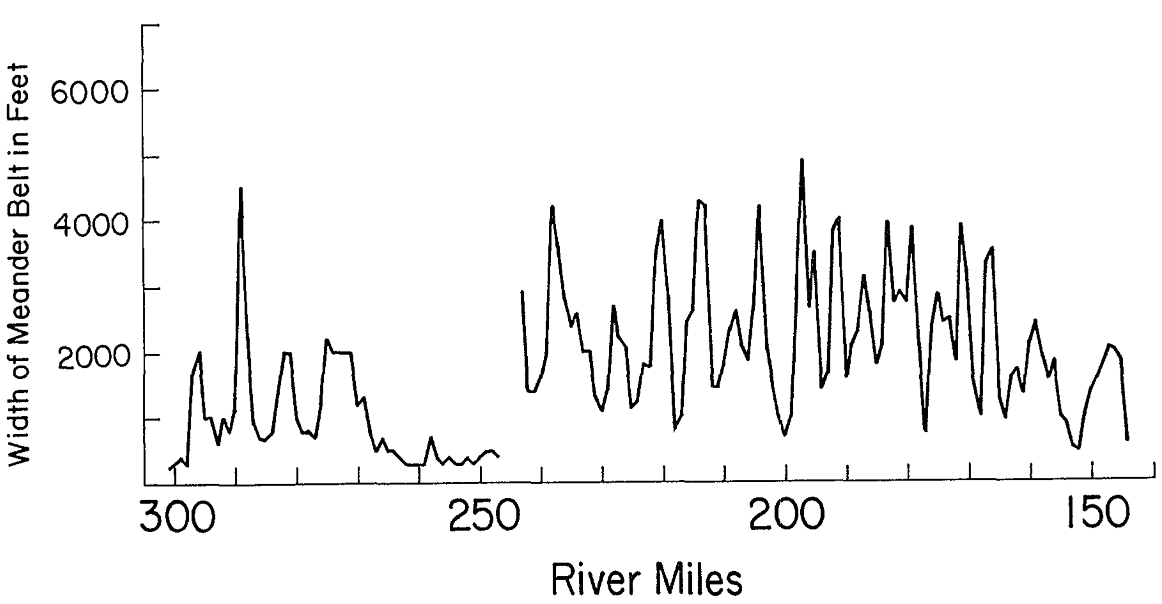

Figure 4. Variation in meander belt width from Keswick Dam (RM 302) to Colusa (143) for the period 1896-1981

## Changes in Length, Width, and Sinuosity

Analyses of channel length and sinuosity were done on eleven sets of maps and photographs dated between 1896 and 1981. Table 7 shows that the length and sinuosity of the river changes considerably with time. No trends are apparent, however, in that some reaches are increasing in length and sinuosity and others are decreasing. The USCE also believes that the width of the Sacramento River has increased since Shasta Dam. Shasta Dam would have a tendency to reduce the width because of less frequent floodflows. However, agriculture and loss of riparian vegetation would tend to increase channel width. This subject requires further study.

## Spawning Gravel Resources

Spawning gravel is a mixture of sand, gravel, and cobbles that a particular species of salmon finds suitable for spawning. Particle size must be small enough for the female to dig a nest with her tail. The voids between particles must be large enough to accept the fertilized eggs. The percentage of fines (sand, silt, and clay) must be small enough to allow the flow of oxygenated water through the nest. In addition, hydrologic parameters, such as water depth, velocity, temperature, etc., must be adequate before the gravel may be used for spawning. Within certain limits, the gravel available in the stream determines what the salmon spawn in. Less than ideal gravel can result in reduced egg survival, however.

There are a number of available studies on spawning gravel criteria. In an Environmental Protection Agency study Shirazi, Seim and Lewis (1979) suggest the use of geometric mean particle diameter ($D_g$) of the substrate gravel as the "appropriate statistic" for describing spawning gravel suitability. A strong correlation between $D_g$ and embryo survival rates was reported. A better correlation was derived by dividing $D_g$ by egg diameter ($D_e$). The findings of EPA are convenient--$D_g$ is easy to calculate from other statistical data and is good as a general indicator or sediment-size distribution. However, the study does not provide definite limits of different size classes (i.e., too many fines) that may not be reflected in $D_g/D_e$. Also, no chinook salmon basic data were used in the compilation of the curves. The EPA study makes the assumption that gravel samples are approximately lognormal. This is generally a good approximation for most samples from the Sacramento River and tributaries.

Between Keswick and Colusa, over 140 surface samples and 35 bulk samples were taken. Surface sampling determines the gravel-size distribution of surficial streambed material. The samples are made by measuring the intermediate axis of 100 gravel particles selected in the manner described by Wolman (1954). Bulk samples are taken from the upper one-foot layer of gravel; unlike surface sampling, it also includes a substantial portion of fines from subsurface layers. Bulk samples are obtained by driving a two-foot-square metal frame into the gravel and removing gravel from the inside of the cylinder. The coarser fraction is measured in the field by volume displacement and the finer fraction is measured in the laboratory by sieving and analyzing by weight percent.

Table 7. Centerline Length and Sinuosity, Sacramento River from Red Bluff to Colusa, 1896-1981

Centerline Length, in Feet

| | 1896 | 1908 | 1923 | 1935 | 1937 | 1946 | 1955-56 | 1960 | 1964 | 1969 | 1981 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reach 6 | | | | | | | | | | | |
| 6A | 17,500 | 17,500 | 17,600 | 17,600 | 17,600 | 22,400 | 22,900 | 22,900 | 22,900 | 19,500 | 19,500 |
| 6B | 33,500 | 33,500 | 37,300 | 37,300 | 37,300 | 33,000 | 32,100 | 32,100 | 32,100 | 39,000 | 39,000 |
| 6C | 13,300 | 13,300 | 13,300 | 13,300 | 13,300 | 13,200 | 12,600 | 12,600 | 12,600 | 13,400 | 13,500 |
| 6D | 48,800 | 48,300 | 50,300 | 50,300 | 50,300 | 47,500 | 47,100 | 47,100 | 47,100 | 57,400 | 52,100 |
| 6E | 11,800 | 11,800 | 12,000 | 12,000 | 12,000 | 12,000 | 12,500 | 12,500 | 12,500 | 12,500 | 12,600 |
| 6F | 68,400 | 68,400 | 65,400 | 65,400 | 65,400 | 68,400 | 66,000 | 66,000 | 66,000 | 76,000 | 61,000 |
| 6G | 17,200 | 17,200 | 17,200 | 17,200 | 17,200 | 17,600 | 19,500 | 19,500 | 19,500 | 18,100 | 18,500 |
| 6H | 30,000 | 30,000 | 33,000 | 33,000 | 33,000 | 21,400 | 21,200 | 21,200 | 21,200 | 22,900 | 19,300 |
| Reach 7 | | | | | | | | | | | |
| 7A | 86,800 | 79,400 | 79,400 | 74,200 | 81,200 | 79,900 | 73,700 | 73,700 | 80,400 | 84,600 | 83,200 |
| 7B | 10,500 | 10,600 | 10,600 | 10,500 | 10,900 | 10,300 | 10,300 | 10,300 | 99,000 | 10,000 | 10,000 |
| 7C | 117,500 | 104,400 | 104,400 | 102,200 | 110,500 | 72,000 | 99,000 | 99,000 | 102,000 | 102,000 | 103,900 |
| 7D | 20,500 | 21,500 | 21,500 | 22,100 | 22,800 | 21,900 | 21,800 | 21,800 | 22,400 | 22,400 | 22,500 |
| 7E | 31,600 | 32,900 | 32,900 | 33,400 | 33,000 | 32,400 | 33,000 | 33,000 | 28,200 | 28,200 | 29,200 |

Centerline Sinuosity

| | 1896 | 1908 | 1923 | 1935 | 1937 | 1946 | 1955-56 | 1960 | 1964 | 1969 | 1981 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Reach 6 | | | | | | | | | | | |
| 6A | 1.15 | 1.15 | 1.15 | 1.15 | 1.15 | 1.50 | 1.50 | 1.50 | 1.50 | 1.28 | 1.28 |
| 6B | 1.20 | 1.20 | 1.33 | 1.33 | 1.33 | 1.18 | 1.15 | 1.15 | 1.15 | 1.40 | 1.40 |
| 6C | 1.16 | 1.16 | 1.16 | 1.16 | 1.16 | 1.15 | 1.10 | 1.10 | 1.10 | 1.17 | 1.17 |
| 6D | 1.28 | 1.27 | 1.32 | 1.32 | 1.32 | 1.25 | 1.24 | 1.24 | 1.24 | 1.35 | 1.37 |
| 6E | 1.24 | 1.24 | 1.26 | 1.26 | 1.26 | 1.28 | 1.32 | 1.32 | 1.32 | 1.32 | 1.33 |
| 6F | 1.41 | 1.41 | 1.35 | 1.35 | 1.35 | 1.41 | 1.36 | 1.36 | 1.36 | 1.57 | 1.26 |
| 6G | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 | 1.30 | 1.44 | 1.44 | 1.44 | 1.34 | 1.37 |
| 6H | 1.71 | 1.71 | 1.90 | 1.90 | 1.90 | 1.22 | 1.27 | 1.21 | 1.21 | 1.31 | 1.10 |
| Reach 7 | | | | | | | | | | | |
| 7A | 1.61 | 1.48 | 1.48 | 1.38 | 1.51 | 1.49 | 1.37 | 1.37 | 1.50 | 1.57 | 1.73 |
| 7B | 1.14 | 1.14 | 1.14 | 1.14 | 1.18 | 1.11 | 1.11 | 1.11 | 1.07 | 1.08 | 1.08 |
| 7C | 1.41 | 1.25 | 1.25 | 1.23 | 1.33 | 1.17 | 1.20 | 1.20 | 1.22 | 1.22 | 1.25 |
| 7D | 1.58 | 1.65 | 1.65 | 1.70 | 1.75 | 1.68 | 1.68 | 1.68 | 1.72 | 1.72 | 1.73 |
| 7E | 1.67 | 1.69 | 1.69 | 1.71 | 1.69 | 1.66 | 1.69 | 1.69 | 1.45 | 1.45 | 1.50 |

Figure 5 shows the variation in $D_g$ of surface samples from upstream ends of point bars from Keswick to Colusa. Upstream ends of point bars approximate the hydrologic conditions of spawning riffles. As to be expected, there is a marked overall increase in geometric mean diameter going upstream. From Colusa to about river mile 282, the increase in $D_g$ is gentle. From 282 to Keswick, the increase is sharp. This reach corresponds closely to the armored section identified by DWR (1980).

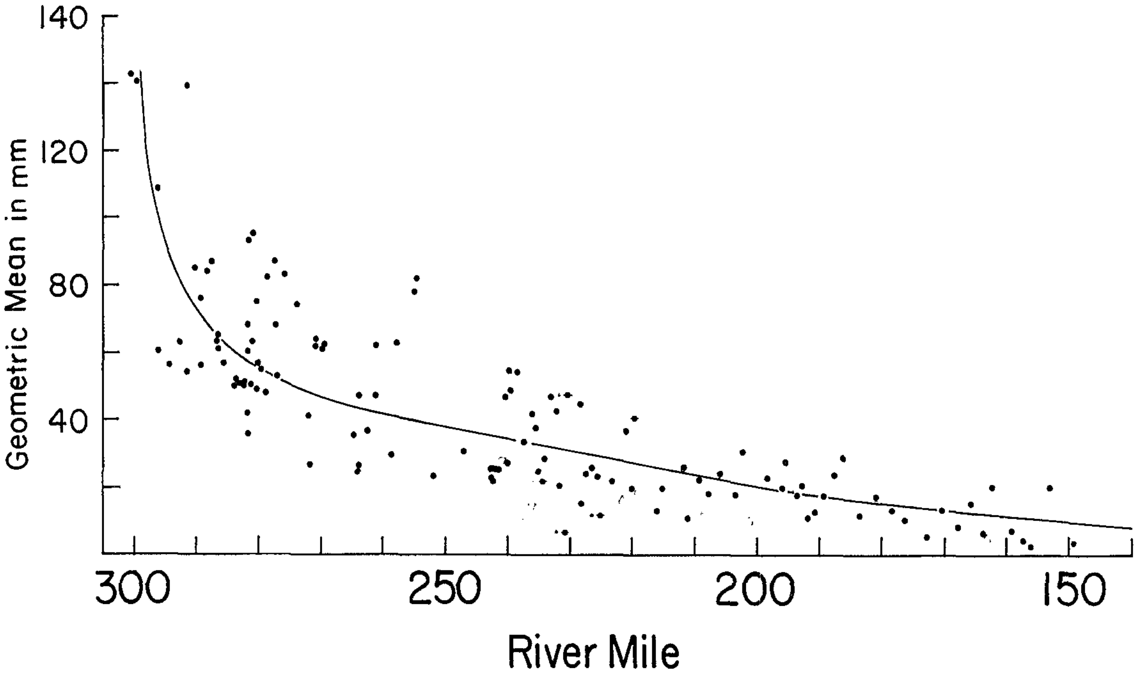

Figure 5. Variation in the geometric mean diameter of surface samples from upstream ends of point bars, Keswick to Colusa. Data are surface samples and triangles are bulk samples.

Using a relationship developed by Shirazi, Seim and Lewis (1979) between percent egg survival and $D_g$, Figure 6 was derived. This figure shows that the percent survival, based on gravel size alone, is only about 40 percent near Colusa, increasing to 80 percent at Hamilton City. The graph shows that the area between the Red Bluff Diversion Dam and about river mile 190 is prime spawning gravel. Above the dam, the gravel is of excellent quality to at least Stillwater Creek near Redding.

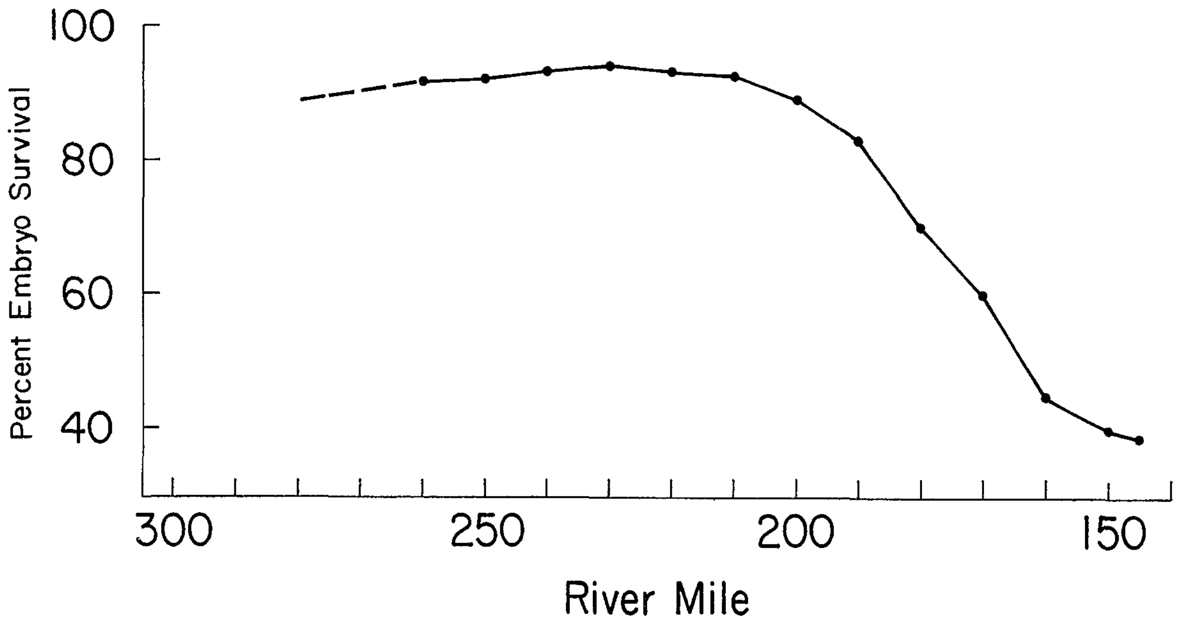

Figure 6. Percent embryo survival based on the geometric mean diameter of surface samples, Keswick Dam to Colusa.

Salmon spawn where a combination of conditions are conducive to spawning and egg survival. Most spawning areas may be classified as to geomorphic characteristics. Table 8 shows these for both the upper and middle Sacramento. In the upper Sacramento, geomorphic features such as islands, point bars, chute cutoffs, etc., are not well developed because of the lack of gravel. Still, about 40 percent of the spawning is associated with the upstream end of point bars, and an additional 25 percent with mid-channel cross-over areas. Only minor spawning is associated with tributary confluences and islands. Spawning occurs in pockets of gravel in the outside of bends and the head of side channels.

On the middle Sacramento, about 35 percent of the spawning is also concentrated at the upstream end of point bars. About 20 percent occurs in side channels, particularly chute cutoffs. Almost no spawning is associated with tributary confluences.

Table 8. Geomorphic Characteristics of Spawning Areas

Percentage of Total Spawning Area

| Geomorphic Characteristic | Upper Sacramento River | Rank | Middle Sacramento River | Rank |
|---|---|---|---|---|
| Head of Point Bars | 40 | 1 | 35 | 1 |
| Head of Islands | 5 | | 12 | 4 |
| Tail of Islands | 2 | | 3 | |
| Tributary Confluences | 2 | | 2 | |
| Side Channel (chute cutoffs) | 8 | | 18 | 2 |
| Anabranching Mid-Channel areas | 25 | 2 | 7 | |
| Outside of Bends | 10 | 3 | 15 | 3 |
| Inside of Bends with no point bars | 8 | | 8 | |
| | 100% | | 100% | |

Figure 4 showed the variation in the 100-year meander belt width. Figure 7 shows the variation in spawning area with river mile. In the upper Sacramento, there is a strong correlation between the wide meander belt and the amount of spawning area. This is mostly due to wider, shallower channel associated with meandering. Hydrologic diversity is also greater here. Bank erosion also provides freshly reworked and uncompacted gravel for spawning. In contrast, the narrow, deep, channelized, erosion-resistant canyon between Table Mountain and Red Bluff has only minor spawning.

The correlation between meander belt width and spawning is not nearly as strong for the middle Sacramento. This is probably because of the abundant gravel and the wide overflow areas that reduce scouring flows during floods.

Dams prevent gravel recruitment from areas above the dams. This in turn causes channel degradation and subsequent armoring and channelization. Many historic spawning riffles below Shasta and Keswick dams are now armored by cobbles too large for salmon to move.

Before the construction of Shasta Dam, about 100,000 tons/yr were derived from areas above. This was the primary source of spawning gravel to the river to at least the confluence of Clear Creek. Since McCormick-Saeltzer (1927) and Whiskeytown (1963) Dams on Clear Creek, significant tributary inputs of spawning gravel do not occur until Stillwater and Cow Creeks at river miles 281 and 280, respectively.

NOTE: A ROUGH ESTIMATE OF THE AMOUNT OF "SPAWNING SIZE GRAVEL" STOPPED BY SHASTA DAM IS ABOUT 25,000 tons/yr. spawning size is 1/2 to 4". ESTIMATE OF BEDLOAD TRAPPED IN SHASTA ≈ 5.6 million tons. ESTIMATE OF SPAWNING GRAVEL TRAPPED ≈ 1.4 million tons

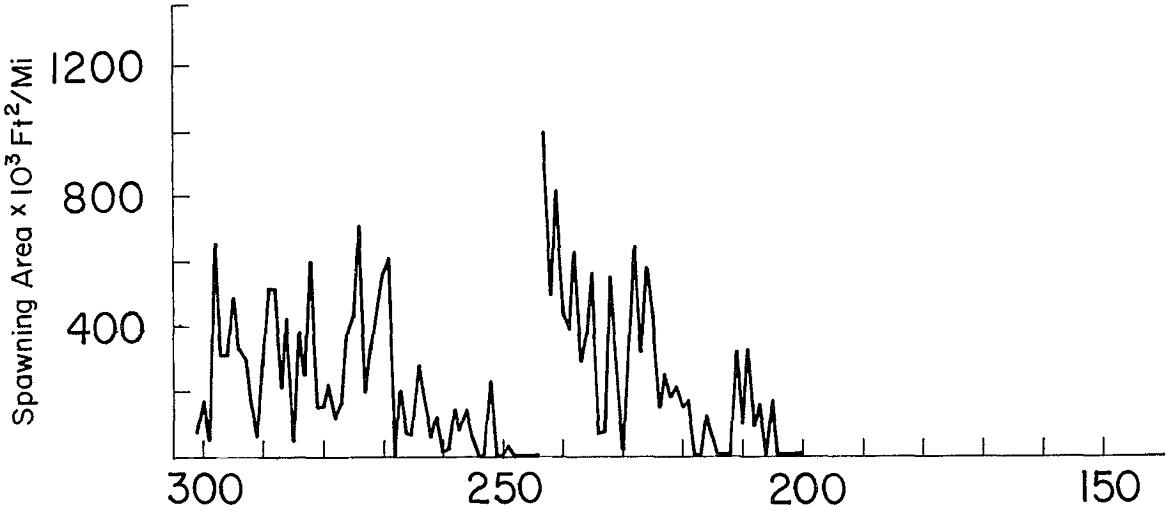

Figure 7. Variation in spawning area with river mile, Keswick Dam to Colusa. The spawning area represents the combined area used by the 1964 and 1983 fall run salmon.

Sand and gravel mining also affects the supply of spawning gravel. When gravel mining in an area exceeds the stream's annual bedload replenishment rate, it causes changes in the stream system. Upstream scouring is the first indication that a stream is being overmined. If the bed material deposited in the extraction site by winter high flows is over-mined year after year, the effects of the operation (scouring, armoring, entrenchment and/or abandonment of the higher terraces) will migrate upstream. Because the streamflow exits the extraction site with little or no bedload, scouring also occurs downstream of the site as the stream picks up sediment to satisfy its discharge-related sediment capacity. When tributary streams are heavily overmined or when pits are located so that they compound the effects of the overmining, the bedload in the stream and the bedload contribution to the Sacramento River is greatly reduced.

The construction of Shasta Dam required over 7 million cubic yards of aggregate from the Sacramento River in Redding. Several million were also used for the construction of Interstate 5. Most of the aggregate came from tributary streams. The present average extraction rate between Keswick and Chico Landing is estimated to be 1.6 million cubic yards a year. Most of this comes from pits in the Sacramento River flood plain, Cottonwood Creek, Red Bank and Thomes Creeks.

In tributary streams, excavation of the stream channel proper is the common method used in commercial pits. The 1603 Agreements between the gravel operators and the Department of Fish and Game generally state that gravel removal will be "skimming", where an effort is made to maintain a constant stream channel gradient throughout the extraction site. However, any time gravel is removed from the channel, the channel slope at the upstream end of the pit is effectively increased and the slope throughout the pit area is decreased. When winter high flows begin to move the bed material, the stream channel will scour at the upstream end of the extraction site because the increased gradient results in higher streamflow velocities than when the material was originally deposited. Bed material brought in from upstream and that derived from the scouring will be deposited in the pit area because of the lowered gradient and flow velocity in that area. The site thus becomes a gravel trap that prevents gravel from moving downstream until it has been filled up and the channel returned to a uniform slope. Cottonwood (river mile 273.4), Stillwater, and Cow Creeks are heavily impacted by gravel mining and probably produce less than half of historic rates.

From about Red Bluff downstream, gravel is supplied to the main river by numerous westside tributaries. Although actual deliveries of spawning-size gravel to the river are not high, considerable gravel is stored in the channel. The large amount of gravel is due in part to erodible watersheds and low gradients; hence, the gravel drops out before reaching the Sacramento River.

The most important source of spawning gravel is bank erosion. Most banks contain gravel in subsoil horizons. As the banks erode, the gravel is moved downstream to the next riffle or point bar, where it is deposited.

The movement and distribution of bedload in a stream is called a gravel budget. Developing a bedload estimate for a stream requires data on the hydrology, streambed gravel size distribution, and stream gage data, including depth, width, cross-sectional area and discharge records. The discharge records are used to develop a flow frequency curve. The curve is then divided into time intervals represented by a median discharge. The bedload, in tons per day, is then calculated for each median discharge using the Myer-Peter and Muller equation (DWR 1984). The bedload is then multiplied by the percent interval that this discharge occurred during the year.

Table 9 shows the gravel budget for the study reach. It should be noted that calculation of bedload transport is an inexact science. Hydrologic conditions change with time, sometimes in a single storm. Changes in the watersheds, including livestock grazing, forest fires, timber harvesting, and farming, will change the available sediment and the nature of the runoff that

## Table 9. Gravel Budget for the Sacramento River from Keswick Dam to Hamilton City1/

| Location | Area in $mi^2$ | Bedload2/ > 16mm tons/yr | Total Bedload tons/yr |
|---|---|---|---|
| Sacramento River at Keswick Dam | 6,468 | 0 | 0 |
| Eastside tributaries | 964 | 5,000 | 35,000 |
| Westside tributaries | 972 | 4,000 | 25,000 |
| Smaller tributaries and intervening areas | 496 | 0 | 0 |
| Total | 8,900 | 9,000 | 60,000 |
| Sacramento River near Red Bluff | 8,900 | 9,000 | 53,000 |
| Eastside tributaries | 705 | 8,600 | 12,400 |
| Westside tributaries | 1,010 | 19,500 | 161,000 |
| Smaller tributaries and intervening areas | 445 | 0 | 0 |
| Bank erosion | | 230,000 | 450,000 |
| Bar deposition | | 230,000 | 450,000 |
| Total | | 37,100 | 226,400 |
| Sacramento River at Hamilton City | 11,060 | 37,000 | 226,000 |

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1/ Source: Keswick Dam to Red Bluff (DWR 1980), Red Bluff to Hamilton City (DWR 1984).

2/ Bedload larger than 16mm (0.63 inch) is equivalent to spawning size gravel.

transports it. Dams, gravel mining, levees, and bank protection have affected the hydrology, sediment transport, and stream geomorphology in the last 100 years. The gravel budget is based on the hydrologic record and present conditions that may not be similar to past or future conditions.

The budget assumes that the river is a graded stream. The USCE (1981) concluded that the overall river gradient has not changed significantly since 1946. This indicates that the river now is neither aggrading or degrading.

It was believed (DWR 1983, USCE 1978) that through bank erosion, high-terrace lands were being replaced by low-terrace point bars because Shasta Dam reduced deposition of soils on the floodplain. Observations made during this study indicate that this is not correct. After the flood of March 1983, floodplain deposition was observed in a number of places. Deposition varied from zero inches to over two feet, with an average of several (3-6) inches within the flooded area. The Department of Water Resources (1983) in a study of land use changes in the Sacramento River Riparian Zone came to a similar conclusion:

> ". . . . . finally, there has been no overall loss of high-terrace prime soils from 1946 through 1982. Erosional losses of soil, both in orchard and riparian vegetation, have been severe, but natural soil building processes have created an equal or slightly greater amount of prime high-terrace soil."

Bank erosion is important for the recruitment of spawning-size gravel. It allows for the re-entrainment of gravel deposited on point bars. In addition, much of the coarser gravel from tributaries reaches the Sacramento River through bank erosion. During floodflows, backwater effects cause much of the bedload and most of the coarser fraction to drop out in tributary channels. Because of the channel infilling, many of the tributaries have developed distributary networks of multiple channels. Thomes, Mill, Antelope, Oat, and Coyote Creeks are examples of this. For example, Millrace, New, Craig, and Butler Creeks are old channels of Antelope. These old gravel channels are then eroded by the river as it meanders across its flood plain. Much of the gravel derived from tributaries then becomes available for spawning through bank erosion.

The total estimated amount of spawning gravel ( 16 millimeters, or about 0.6 inches) from above Bend Bridge and the tributaries, is about 38,000 tons per year. Bank erosion in the intervening reach is estimated to contribute about 230,000 tons per year, or about 85 percent of the total available spawning gravel. Bank protection, therefore, has a significant effect on the amount of available spawning gravel in the study reach.

Sand and gravel mining also affects the movement of spawning gravel. The effects tend to be gradual and accumulate over a period of years. For example, on Thomes Creek, mining exceeds the average bedload contribution by an order of magnitude. However, a large amount of gravel is in channel storage. The effect of the mining then is to gradually degrade and coarsen the channel downstream. Subsequently a larger flood will be necessary to move the same amount of bedload. The magnitude of this effect is dependent on such quantities as channel storage, annual bedload, extraction volumes, and location of sand and gravel extraction areas.

## Spawning Gravel Management Plan

> "It is of the utmost importance that California's natural environmental resources be properly and adequately managed for the benefits of this and future generations. Programs to preserve or enhance one resource must not achieve their goals by means which could lead to the deterioration of another resource." (In: "California Resources", The Resources Agency, August 1974.)

Salmon are ascending the Sacramento River to spawn in ever dwindling numbers. Salmon now passing the Red Bluff Diversion Dam represent only about 13 percent of the 1950s population. The total salmon run above the confluence with the Feather River is now only about 75,000 fish, about 30 percent of the 1950s average. Tributaries below Red Bluff now support less than 10 percent of historic averages. A management plan for the Sacramento should take into account that further degradation may lead to the eventual extinction of this valuable resource.

The management plan outline is as follows. Part I identified goals and objectives. Part II lists action alternatives for implementing objectives and fulfilling goals.

### Part I: Planning Goals

Planning goals for the management of the Sacramento River salmon may include:

1. Increasing salmon-spawning escapement.
2. Protecting, rehabilitating and enhancing spawning and rearing habitat.
3. Formulating policy concerning channel modification such as gravel mining, levee construction, and bank protection.
4. Implementing a monitoring program.

### Goal 1: Increasing Salmon Spawning Escapement

Salmon escapement has been declining to the point that most of the present spawning habitat is under-used. Without adequate returning spawners, spawning-gravel enhancement and rehabilitation programs will not be effective.

Action alternatives may include:

1. Screening all water diversions are properly and effectively to prevent fry mortality.
2. Giving high priority to solving fish-passage problems at the Red Bluff Diversion Dam.
3. Developing a "Payment-in-Kind" type program for the commercial ocean fishery. A program of this nature over a 2- to 4-year period could significantly reduce the ocean catch and increase escapement. It should pay for itself with increased commercial catches in future years.

## Goal 2: Protecting, Rehabilitating and Enhancing Spawning and Rearing Habitat

The concept of constructing spawning habitat is not new and has been widely used as a mitigating measure for losses of habitat incurred by construction projects. In the Upper Sacramento River, the reach between Keswick Dam and Cottonwood Creek is now in many places armored and too coarse for spawning. In the Middle Sacramento River, spawning habitat is adequate for serving the present run. However, such human induced changes as gravel mining, hydrologic changes, channelization, and bank protection may degrade this resource in the future.

Action alternatives include:

1. Migrating the downstream armoring effect of Shasta and Keswick Dams by the placement of artificial spawning gravel in suitable side channel areas.
    a. The reach between Keswick Dam and Clear Creek warrants first priority.
    b. The reach between Clear and Cottonwood Creeks warrants second priority.
2. Developing mitigating measures for losses in spawning and rearing habitat incurred by bank protection, gravel mining, channelization, and other instream projects.
3. On westside tributaries,removing during gravel mining only the finer fraction of the gravel and/or returning the coarser fraction (spawning-gravel sizes) back to the stream channel. On eastside tributaries, no gravel-mining permits should be issued. These tributaries produce only a small part of the available gravel. The gravel, however, is of higher quality than westside tributaries. Tributaries near Redding, such as Cow and Stillwater, have been severely impacted by gravel mining.
4. Surveying streams with gravel-mining operations to determine the amount of gravel in storage, and planning gravel removal so as not to scour streambed to bedrock.
5. Mitigating the effects of (a) placing rock riprap for bank protection, since bank erosion along the Sacramento River is a primary source of spawning gravel, and (b) considering alternative measures to bank protection, such as setback levees and/or allowing the river to meander within the ±100-year meander belt and protecting banks where the river threatens to leave this belt.
6. Studying feasibility of operating the Red Bluff Diversion Dam during floods so that gates are up when peak flows occur on Dibble, Blue Tent, Reeds and Red Bank Creeks. This would facilitate gravel recruitment to the Sacramento by reducing the backwater effect of Lake Red Bluff.

## Goal 3: Formulating Policy

The construction of Shasta, Keswick and Whiskeytown Dams has reduced the quality of gravel recruitment to the Sacramento River. The flood control provided by dams and levees enabled urban and agricultural encroachment to confine the river for extended reaches. Gravel mining has removed millions of cubic yards from the river and tributaries. The Red Bluff Diversion Dam has affected both upstream and downstream salmon migration. Today, salmon escapement is much reduced from historic levels, and salmon are perhaps threatened with extinction in areas above the diversion dam.

Action alternatives include:

1. Giving primary management priority to survival of salmon in the Sacramento River.
2. Making the solution to the salmon-migrating problems at the Red Bluff Diversion Dam the number one task.
3. Continuing gravel rehabilitation and enhancement projects in the upper river.
4. Formulating policy guidelines regarding gravel extraction.
5. Mitigating loss of gravel recruitment from bank protection.
6. Helping Tehama County adopt ordinances regulating encroachment on the flood plain and the ±100-year meander belt of the Sacramento River.

## Goal 4: Implementing a Monitoring Program

Alluvial streams may change rapidly in response to changes in the watershed. A program should be instigated to monitor spawning-gravel quantity and quality, riffle degradation, bank erosion and meander rates, gravel mining and bank protection.

Action alternatives include:

1. Closely monitoring gravel-extraction quantities on a yearly basis and comparing stream cross-section data from year to year. This will require the surveying of stream cross-sections above and below gravel operations.
2. Plotting spawning areas on a yearly basis. At present, the number of redds are recorded. Outlining by DFG of the actual spawning areas on atlas sheets or aerial photographs would assist in detecting significant yearly changes.
3. Establishing monitoring sites on key riffles and recording aggradation or degradation. Riffles directly below the diversion dam are key spawning areas where changes should occur first. Adequate gravel recruitment from areas above the dam may be a long-range problem.

## Acknowledgements

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