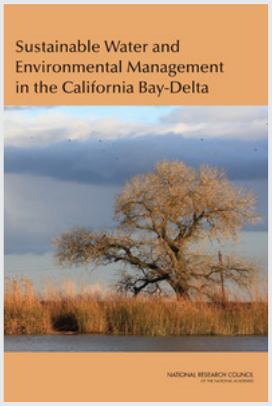

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Committee on Sustainable Water and Environmental Management in the California Bay-Delta

Water Science and Technology Board

Ocean Studies Board

Division on Earth and Life Studies

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Michael C. Kavanaugh, Geosyntec Consultants, and Leo M. Eisel, Brown and Caldwell (retired). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

INTRODUCTION

California's San Francisco Bay Delta Estuary encompasses the deltas of the Sacramento and San Joaquin rivers as well as the eastern margins of San Francisco Bay. Extensively modified over the past century and a half, it remains biologically diverse and functions as a central element in California's water supply system. Uncertainties about the future, actions taken under the federal Endangered Species Act (ESA) and companion California statutes, and lawsuits have led to conflict concerning the timing and amount of water that can be diverted from the delta for agriculture and municipal and industrial purposes and concerning how much water—and of what quality—is needed to protect the delta ecosystem and its component species.

The delta is among the most modified deltaic systems in the world. Millions of acres of arid and semiarid farmlands depend on the delta for supplies of irrigation water, and approximately 25 million Californians depend on transport of water through the delta for at least some of their municipal water supplies. Population growth anticipated for the first half of the 21st century is likely to create additional water demands in spite of significant reductions in per capita urban consumptive uses. In addition to supporting these consumptive uses, the delta provides habitat for animals and plants. The delta also supports recreational boating and fishing.

Diversions from the delta are dominated by the exports to the irrigation and urban service areas of the federal Central Valley Project (CVP) and the State Water Project (SWP) service area, which include southern portions of the San Francisco Bay Area, the western side of the San Joaquin Valley, and much of southern California. Substantial amounts of water also are diverted upstream for use in the Bay Area and Central Valley cities and farms, and within the delta itself for local irrigation. Irrigation return flows are discharged upstream and into the delta itself. Water supplies are highly variable from one year to another.

Despite statewide water conservation efforts, which are particularly pronounced in the urban sector, increasing seasonal restrictions on diversions have been applied, although the total amount of water diverted for export by SWP and CVP has not decreased. The CVP withdraws water from the delta and conveys it southward into the San Joaquin Valley through a system of canals built and operated by the federal Bureau of Reclamation and various water user groups. Most of this water is used for agricultural purposes; a small amount is contracted for domestic use. The SWP withdraws water separately from the delta and conveys it southward to agricultural users on the west side and at the very southern end of the San Joaquin Valley and subsequently over the Tehachapi Mountains into the conurbation of the South Coast Basin. Total available supplies to both CVP and SWP have been constrained in recent years by court decisions restricting diversions because of environmental concerns. In addition, many of the levees have become weak and some of the natural riparian zones of the delta have been eroded. Resolution of these problems is complicated by water scarcity generally and because alternative solutions impose differing degrees of scarcity for the uses advocated by different groups of stakeholders. The risk of change in water supplies, which could be manifested either by increases in the already substantial intraseasonal and intra-annual variability or through an absolute reduction in available supplies, underscores the existence of water scarcity and illustrates ways in which such scarcity could be intensified.

In addition to serving economic purposes, delta water has been managed for other purposes. Since the beginning of CVP operations, water diversions to users outside the delta have been managed to reduce the effects of salinity intrusion on local water users in the western margins of the delta. Additionally, the constitution of California requires that the waters of the state be put to "beneficial use." Although not defined, this criterion is subject to judicial review and determination. The enactment of both state and federal environmental laws has led to increased allocation of natural and stored water to environmental (instream) uses. The importance of environmental uses of water has been reflected further in many state regulatory decisions and, more recently, in judicial interpretations of the federal ESA and the California Endangered Species Act that have led to specific water allocations. Five taxa of fish residing in or migrating through the delta (one steelhead population, two populations of Chinook salmon, delta smelt, and green sturgeon) have been listed as threatened or endangered under the federal ESA and similarly listed under the California Endangered Species Act. There has not been a comprehensive agreement about how to allocate delta water to these various purposes.

The Current Study

Given the complex backdrop surrounding the California delta and the importance of this water source to human and ecosystem needs, Congress and the Departments of the Interior and Commerce asked the National Research Council (NRC) to review the scientific basis of actions that have been taken and that could be taken for California to achieve simultaneously both an environmentally sustainable bay-delta ecosystem and a reliable water supply. To balance the need to inform near-term decisions with the need for an integrated view of water and environmental management challenges over the longer term, the National Research Council addressed this task over a term of more than 2 years, resulting in three reports.

First, the committee issued a report, *A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta*,[1] focusing on scientific questions, assumptions, and conclusions underlying water-management alternatives in the U.S. Fish and Wildlife Service's Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project (December 15, 2008) and the National Marine Fisheries Service's Biological Opinion on the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan (June 4, 2009). The Executive Summary of this report is in Appendix A.

Second, a separate but related NRC panel issued a short report that reviews the initial public (November 2010) draft of the Bay Delta Conservation Plan (BDCP) in terms of the adequacy of its use of science and adaptive management—*A Review of the Use of Science and Adaptive Management in California's Draft Bay Delta Conservation Plan*.[2,3]

This third report addresses the following tasks (the full statement of task is in Appendix C):

- Identify the factors that may be contributing to the decline of federally listed species and, as appropriate, other significant at-risk species in the delta. To the extent practicable, rank the factors contributing to the decline of salmon, steelhead, delta smelt, and green sturgeon

[1] Available through The National Academies Press: http://www.nap.edu/.
[2] Available through The National Academies Press: http://www.nap.edu/.
[3] The summaries of both the recent NRC reports are provided at the end of this report as appendixes.

in order of their likely impact on the survival and recovery of the species, for the purpose of informing future conservation actions.
- Identify future water-supply and water-delivery options that reflect proper consideration of climate change and compatibility with objectives of maintaining a sustainable bay-delta ecosystem.
- Identify gaps in available scientific information and uncertainties that constrain an ability to identify the factors described above.
- Advise, based on scientific information and experience elsewhere, what degree of restoration of the delta system is likely to be attainable, given adequate resources. Identify metrics that can be used by resource managers to measure progress toward restoration goals.

The statement of task focuses primarily on science and does not ask for policy, political, or legal advice. The report organization does not follow the statement of task because the committee concluded the current organization provides a more logical flow. The factors affecting the listed species are discussed in detail in Chapter 3. Future water-supply and water-delivery options are discussed in Chapters 2, 4, and 5. Scientific uncertainties are discussed throughout the text in Chapters 3 and 4, and the degree of restoration likely to be attainable is in Chapter 4.

CHALLENGES AND OPPORTUNITIES

The challenges of managing water and achieving ecological rehabilitation in the delta are numerous, including the reluctance of many participants to confront the reality that water is scarce; the distribution of water-management responsibilities among many agencies and organizations; the suite of environmental factors (stressors) that affect the structure and functioning of the delta ecosystem, including the many biological and physical changes that have occurred in the delta; and the lack of detailed understanding of future socioeconomic, climate, biological, and other changes and the consequent lack of ability to plan for them. The following sections discuss the individual challenges; opportunities are reflected in the conclusions and recommendations.

Scarcity

Scarcity means that there is simply not a sufficient quantity of some resource or commodity to satisfy all wants for it. Scarcity is a pervasive phenomenon and it is persistent. Water scarcity has always been a fact in California (save, perhaps, for unusually wet periods), and therefore the committee cannot evaluate the items in its charge above without addressing scarcity. The magnitude or intensity of scarcity has grown over time and it continues to grow because demands have grown. There are numerous manifestations of scarcity. For example, legal rulings that require larger allocation of water to support fisheries and environmental flows are a manifestation of scarcity. Concerns about the delta itself and differing positions about how delta waters should be allocated are also manifestations of scarcity. The failure to acknowledge scarcity as a fact of life and to craft water plans and policies to address scarcity has made the management of delta waters far more difficult than it needs to be. The issue of scarcity is discussed in detail in Chapter 2.

Conclusions and Recommendations

California's Two "Co-equal Goals"

Contemporary planning for water management in the bay delta is directed at two "co-equal goals": providing a more reliable water supply for California and protecting and rehabilitating the delta ecosystem. There are benefits of having established these goals, but the planning needed to implement these goals has not yet led to clarity on how the inevitable trade-offs between the goals will be managed when water is short. Thus, the benefits of treating environment and water supply equally cannot be fully realized until some additional conditions are met. The implementation objectives associated with the goals need to be made specific so that when inevitable conflicts between the co-equal goals arise, guidance on how those conflicts should be resolved will be available.

Water-Planning Principles and Guidelines for Addressing Scarcity

The committee recommends consideration of the following principles and guidelines for addressing scarcity in planning:

- Recognize that not all uses of water are always compatible with each other.
- Provide better definition of competing uses; acknowledge, specify, and account for trade-offs in planning and decision making. The cost of water to users should reflect its scarcity and allocation should be based on analysis that allows for informed decision making.
- Modify practices that do not reflect the scarcity value of water. The fact of water scarcity does not mean that the state is "running out of water." Although most surface flows have been fully allocated or overallocated, the state can use a number of tools that optimize the use of existing supplies. As described below there are several tools currently available for use within existing legal authority. Other tools may require additional legislative authorization.

- Enforce California's constitutional prohibition against nonbeneficial, unreasonable, and wasteful water use.
- Protect values recognized under the public trust doctrine.
- Practice water conservation (including improved efficiency and productivity of use).
- Improve groundwater monitoring and regulation in all sectors.
- Consider using water markets to address scarcity. Long-term transfers of water from willing sellers to the state offer a significant opportunity for better management of California's waters consistent with the state constitutional provision. The state could then improve the availability of water for supplemental supplies and instream uses, particularly south of the delta.

The Need for Integrated, Coordinated Planning

Water management for the bay and delta is distributed among many agencies and organizations, a structure that hinders the development and implementation of an integrated, comprehensive management plan. Recent and current bay-delta planning efforts have not yet resulted in a resolution of what is best for the environment or for satisfying anticipated water needs.

Conclusions and Recommendations

Those engaged in policy making and management should refresh the overall approach to management of water in California that has not been addressed significantly since the late 1960s, when a partial effort was made in the Porter-Cologne Water Quality Act of 1969, which established the State Water Resources Control Board and nine Regional Water Quality Control Boards.

The current organizational structure (or absence of structure), which lacks clear, unambiguous assignments of authorities and responsibilities, makes it difficult to develop and implement a balanced, sustainable plan. The Delta Plan and other efforts under way attempt to satisfy independent legislative enactments, but not the fundamental principles of water management reflected in the Porter-Cologne Act or the state constitution. For instance, the current version of the Delta Plan deals at length with issues related to financing of various activities. There is no discussion of benefit/cost, efficiency, or priorities for action, all of which are essential parts of effective resource planning.

The committee is not constituted to recommend a specific organizational strategy but does conclude that the current structure, with distributed authorities and responsibilities, has not been effective and is unlikely to be effective in the future. Issues related to planning and water management are discussed in detail in Chapters 2 and 5.

Environmental Stressors

Many environmental factors, including water diversions, affect the structure and functioning of biotic communities in the delta. Although it would be convenient if one or only a few of these factors could be identified as the source of the "problem," or even ranked with some certainty, it is not possible to do that.

Interactions among stressors and between stressors and ecosystem processes are common and can be synergistic or antagonistic. Nutrient enrichment, toxic chemicals, and temperature, for example, are affected by physical forces in the system such as hydrologic and hydrodynamic factors. This complicates the interpretation and evaluation of positive, negative, neutral overall effects of any single stressor on the ecosystem and its attributes. Furthermore, species differ in their responses to most types of stress. The result is a complex biological, spatial, and temporal mosaic of impacts from this complex combination of influences.

The ecosystem and its components do not necessarily respond as a unit to most environmental factors. For example, Chinook salmon spend several years at sea and then return to pass through the delta as adults to spawn; their eggs and young spend time in delta tributaries before passing through the delta on their way to the ocean to grow. Returning adult Chinook salmon always die after spawning, so they are not susceptible to chronic environmental stressors, because they die before they can be affected by them. By contrast, delta smelt spend their entire (short) lives in the delta and so they can be chronically exposed to contaminants in the water. Being smaller and weaker swimmers than salmon, they likely are more susceptible to changes in flow than salmon. In addition, the behaviors, food, distribution in the water column, and physiologies of salmon and smelt are different, so even if they are exposed for a time to the same adverse environmental conditions, their responses to them almost certainly are different.

The above discussion compared only two species, but other species are important as well, including those that are not listed as endangered or threatened. Other species are part of the ecological community and yet they, too, differ in behavior, distribution, physiology, and susceptibility to a wide variety of environmental conditions, including contaminants. There is a complex interplay between key water quality, habitat, and sustainability issues and the drivers affecting them. Furthermore, uncertainties and scientific gaps further compound the problem.

Conclusions and Recommendation

For all the above reasons, the committee concludes that only a synthetic, integrated, analytical approach to understanding the effects of suites of environmental factors on the ecosystem and its components is likely to provide important insights that can lead to enhancement of the delta and its species. Nevertheless, the committee has evaluated several stressors in terms of their general importance. Those evaluations are summarized below and presented in detail in Chapter 3.

Given the diverse set of organisms and processes that constitute the delta ecosystem, the ultimate success of any approach targeted to particular species seems doubtful. In contrast, broad standards established, admittedly in the face of some uncertainties, do provide broad protection for the ecosystem; that is, they adhere to the precautionary principle of doing no harm, but do so at higher water cost, potentially using water that could be used to support economic activity, sanitation, and other needs. Thus, the hard decisions will need to be made about balancing different kinds of risk. These will be matters of policy rather than being the result of a straightforward application of "good science." Exactly because statistical correlations are not adequate to fully explain the responses of aquatic species to either flows or flow pathways, continuing the effort to better understand the processes that control the implications of both flows and flow paths is essential into the future.

Although many stressors are interacting in a complex way, some conclusions are possible with respect to individual stressors.

For migratory salmonids, and probably green sturgeon, dams are significant stressors. They impede passage, cause the loss of spawning and rearing habitat, change the abundance of predators, and affect temperature and flow.

Migrating salmon and steelhead smolts appear to incur substantial levels of mortality during delta passage. Increasing passage of smolts through Yolo Bypass to reduce delta passage may be a viable action for Sacramento runs.

Entrainment effects of SWP and CVP pumping are likely large in some years for some species, and thus entrainment acts as an episodic stressor that has a significant adverse effect on delta smelt population dynamics, although it is very difficult to quantify the effects in simple ways.

There is room for improvement in managing volume and timing of flows and flow paths. The committee reemphasizes the need for life-cycle modeling and a collaborative process to reduce the paralysis that can occur from the adversarial use of models and to encourage cross-comparisons and cross-fertilization. The recent increase in life-cycle modeling for both delta smelt and salmonids is an encouraging development.

The committee has not analyzed the benefits and disadvantages of an isolated conveyance facility, because not enough specific information was available about it, and we make no recommendation with respect to its adoption as a major part of water management in the delta. However, the committee does recommend that before a decision is made whether to construct such a facility and in what form, the sizing of the facility, its location, and the diversion design and operation, including the role of current diversions, should be analyzed as part of any integrated delta plan and compared to alternative water management options, including current operations.

Changes in nutrient loads and concentrations in the delta and bay, especially those for nitrogen and phosphorus, are stressors of increasing concern from water quality and food web perspectives. Toxic pollutants such as selenium also appear to be significant stressors, especially for sturgeon, with San Francisco Bay and the San Joaquin River being the areas of greatest concern.

The stressors also interact with each other and with changes in salinity, turbidity, and freshwater discharges resulting from hydrologic changes in the delta and its tributaries, changes that have been attributed to water exports, changes in land use, and changes in the morphology of the delta. The last factor, caused by canalization and the abundance of hardened structures that also have eliminated tidal wetlands, has affected delta smelt by changing their aquatic habitats. Support for better understanding the processes that link flows, habitat structure, and habitat characteristics such as salinity, turbidity, and temperature should remain a high priority. Reductions in outflow caused by diversions tend to reduce the abundance of some delta and bay organisms.

Introduced species have caused dramatic changes in habitat, prey, and predators of the listed fish species in the delta. Introductions of nonnative species will continue into the future as management controls that substantially reduce risk are difficult and expensive to implement. Changes in human activities and climate change could exacerbate the frequency of invasions and persistence of invading organisms in the future. Early detection through monitoring is useful in order to prepare for likely changes to the ecosystem.

Largely because negative effects of hatcheries are difficult to observe, the committee cannot reach a conclusion as to whether and how much hatcheries have contributed to the decline in wild populations of salmonids in the Central Valley. The committee judges that adoption of recent conservation guidelines under a unified hatchery management plan will reduce (but not eliminate) risk to wild populations from hatcheries and probably represents the most viable option for maintaining populations of salmonids in the Central Valley unless or until other methods are found to increase the productivity of wild populations.

Coastal ocean productivity is one of the most significant factors determining the ocean survival of juvenile salmon and the number of adult salmon that return to spawn. When ocean conditions are unfavorable for salmon and steelhead, those effects can be partially ameliorated by increasing the diversity of wild and hatchery salmon ocean entrance timing.

Currently, disease does not appear to be a significant stressor factor for juvenile or adult salmon or other fish species in the delta.

Consideration of the large number of stressors and their effects and interactions leads to the conclusion that efforts to eliminate any one stressor are unlikely to reverse declines in the listed species. Opportunities exist to mitigate or reverse the effects of many of the above stressors. To make it more likely that any actions to rehabilitate the ecosystem are cost effective, continued effects analyses, modeling, and monitoring will be needed.

Environmental Change and Ecosystem Rehabilitation

Climate change is one of the most challenging and important issues confronting the management and rehabilitation of the delta ecosystem. Changes in climate are expected to have profound effects on the physical and ecological structure of the delta as well as the nature of water issues in California. The cascading effects of climate change begin with increasing air temperature, which, over the 50-year planning horizon of the delta's BDCP, is predicted to increase between 1°C and 3°C. As a result, snowmelt will occur earlier than currently, and more winter precipitation will fall as rain, as opposed to snow, than currently. The changes are expected to have large effects on temporal and spatial hydrologic patterns even if the average annual precipitation volume did not change.

In addition to changes in hydrologic patterns, sea level also is expected to rise as a result of climate warming. Sea level rise would interact in complex ways with altered hydrologic patterns and the effects are not easy to predict. However, it does seem clear that the combination of sea level rise and altered hydrologic patterns would increase the risk to delta infrastructure, such as levees.

Increased temperature likely would reduce the distribution of salmonids in the Central Valley. In many parts of their range they encounter summer temperatures near the lethal limit for them. The frequency and duration of such temperatures is expected to increase, and their effects likely would be exacerbated by changes in hydrologic patterns.

If the climate projections are correct, more frequent extreme events will increase the need for Central Valley water for both environmental and human uses. In this case, managers may be asked to consider hard choices. While the predicted changes may not come to pass, the committee encourages continued critical and comprehensive studies of the full range of future possibilities and how to adapt to climate change. The implications of climate change for the delta and for environmental rehabilitation and water supplies are discussed in detail in Chapter 4.

Conclusions and Recommendations

Habitat loss and alterations, climate change, and unpredictable levee failure pose significant challenges in the formulation of plans for sustaining the bay and delta ecosystem. However, there are many opportunities to steer the future evolution of the ecosystem by addressing future challenges.

Extensive physical changes in the delta ecosystem and the tributary watersheds, and continuously evolving changes, such as land subsidence in the delta islands, will not allow the re-creation of habitat as it once existed in the predisturbance state. Delta restoration programs will need to balance consideration of an ecosystem approach with the ESA's emphasis on individual species. Programs will need to focus on the interaction of biological, structural, and physical aspects of habitats and how they may change in the future. Even without ESA-listed species, there still would be a need to guide the ecosystem toward desirable states.

Assessments suggest that many species will be affected by changes in the pattern and types of precipitation. Changes already are being observed. Projected increases in the mean sea level and the extremes have the potential to increase the frequency of levee failures and inundation of islands, in part because the land inside the levees continues to subside through oxidation of peat. Sea level rise also has the potential to enhance saltwater intrusion and alter water quality.

Planning and evaluation of future environmental and economic scenarios will need to address the uncertainties in projections, integrated analysis, and the development of risk-management strategies (e.g., adaptive management). The uncertainties are higher about the environmental aspects of operations than about the reliability aspects of water deliveries. Climate change implications and the continued increase in water demands in the bay-delta system and beyond will exacerbate the competition for water and limit the ability to meet the co-equal goals.

Future planning should include the development of a climate change–based risk model and analysis that incorporates data on the actual changes in delta conditions as well as alternative future climate scenarios and their probability. The real challenge is deciding how to adapt to a new environment. Strategies to deal with the expected and unprecedented changes will need to consider many factors, including targeted demand management, increased surface and groundwater storage consistent with minimizing environmental impacts, enhanced flexibility in the water-management system through operational optimization and maximum flexibility for moving water, and developing an understanding of and establishing environmental flows for the ecosystem.

The instability and interdependence of levees—failure of one levee can affect others—are likely to be major issues for achieving any measure of water-supply reliability or ecosystem rehabilitation. Continuing the status quo of improving levees will not always be the most environmentally sustainable or economically defensible response in the years ahead. Changes in the levee system, and even removal or modification of some levees, could be good for at least parts of the ecosystem.

Resource managers dealing with the delta will need to determine the degree of "restoration" achievable through intervention and adaptation. The delta as it existed before large-scale alteration by humans cannot be re-created. With respect to species, habitats, productivity, and other aspects, the future delta will still be a functioning ecosystem but different from the one that exists today. However, there is a considerable capacity to guide the direction of the delta toward a more desirable future by focusing on a functioning resilient ecosystem without abandoning individual efforts to protect individual native species. Achieving the above will require extensive, thoughtful, and transparent planning. That planning will need to include finding ways to reconcile diverse interests without pretending that everybody can have what they want.

The Role of Science and Planning: A Path Forward

Science is necessary to inform actions and proposals related to restorations of all kinds. However, science alone does not provide the entire prioritized, integrated analysis that the committee recommends. For instance, science can provide information on options regarding the control of ammonium to maintain an adequate food supply for fish, on the consequences of different schedules for investment in delta levees to protect agriculture, and on the degree of effectiveness of future diversion restrictions to protect salmon in the mainstream of the Sacramento River. However, science cannot decide which choice is the best policy. That requires societal and political considerations as well as information on potential benefits and costs. Using the best science is only part of what is needed to resolve the competing interests. The role of science, including its limitations, is discussed in detail in Chapter 5.

Conclusions and Recommendations

The committee concludes that the lack of explicitly integrated comprehensive environmental and water planning and management results in decision making that is inadequate to meet the delta's and state's diverse needs, including environmental and ecological conditions in the delta. In addition, the lack of integrated, comprehensive planning has hindered the conduct of science and its usefulness in decision making. Lack of transparency exacerbates these matters and erodes public trust.

The committee recommends California undertake a comprehensive review of its water-planning and management functioning and design modifications to existing responsibilities and organizations that will anticipate future needs, including those identified in this report. These needs include dealing with scarcity, balanced consideration of all statewide water-use practices and water-engineering alternatives, and adaptive management that can adjust to changing conditions. The result should be that regions such as the delta can be effective partners in a coordinated statewide effort.

The committee makes no recommendation of any specific organizational strategy for institutional changes. Any strategy should incorporate the public's desires and achieve the public's trust while allowing for decisions to be made.

Delta conditions identified in the following chapters suggest that scarcity of water for all needs will become severe. While more effective planning is being developed, the state will need to use its water resources efficiently and productively. A variety of tools are available, including demand-side management (conservation, including more efficient and more productive water use) and supply-side management (water transfers conducted by the state or within a new central planning function, new sources of supply, more integrated management of groundwater and surface water, enforcement of the constitutional reasonable and beneficial use limitations, and invocation of the state public trust doctrine to reconsider past allocation decisions). Thus, reliability-dependent users (urban, industrial, and agricultural) would have some long-term confidence that supplies will be more predictable. As part of its oversight of such transfers, the state needs to ensure that necessary instream flow levels are maintained. Continued, substantial investments in monitoring, modeling, and other research to inform policy choices will be essential.

1

Introduction

BACKGROUND[1]

California's San Francisco Bay Delta Estuary (Figure 1-1) encompasses the deltas of the Sacramento and San Joaquin rivers as well as the eastern margins of San Francisco Bay. Although the area has been extensively modified over the past century and a half, it remains biologically diverse while simultaneously functioning as a central element in California's water supply system. The delta system is subject to several forces of change, including seismic activity, land subsidence, sea level rise, and changes in flow magnitudes due to engineering and climate change, which threaten the structural integrity of the delta and its capacity to function both as an important link in the state's water supply system and as habitat for many species, some of which are threatened and endangered. In anticipation of the need to manage and respond to changes that are likely to beset the delta, a variety of planning activities have been undertaken. In addition, there have been actions taken under the federal Endangered Species Act (ESA) and companion California statutes, including lawsuits. The net result has been considerable uncertainty and conflict concerning the timing and amount of water that can be diverted from the delta for agriculture and municipal and industrial purposes and how much water—and of what quality—is needed to protect the delta ecosystem and its component species.

The delta is among the most modified deltaic systems in the world (Kelley 1989, Lund et al. 2010). The Sacramento–San Joaquin Delta is an

[1] Much of the following material was adapted from NRC (2010, 2011).

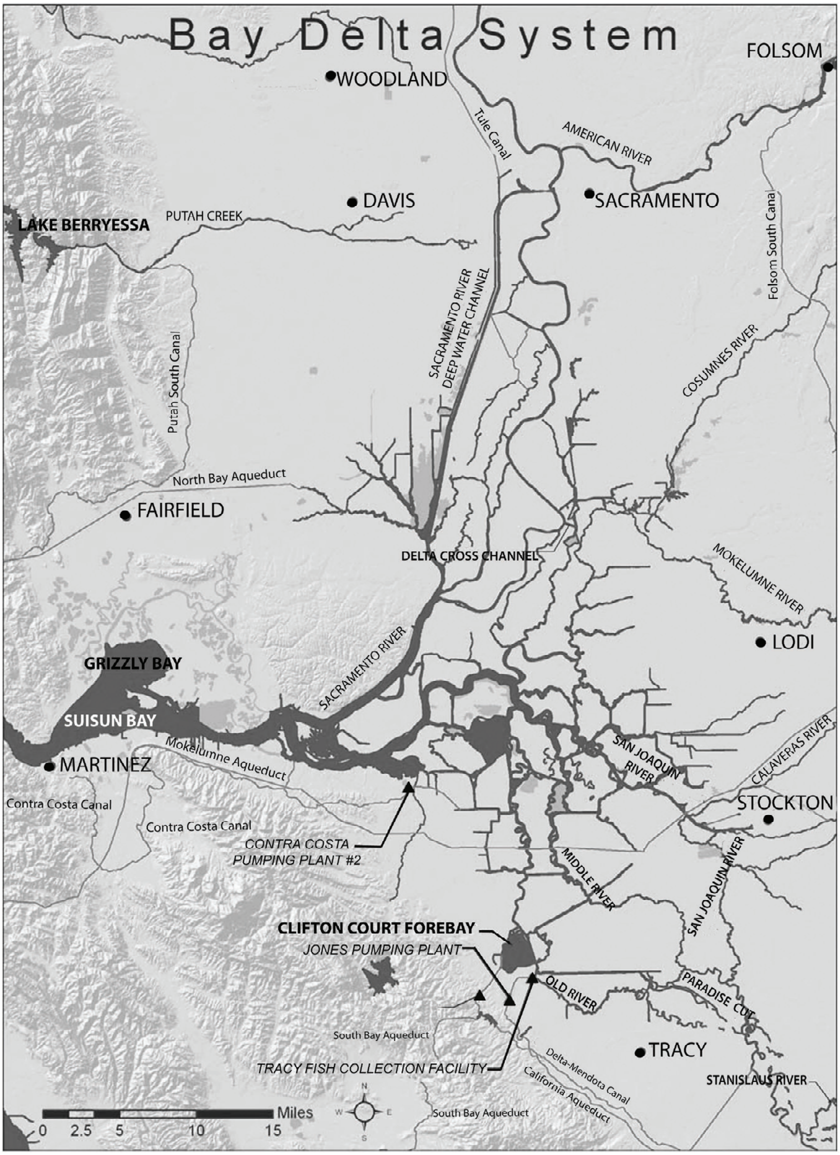

FIGURE 1-1 The Delta.
SOURCE: Reproduced from NRC (2010), modified from FWS (2008).

integral part of the water supply delivery system of California. Millions of acres of arid and semiarid farmlands depend on the delta for supplies of irrigation water, and approximately 25 million Californians depend on transport of water through the delta for at least some of their urban water supplies. If California's population grows from the current 37.25 million to nearly 50 million people by 2050, as projected by the California Department of Finance (2007), there likely will be additional water demands even if there continue to be significant reductions in per capita consumptive uses. In addition to supporting these consumptive uses, the delta provides habitat for animals and plants. Five taxa of fish residing in or migrating through the delta [one steelhead (*Oncorhynchus mykiss*) population, two populations of Chinook salmon (*Oncorhynchus tshawytscha*), delta smelt (*Hypomesus transpacificus*), and green sturgeon (*Acipenser medirostris*)] have been listed as threatened or endangered under the federal ESA and similarly listed under the California Endangered Species Act. The delta also supports recreational boating and fishing.

The various activities that have taken place in the delta over recent decades have taken place in a complex and uncertain environment. Those qualities apply to the biophysical environment, including complexities and changes in the hydrologic system, such as interactions of altered freshwater discharge regimes with complexities associated with tidal influences, changes in the composition and numbers of many species, variability and changes in precipitation, and changes in the built environment.

They apply also to the human environment, particularly in growth of the human population, complexities and changes in people's livelihoods and lifestyles, political changes, financial and economic changes, changes in people's occupations, changes in technology, and changes in people's understanding of these systems. Uncertainty is inherent in many of the above factors.

The delta includes the lower reaches of the two largest rivers in California and the eastern estuary and associated waters of San Francisco Bay. Most references to the delta do not include San Francisco Bay itself—typically, the western extent is around Suisun Bay—but hydrologically, chemically, and biologically, San Francisco Bay is an integral part of the system and too often is not considered in analysis of the delta. The Sacramento and San Joaquin rivers and their tributaries include all of the watersheds that drain to and from the great Central Valley of California's interior. The respective deltas of these rivers merge into a joint delta at the eastern margins of San Francisco Bay and estuary. The delta proper is a maze of canals and waterways flowing around more than 60 islands that are protected by levees. The islands themselves were historically converted from marshlands as agricultural lands[2] and most of them still are farmed.

Unimpaired inflows of water to the delta originate in the watersheds of the Sacramento and San Joaquin rivers. In an average year those flows are estimated to be 40.3 million acre-feet (MAF) or 48.8 percent of California's average annual total water resource of approximately 82.5 MAF. Of the total unimpaired average inflow, 11.4 MAF are diverted upstream of the delta for agricultural (83.8 percent), urban (15.0 percent), and environmental (1.2 percent) uses. Diversions from the delta average 6.35 MAF, a little more than one-third of all diversions in the Sacramento–San Joaquin system. Diversions from the delta are dominated by the exports to the irrigation service areas of the federal Central Valley Project (CVP) and the State Water Project (SWP), which include southern portions of the San Francisco Bay Area, the western side of the San Joaquin Valley, and much of southern California. Significant amounts of water are diverted to irrigate delta lands, and irrigation return flow is discharged into delta channels. The average yearly outflow from the delta remaining after diversions equals 22.55 MAF (Lund et al. 2010).

The quantities of water reported above are for an average water year, but hardly any water year in California is average. Water supplies are highly variable from one year to another. Thus, for example, in the Merced River, which drains the watershed including most of Yosemite National Park and is a tributary of the San Joaquin River, the average annual flow is 1.0 MAF. Yet the low flow of record for the Merced River is 150,000 acre-feet, only 15 percent of the average flow, whereas the high flow of record is 2.8 MAF, 280 percent of the average flow. The variability in flows, which is characteristic of all of the state's rivers, is largely a function of the interannual variability in amount and patterns of California's Mediterranean climate, which has a wet and a dry season with precipitation falling mainly in the late fall and winter months. In addition, there is considerable variability in the proportion of the precipitation that falls in the mountains as snow, which adds to the variability of the hydrologic regime.

Until recently, planning for water shortage was based on a 5-year dry cycle from the 1930s, or on 1977, the driest year of record. However, recent analyses by the California Department of Water Resources (CDWR 2008, 2011) and Hanak (2012) indicate that changes in precipitation resulting from different anticipated climate conditions (see Chapter 4) will affect water availability for all users. Despite statewide conservation efforts, particularly in the urban sector, increasing seasonal restrictions have been

[2] Recent historical ecology studies at the San Francisco Bay Institute are revealing that the original delta landscape was more complex than formerly thought, and had been modified by humans long before the 19th century (http://sfei.org/node/1088).

applied to diversions, although the total amount of water available for delivery under the terms of SWP and CVP water-supply contracts has not decreased. These projects, which export water to regions of the state that have experienced persistent water scarcity for many decades, are particularly important features of the California waterscape.

The CVP withdraws water from the delta and conveys it southward into the San Joaquin Valley through a system of canals built and operated by the federal Bureau of Reclamation and various municipal and agricultural water-user groups. Most of this water is used for agricultural purposes in the eastern regions of the San Joaquin Valley and the Tulare subbasin at the southern end of the valley. Some is contracted for domestic use. The SWP withdraws water separately from the delta and conveys it southward to agricultural users on the west side and at the very southern end of the San Joaquin Valley and subsequently over the Tehachapi Mountains into the conurbation of the South Coast Basin, including Los Angeles and San Diego. The SWP supplies domestic water users in southern California (and domestic use in the southern San Francisco Bay Area) as well as Central Valley agriculture in proportions that are determined in any given year by the CDWR based primarily on water in surface storage and anticipated runoff. Available supplies, especially seasonally, have been constrained in recent years by court decisions mandating additional seasonal supplies for environmental purposes.

Changes in hydrologic and physical conditions in the delta could constrain and threaten the ability of state and federal water managers to continue exporting water in accustomed quantities through the two major projects. This is a concern since the levees, other infrastructure, and the original geomorphology of the delta are eroding. Lund et al. (2010) identify several factors that today pose significant threats to human uses and ecological attributes of the delta, including (1) subsidence of the agricultural lands on the delta islands; (2) changing inflows of water to the delta, which appear to increase flow variability and may skew flows more in the direction of earlier times in the water year in the future; (3) sea level rise that has been occurring over the last 6,000 years and may accelerate in the future; and (4) earthquakes, which threaten the physical integrity of the entire delta system. There is a long history of efforts to solve these physical problems as well as persistent problems of flood control and water quality (salinity). Salinity intrusion from the waters of San Francisco Bay now requires a specific allocation of delta inflows to repel salinity and maintain high qualities of low-salinity water at the western margin of the delta. This management of salinity is accomplished by monitoring and management of the average position of the contour line of a specified salinity ("X_2").[3] Controlling salinity requires outflow releases from reservoirs that could be used to satisfy other demands.

Resolution of these problems is complicated by water scarcity generally and because alternative solutions impose differing degrees of scarcity on different groups of stakeholders. There are additional allocation problems that arise from a complex system of public and private water rights and contractual obligations to deliver water from the federal CVP and California's SWP. Some of these rights and obligations conflict and in most years there is insufficient water to support all of them. This underscores the inadequacy of delta water supplies to meet demands for various consumptive and instream uses as they continue to grow. Surplus water to support any new use or shortfalls in existing uses are unavailable and any change in the hydrologic, ecological, or physical elements in the delta could reduce supplies further. The risks of change, which could be manifested either by increases in the already substantial intraseasonal and intra-annual variability or through an absolute reduction in available supplies, underscore the existence of water scarcity and illustrate ways in which such scarcity could be intensified.

In its natural state, the delta was a highly variable environment. The volume of water inflows changed dramatically from season to season and from year to year. The species that occupied the delta historically were adapted to variability in flow, quality, and all the various factors they helped to determine. The history of human development of land and water use in the delta is a history of attempts, with varying degrees of success, to constrain this environmental variability, to reduce environmental uncertainty, and to make the delta landscape more suitable for farming and as a source of water supplies. It also included the deliberate and accidental introduction of a large number of species of fishes, invertebrates, and plants into the delta and the surrounding uplands. A full understanding of the historical pervasiveness and persistence of environmental variability underscores the need to use adaptive management[4] in devising future management regimes for the delta (Healey et al. 2008).

The history of water development and conflict in California focuses in

[3] X_2 is the salinity isohaline—the contour line—of salinity 2. Often X_2 is used as shorthand for the mean position of the contour line of salinity 2, measured in kilometers east of the Golden Gate Bridge (across the mouth of San Francisco Bay), but in this report, X_2 refers to the isohaline and not its position.

[4] "Adaptive management is a formal, systematic, and rigorous program of learning from the outcomes of management actions, accommodating change, and thereby improving management" (NRC 2011). Adaptive management and its relevance to the delta are extensively discussed in that report; the summary reprinted in Appendix B of this report provides a brief version of that discussion.

part on the delta. Beginning with the California gold rush in 1848 early settlers sought to hold back the seasonal influx of water and create agricultural lands. The construction of levees played a central role in this effort, an effort that was threatened in the late 1800s and early 1900s by the movement of hundreds of millions of cubic yards of debris from upstream hydraulic mining that passed through the delta. Further work throughout the first third of the 1900s helped to stabilize a thriving delta agriculture (Jackson and Patterson 1977, Kelley 1989). The CVP, begun in the 1930s, and the SWP of the 1960s required conveyance of water from mainstream river channels through the channels and sloughs of the delta to the extraction points located in the southern delta from where water is pumped into the Delta-Mendota Canal (CVP) and the California Aqueduct (SWP) for transport south, as illustrated in Figure 1-2. Once these projects became operational, there was a need to keep the waters of the delta fresh, and salinity control became a problem that was decided by the courts (Hundley 2001, Lund et al. 2010).

In addition to serving economic purposes, delta water has been managed for other purposes. Since the beginning of CVP operations, diversions of water to users outside the delta have been managed to limit salinity intrusion to local domestic water users in the western margins of the delta. Additionally, California's constitution (article 10, § 2) requires that the waters of the state be put to "beneficial use"; this criterion is subject to judicial review and determination. The enactment of both state and federal environmental laws, including the California Environmental Quality Act and the National Environmental Policy Act (NEPA), have led to greater allocation of natural and stored water to environmental (instream) uses. The importance of environmental uses of water has been reflected further in many state regulatory decisions and, more recently, in judicial interpretations of the federal Endangered Species Act and the California Endangered Species Act. Several taxa of delta fishes that live in or migrate through the delta have been listed as threatened and endangered. The courts became involved and specific water allocations followed from court findings. The maze of federal and state laws as well as dozens of stakeholder groups have combined to create a gridlock that sometimes appears penetrable only by state and federal courts (Lund et al. 2010). As a result, most recent reallocation of water has tended to be based on legislative requirements mandating the protection of individual species rather than the optimization of water allocation among all purposes. The legal backdrop is explored further, below.

There have been several efforts to resolve differences, find areas of agreement, and identify solutions to the problems of the delta and the allocation of the waters that flow through it. These efforts assumed particular urgency as California was beset by severe droughts in the period 1987-1992 and another late in the first decade of 2000. A collaboration of 25

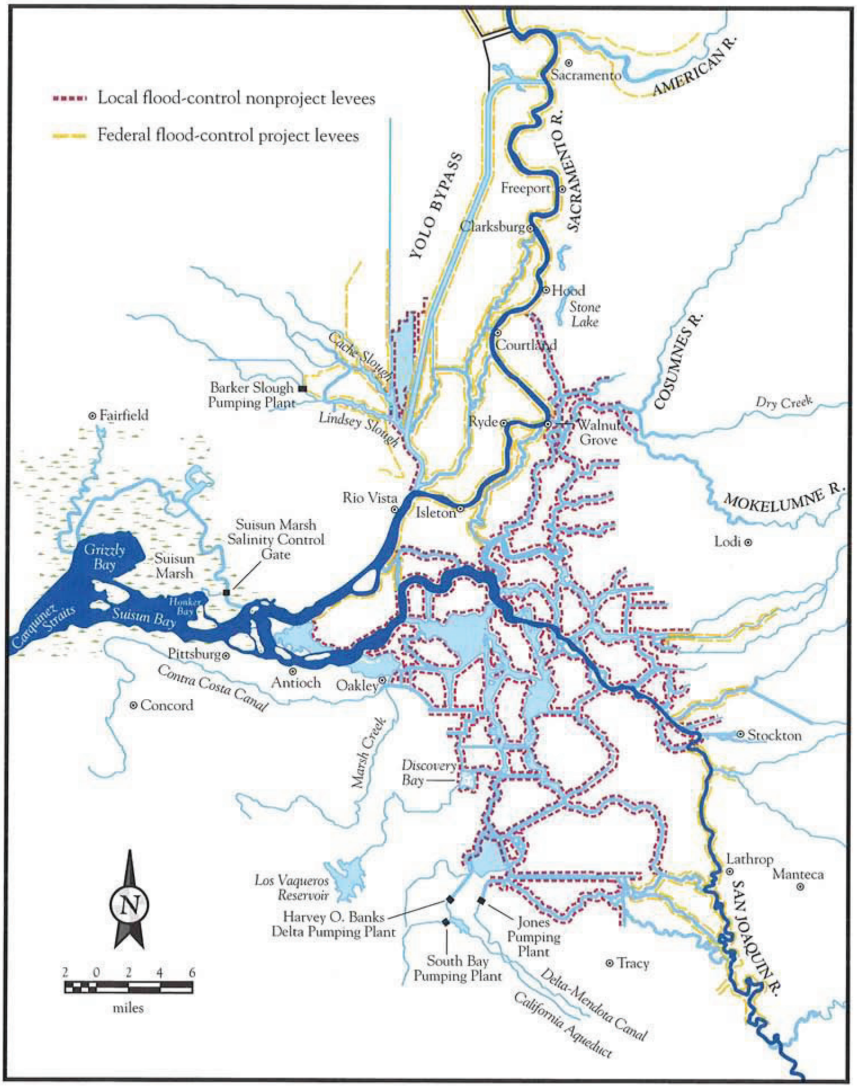

FIGURE 1-2 Delta levees, 2006. There are approximately 1,100 miles of levees in the delta.
SOURCE: Lund et al. (2010).

state and federal agencies called the CALFED program was established in 1994; it was unusual in that it had no federal or state legislative mandate (Booher and Innes 2010). It had the mission "to improve California's water supply and ecological health of the San Francisco Bay/Sacramento-San Joaquin Delta."[5] State and federal agencies quickly developed a science-based approach to water-quality standards titled *Principles for Agreement on Bay-Delta Standards between the State of California and the Federal Government*, otherwise known as the Bay Delta Accord. State and federal agencies with responsibilities in the delta and stakeholders engaged in a decade-long CALFED process, which resulted in the conclusion that the strategy of relying on the delta to convey crucial elements of the water supply to California would continue. CALFED would also be used to attain the four main goals of water-supply reliability, water quality, ecosystem restoration, and enhancing the reliability of the levees (CALFED 2000). CALFED's functions were taken over by the Delta Stewardship Council under California's Delta Reform Act of 2009, as described below. Booher and Innes (2010) provide more detail about the formation, functioning, and evolution of CALFED into the current organizational structure.

The Sacramento-San Joaquin Delta Reform Act of 2009 ("Delta Reform Act") designated the Delta Stewardship Council as "successor" to the California Bay-Delta Authority (the agency that coordinated CALFED) and provided that the Stewardship Council should take over from the Bay-Delta Authority all of its "administrative rights, abilities, obligations, and duties" (California Water Code § 85034(b)). The Delta Reform Act also specified that the newly created Delta Science Program "shall function as a replacement for, and successor to, the CALFED Science Program" and that the newly created Delta Independent Science Board "shall replace the CALFED Independent Science Board" (California Water Code § 85280(c)).

The Bay-Delta Accord of 1994[6] and the CALFED process began to unravel around 2003 as environmentalists and water users came to believe that their interests were not being well served and legislators were not satisfied by the CALFED process (Booher and Innes 2010, Lund et al. 2010, Owen 2011). There followed an attempt by the governor to develop a Delta Vision Strategic Plan or "Delta Vision" with the aid of an independent Blue Ribbon Task Force. The Delta Stewardship Plan ("Delta Plan") resulted from this effort. The Delta Plan is a broad umbrella plan mandated by the California Delta Reform Act of 2009 (California Water Code § 85300) to advance the "co-equal goals" of providing a more reliable water supply for

[5] See http://calwater.ca.gov/calfed/about/index.html.

[6] Principles for Agreement on Bay-Delta Standards between the State of California and the Federal Government 1 (Dec. 15, 1994), available at http://www.calwater.ca.gov/content/Documents/library/SFBayDeltaAgreement.pdf.

California and "protecting, restoring and enhancing the Delta ecosystem" (California Water Code §§ 85020, 85054). The act requires the Delta Stewardship Council to "develop, adopt, and commence implementation" of the plan by January 1, 2012, and specifies that the membership of Delta Stewardship Council must reflect broad California water interests. Also beginning in mid-decade, federal, state, and local water agencies, state and federal fishery management agencies, environmental organizations, and other parties began work on the Bay Delta Conservation Plan (BDCP), an early draft of which was the subject of a recent National Research Council report (NRC 2011).

Developing the BDCP has been a large and expensive endeavor (NRC 2011). The BDCP is technically a habitat conservation plan under the federal ESA and similarly is a natural community conservation plan under California's Natural Community Conservation Planning Act. "It is intended to obtain long-term authorizations under both the state and federal endangered species statutes for proposed new water operations—primarily an 'isolated conveyance structure,' probably a tunnel, to take water from the northern part of the delta to the southern thus reducing the need to convey water through the delta and out of its southern end" (NRC 2011). The initial public (November 2010) draft of the BDCP was reviewed by the NRC (2011)[7]; the summary of that report is reprinted in Appendix B.

WATER RIGHTS IN CALIFORNIA

All of the above activities have taken and continue to take place in a complex legal environment. Below is a description of the legal backdrop surrounding California water.

Surface Rights

California water law is a unique and complicated system that recognizes both riparian water rights (the system that predominates in the wetter eastern states) and the prior appropriation doctrine (the system that predominates in the arid western states) (Cal. Constitution, article 10, § 2). From time to time, the state legislature has tried to diminish the importance of riparian rights to simplify the legal system but has met with obstacles in the nature of constitutional property rights protections (see *in re Waters of Long Valley Creek Stream System*, 599 P.2d 656 [Cal. 1979]).

If there is not enough water to satisfy both riparian and appropriative rights, riparian rights must be satisfied first (*Tulare District v. Lindsay-*

[7] The NRC's review focused on the use of science and adaptive management in the draft BDCP.

Strathmore District, 45 P.2d 972 [Cal. 1935]). However, in some cases, unexercised riparian rights may not enjoy this superior priority (*in re Waters of Long Valley Creek Stream System*, 599 P.2d 656 [Cal. 1979]). If surplus water remains, appropriative rights can be satisfied in order of priority.

Riparian Rights

Riparian landowners—those who own property that abuts a natural watercourse—are entitled to make reasonable use of the adjacent water. Riparian uses can be initiated at any time and they are generally not lost through nonuse (some older rights may have been lost under the doctrine of prescription, a type of "squatter's right"). However, several important limitations apply to riparian rights:

1. *Reasonable use:* The type of use must be "reasonable." The amount of use must also be "reasonable" in light of the purpose to be accomplished and in comparison to the needs of other riparian land owners sharing the same water source.
2. *Storage:* The riparian right allows for the diversion of water, but generally not for its storage for later use.
3. *Place of use:* Generally, water must be used on the tract of land adjacent to the water source.
4. *Shortage:* In times of shortage, all riparians must share the loss through pro rata reductions (percentage cutbacks often correlate with the percentage of land owned along the common watercourse). The state constitution restricts all water rights to uses that are reasonable and beneficial (Cal. Constitution, article 10, § 2).

Riparian rights are imprecise. Not only must they be cut back in times of shortage, but the determinations of "reasonableness" are made by courts on a case-by-case, after-the-fact basis when conflicts arise. Thus, it is difficult to know in advance the precise scope of a riparian water right.

Appropriative Water Rights

Water rights may be acquired independently of riparian land ownership under the doctrine of prior appropriation. The primary requirement is that the water be placed to "beneficial" use through a "reasonable" means of diversion. Appropriative rights differ from riparian rights in several important respects:

1. *Permit process:* Before using water, one must acquire a permit (authorizing the development of a water diversion or project) or a

license (confirming the water right) from the State Water Resources Control Board ("State Water Board"). Early appropriations known as "pre-1914" rights are exempt from the permit scheme.

2. *Storage:* Appropriative rights may be stored for later use.
3. *Place of use:* Water may be used on land apart from the place of diversion, and even transported to other watersheds.
4. *Shortage:* Water rights are administered according to the maxim "first in time, first in right." In times of shortage, the most senior priority is satisfied before the next most senior user receives any water. This gives rise to the phenomenon of "paper water rights," under which junior water users may have state-issued water rights that do not yield "wet water" except in years of exceptional precipitation.
5. *Nonuse:* Because beneficial *use* is the basis and measure of appropriative rights, they can be lost through nonuse (Cal. Water Code § 1241). At times, this might create a perverse incentive for users to waste water in order to maintain a historic record of diversion not subject to loss through nonuse. To counteract this tendency, 1977 legislation recognizes water conservation as the equivalent to a reasonable beneficial use (Cal. Water Code § 1011(a)).

The priority system provides a measure of predictability lacking under riparian rights. For example, agricultural water users with relatively senior priorities may plant higher priced, permanent crops such as grapes and fruit trees, whereas more junior users might not feel comfortable making an investment in such permanent crops. Despite this relative predictability, appropriative rights can be modified by the State Water Board, which has continuing jurisdiction to modify water permits with conditions to protect other water users and the environment. This authority derives, in part, from California's rigorous interpretation of the ancient public trust doctrine, under which the state has a duty to supervise flowing waters, tidelands, and lakeshores to protect the public interest in resource preservation, fishing, navigation, and commerce (*National Audubon Society v. Superior Court of Alpine County*, 658 P.2d 709 (Cal.), *cert. denied,* 464 U.S. 977 (1983); State Water Resources Control Board Cases, 136 Cal. App. 4th 674 (2006)).

Groundwater Rights

There is no comprehensive permit system for the regulation of groundwater in California, although the State Water Board has some (largely untested) authority to restrict "unreasonable use"; local groundwater districts do engage in planning; and the courts can adjudicate groundwater rights (Nelson 2011). Overlying landowners can freely withdraw the percolating groundwater (that is, groundwater that does not flow as an underground stream) beneath their property for reasonable and beneficial use. This right, similar to the surface doctrine of riparianism, is subject to the "correlative" right of other overlying landowners withdrawing from the same source.

Water Rights for the Environment

California recognizes "recreation" and "preservation and enhancement of fish and wildlife resources" as beneficial uses (Cal. Water Code § 1243). New water rights may not be appropriated for the purpose of "instream flows," as recognized in many western states, because the use of water *within a stream* runs afoul of the traditional requirement of *diverting* water from the streambed. However, since 1991 state law has allowed existing appropriations (originally including a quantified diversion) to be changed to instream flow purposes. As provided by Water Code § 1707(a)(1), "Any person entitled to the use of water, whether based on an appropriative, riparian, or other right, may petition the board . . . for a change of purposes of preserving or enhancing wetlands habitat, fish and wildlife resources, or recreation in, or on, the water." This provision has been used in several cases, including applications in the Sacramento River basin. California has no comprehensive, statewide instream flow program to supplement these privately held instream flow water rights.

WATER RIGHTS AFFECTING THE BAY-DELTA

Water Contracts

The federal Bureau of Reclamation (operator of the CVP) and the State Department of Water Resources (DWR; operator of the SWP) hold appropriative water rights. Like any appropriative rights, they are subject to a variety of permit conditions and other limitations to protect the environment and other water users. These water rights have relatively recent (junior) priorities, generally dating back no earlier than the 1920s. As a result, in drought years, the priority system may limit the water diversions to which the Bureau and the DWR are entitled.

Water contracts add an additional layer of complexity to California's water rights system. By contract, the Bureau and the DWR have agreed to deliver prescribed quantities of their appropriative water rights to numerous water user groups. Whereas most CVP water goes to agricultural users, urban users are the primary recipients of SWP water. The contracts are not uniform, and some have been amended over time. Many, but not all, contain provisions designed to relieve the Bureau and the DWR of their contractual obligations when the agencies' water rights are not fully satisfied due to drought, permit conditions, environmental regulations, or other factors. A typical provision (often found in para. 18(f) of the DWR's contracts) might provide that neither the state nor its agents may be held liable for "any damage, direct or indirect, arising from shortages in the amount of water to be made available for delivery . . . under this contract caused by drought, operation of area of origin statutes, or any other cause beyond its control" (e.g., *Tulare Lake Basin Water Storage District v. United States*, 49 Fed. Cl. 313 (2001)).

As a result of these factors, there has been uncertainty and dispute over the precise entitlements of those who hold contracts for the delivery of water. The DWR publishes annually a document known as "Table A" that tabulates actual SWP water deliveries as a percentage of 4.133 MAF per year—the maximum amount allocated under SWP contracts (corresponding to the volume of water rights held by the DWR itself for use in the SWP). In its January 2010 draft report, for example, the DWR lists 2009 average annual deliveries as 60 percent of the maximum contract amount. The DWR notes "very significant reductions" in deliveries since 2005. The reductions are attributable, in part, to severe drought, as well as in part to restrictions imposed on the state and federal agencies based on salmon and smelt biological opinions (California Department of Water Resources, Bay-Delta Office, *Draft State Water Project Delivery Reliability Report, 2009*, January 26, 2010).

Some claim that the maximum amount allocated by contract is not the appropriate baseline because it treats limitations inherent in the California water rights system as extraneous interferences with water rights. Rather, limitations such as the curtailing of junior water rights, water permit conditions, and the public trust doctrine define the contours of the water right. The California Water Impact Network, for example, asserts that "The [SWP] project has never in its history delivered [the full contract amount], and has delivered no more than about 2.6 million acre-feet in its peak year" (California Water Impact Network, *California Water Rights Primer: The Monterey Amendments to State Water Project Contracts*).

The Environment

The Bay-Delta Plan of 2006 and State Water Board Decision 1641 specify bay-delta flow requirements. In 2009, California passed a comprehensive package of legislative reforms known as the Sacramento-San Joaquin Delta Reform Act of 2009. Among other things, the new legislation required the SWB to develop new flow criteria to protect public trust resources of the delta ecosystem (Water Code § 85086). On August 3, 2010, the State Water Board issued its final report, *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem*. The report concluded "[t]he best available science suggests that current flows are insufficient to protect public trust resources" and "[r]estoring environmental variability in the Delta is fundamentally inconsistent with continuing to move large volumes of water through the Delta for export." The recommended flow criteria include "75 percent of unimpaired Delta outflow from January through June; 75 percent of unimpaired Sacramento River inflow from November through June; and 60 percent of unimpaired San Joaquin River inflow from February through June."

The Water Board noted that its recommendations lack binding legal effect unless and until they are implemented through an adjudicative or regulatory proceeding. The recommendations were intended, in part, to inform the development of the BDCP.

ENVIRONMENTAL CONSIDERATIONS

In addition to water rights, including for the environment, actions in the delta are affected by federal and state environmental statutes. The federal ESA of 1973 and 1988 amendments (16 U.S.C. §§ 1532-1544) has had a far-reaching effect through its application to pumping operations as a result of lawsuits as described above. The act prohibits the taking of species listed as endangered, and, by regulation, threatened species are protected as well. It requires federal agencies to make sure their actions, or actions they authorize or fund, are not likely to jeopardize the continued existence of listed species or adversely modify their critical habitats. The agencies do this by consulting with the U.S. Fish and Wildlife Service or the National Marine Fisheries Service (NMFS) if they consider the proposed action might imperil listed species, or sometimes if a court requires them to do so as the result of a lawsuit. The requirements and processes of the ESA have been described in detail by the NRC elsewhere (e.g., NRC 1995, 2010, 2011).

Other environmental statutes that have relevance to the delta include the federal Clean Water Act and NEPA and the state Natural Communities Conservation Planning Act, the California Endangered Species Act, and many provisions of the California Water Code.

THE CURRENT STUDY

Given the complex backdrop surrounding the California bay delta and the importance of this water source to human and ecosystem needs, Congress and the Departments of the Interior and Commerce asked the NRC to review the scientific basis of actions that have been taken and that could be taken for California to achieve simultaneously both an environmentally sustainable bay-delta ecosystem and a reliable water supply. In order to balance the need to inform near-term decisions with the need for an integrated view of water and environmental management challenges over the longer term, the NRC addressed this task over a term of 2 years, resulting in three reports.

First, this[8] committee issued a report focusing on scientific questions, assumptions, and conclusions underlying water-management alternatives in the U.S. Fish and Wildlife Service's (FWS) Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project (December 15, 2008) and the NMFS's Biological Opinion on the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan (June 4, 2009). This review, *A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta*,[9] considered the following questions:

- Are there any "reasonable and prudent alternatives" (RPAs), including but not limited to alternatives considered but not adopted by FWS (e.g., potential entrainment index and the delta smelt behavioral model) and NMFS (e.g., bubble-curtain technology and engineering solutions to reduce diversion of emigrating juvenile salmonids to the interior and southern delta instead of toward the sea), that, based on the best available scientific data and analysis, (1) would have lesser impacts to other water uses as compared to those adopted in the biological opinions, and (2) would provide equal or greater protection for the relevant fish species and their designated critical habitat given the uncertainties involved?
- Are there provisions in the FWS and NMFS biological opinions to resolve potential incompatibilities between the opinions with regard to actions that would benefit one listed species while causing negative impacts on another, including, but not limited to, prescriptions that (1) provide spring flows in the delta in dry years primarily to meet water quality and outflow objectives pursuant to Water Board Decision-1641 and conserve upstream storage for summertime cold water pool management for anadromous fish species; and (2) provide fall flows during wet years in the delta to benefit delta smelt, while also conserving carryover storage to benefit next year's winter-run cohort of salmon in the event that the next year is dry?
- To the extent that time permits, the committee would consider the effects of other stressors (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the bay delta. Details of this task are the first item discussed as part of the

[8] There were some changes in committee composition after the publication of the first report.
[9] Available through The National Academies Press: http://www.nap.edu/.

committee's second report, below, and to the degree that they cannot be addressed in the first report they will be addressed in the second.

Second, a separate but related NRC panel issued a short report that reviews the initial public draft of BDCP in terms of the adequacy of its use of science and adaptive management—*A Review of the Use of Science and Adaptive Management in California's Draft Bay Delta Conservation Plan.*[10]

The current report addresses how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the bay delta. This advice, to the extent possible, should be coordinated in a way that best informs the BDCP development process. The present report includes discussion of topics raised in both of the earlier reports but it is not a recap or reissue of either of them.

This report addresses tasks such as the following (from the committee's statement of task, see Appendix C):

- Identify the factors that may be contributing to the decline of federally listed species, and as appropriate, other significant at-risk species in the delta. To the extent practicable, rank the factors contributing to the decline of salmon, steelhead, delta smelt, and green sturgeon in order of their likely impact on the survival and recovery of the species, for the purpose of informing future conservation actions. This task would specifically seek to identify the effects of stressors other than those considered in the biological opinions and their RPAs (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the delta, and their effects on baseline conditions. The committee would consider the extent to which addressing stressors other than water exports might result in lesser restrictions on water supply. The committee's review should include existing scientific information, such as that in the NMFS Southwest Fisheries Science Center's paper on decline of Central Valley fall-run Chinook salmon, and products developed through the Pelagic Organism Decline studies (including the National Center for Ecological Analysis and Synthesis reviews and analyses that are presently under way).
- Identify future water-supply and delivery options that reflect proper consideration of climate change and compatibility with objectives of maintaining a sustainable bay-delta ecosystem. To the extent that water flows through the delta system contribute to ecosystem structure and functioning, explore flow options that would contribute to sustaining and restoring desired, attainable ecosystem attributes,

[10] Available through The National Academies Press: http://www.nap.edu/.

while providing for urban, industrial, and agricultural uses of tributary, mainstem, and delta waters, including for drinking water.

- Identify gaps in available scientific information and uncertainties that constrain an ability to identify the factors described above. This part of the activity should take into account the Draft Central Valley Salmon and Steelhead recovery plans (NOAA 2009), particularly the scientific basis for identification of threats to the species, proposed recovery standards, and the actions identified to achieve recovery.
- Advise, based on scientific information and experience elsewhere, what degree of restoration of the delta system is likely to be attainable, given adequate resources. Identify metrics that can be used by resource managers to measure progress toward restoration goals.

The statement of task focuses primarily on science, and does not ask for policy, political, or legal advice. The report organization does not follow the statement of task because the committee concluded the current organization provides a more logical flow. The factors affecting the listed species are discussed in detail in Chapter 3. Future water-supply and water-delivery options are discussed in Chapters 2, 4, and 5. Scientific uncertainties are discussed throughout the text in Chapters 3 and 4, and the degree of restoration likely to be attainable is in Chapter 4.

The membership of the committee that produced this report overlaps considerably with that of the committee that produced the review of the BDCP, but it is not identical. The committee met three times after the BDCP review was produced; once in Sacramento, California, once in Washington, DC, and once in Seattle, Washington. At its Sacramento meeting the committee included a public session during which it heard from a variety of speakers (Appendix D). The committee was able to review information received by September 2011. The report has been reviewed in accordance with NRC procedures: the reviewers are listed in the acknowledgments.

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2

Scarcity: The Challenges of Water and Environmental Management in the Delta and Beyond

INTRODUCTION

Ecological rehabilitation in the delta faces many challenges, reflected in the long and difficult history surrounding the delta and ongoing political and legal controversies. The challenges include the reluctance of many interested parties to confront several crucial facts. These include the reality that water is scarce; the many biological and physical changes that have occurred in the delta; the presence of many policy and legal directives that have independent and conflicting objectives; and the inherent uncertainty regarding future socioeconomic, climate, biological, and other changes, and our consequent inability to plan for them in a comprehensive manner. In this chapter, we discuss these challenges, but because the historical context is critical to understanding the challenges, we begin with it.

THE HISTORICAL SETTING

The modern history of California has been characterized by steady and occasionally explosive population growth. During the 20th century the state's population grew more than 20-fold, from 1.5 million in 1900 to almost 34 million in 2000. There were two periods of astonishingly rapid growth. Between 1900 and 1930 population grew by 382 percent and between 1940 and 1970 it grew by 289 percent (U.S. Bureau of the Census 1996). Almost all of this growth occurred in the southern three-quarters of the state, most of which is arid or semiarid and has a Mediterranean climate with a wet season between November and April followed by a dry season from May through October. The climate is unfavorable to development in the sense that water demands for irrigated agriculture, air conditioning, outdoor domestic uses, and recreational purposes tend to peak in the warm dry season. However, precipitation throughout California is generally unreliable, and California is subject to persistent and sometimes severe droughts, even in the seasons when precipitation is expected.

The combination of rapid population growth and general aridity led to a 20th-century water resources development program punctuated by the construction of major water storage and conveyance projects. The Los Angeles and San Francisco metropolitan areas, the foci of urban settlement, outstripped local water supplies early on and began to import supplemental supplies from remote locations. Most famously, the City of Los Angeles acquired land and water resources in the Owens Valley on the eastern side of the Sierra Nevada and constructed conveyance facilities to bring the water to the Los Angeles basin (Kahrl 1983). At about the same time, San Francisco developed a storage and conveyance project to the east in the Tuolumne River basin, which drains a portion of the west side of the Sierra Nevada. There followed, in 1929, further development of the Mokelumne River basin, also a western Sierra drainage, to supply the growing demands of the East San Francisco Bay region and, in 1939, the Colorado River Aqueduct to bring water from the Colorado River to support growth throughout the South Coast basin of southern California (Hundley 2001).

During the 20th century, California also became the largest agricultural state in the nation. Although there had been extensive rain-fed ("dryland") farming in the late 1800s, it thrived only during an exceptionally wet period, and most subsequent agriculture was irrigated. Early irrigation communities relied on water from neighboring streams and groundwater. Dating back at least as early as 1855, California recognized the "prior appropriation doctrine" for the allocation of surface-water rights. This system, which follows the maxim "first in time, first in right," allows the first water users (known as "senior" appropriators) on a stream system to divert their entire allotment before the chronologically next water user is entitled to divert a single drop. Because water rights are of theoretically infinite duration, many senior irrigators in California could argue that they hold more secure water rights than later-initiated uses, such as the application of water for the protection of the natural environment. Recent court decisions, combined with the state constitution, the developing public trust doctrine, and legislation have combined to create in practice a more rational method of allocation. The construction of large storage and conveyance projects, which began with the federal Central Valley Project (CVP) in the 1930s and 1940s, allowed the expansion of agriculture in both the Sacramento and San Joaquin valleys and offset, to some degree, the significant groundwater overdraft that was present in the San Joaquin valley. Subsequently, in the 1960s and 1970s, the state of California built its own State Water Project (SWP), which served agricultural users in the San Joaquin valley and urban users in both the San Francisco Bay Area and the South Coast basin (Hundley 2001). Both the CVP and the SWP use the Sacramento–San Joaquin Delta to move water from the Sacramento River and other waterways draining into the delta to the pumps at the southern end of the delta for conveyance to users located to the south. Figure 2-1 is a water-balance table for California.

All of these water projects were constructed in response to increasing concerns about the local or regional scarcity of water supplies to support the large population and economic growth and in anticipation of more such growth. An important consequence of the pattern of increased demands followed by new water storage and conveyance projects was that it created the assumption that with investment more water could be made available to support such growth. This assumption continues to be true except that for a variety of reasons the cost of additional supplies has risen dramatically.

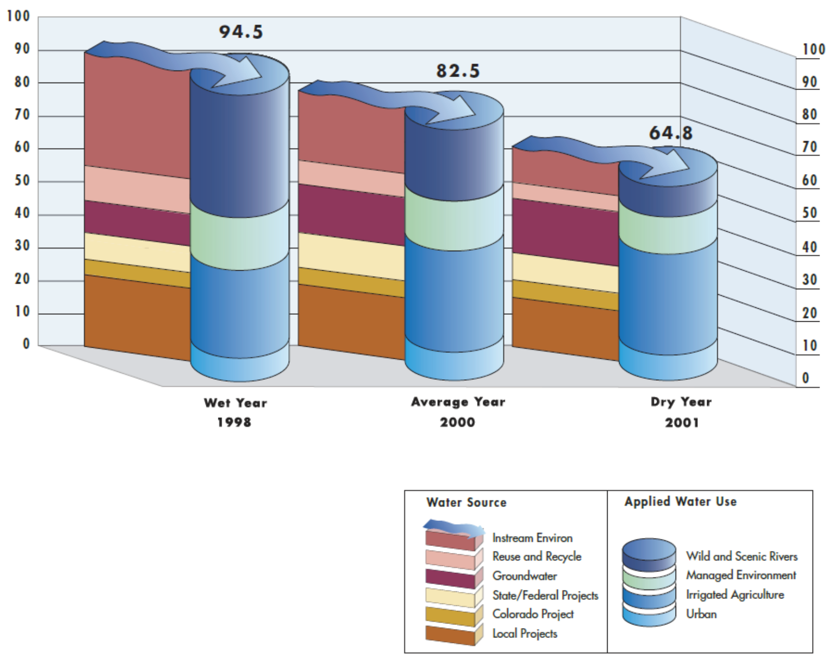

FIGURE 2-1 California water balance.
SOURCE: California Department of Water Resources (2005).

Increasing commitment to water conservation, including more efficient and more productive use,[1] and economic changes, particularly in the urban sector, have resulted in reductions of per capita water use. Improvements in agricultural efficiency have occurred to some degree but more is expected. In recent decades, new increments of water supply, exclusive of what has been conserved, have become more costly and the reliability of sources has decreased for all uses. In California and the arid southwest, urban wastewater reuse for golf course and public landscape irrigation has become common. Agricultural reuse that entails recycling of surface runoff from irrigation is also found with increasing frequency. There has been little recognition in recent and current planning for the delta that water is a scarce resource and that modern management plans should be tailored to manage scarcity (NRC 2011).

The historic strategy of developing storage and conveyance facilities in response to growth in water demand is being replaced with a variety of supply- and demand-management alternatives, including conservation. Competition for water for all purposes, including recreation, fishery resources, protecting water quality, and ecological functioning, will remain intense. Fewer high-yielding source areas and storage sites are available now than formerly, because most such areas and sites have already been developed. Nonetheless, they should be considered during objective comparison of alternatives for improving streamflow and meeting water-supply needs. This would include consideration of environmental effects.

Water impoundment and transfer facilities can result in significant environmental damage, by altering streamflow regimes (Junk et al. 1989, Poff et al. 1997), blocking the migration paths of anadromous fish and altering their life cycles (Andersson et al. 2000, Dudgeon 2000, Jansson et al. 2000, Morita et al. 2000), damaging downstream habitats (Kondolf 1997), and modifying water temperatures and impairing water quality (Clarkson and Childs 2000, Walks et al. 2000). These environmental costs, although usually not monetized, are real costs that must be counted together with the other costs of construction for a full accounting.

Storage facilities in the Sacramento–San Joaquin system were designed based on precipitation and streamflow data of the historical period of record (since the late 1800s). The assumption that past climate is a reasonable approximation of the future is no longer valid (NRC 2007, Milly et al. 2008). Sound planning now requires consideration of a much wider range of assumptions regarding rainfall and runoff. Most projections suggest that there will be an increase in the frequency and intensity of droughts

[1] In general, the committee uses the term "conservation" as shorthand for "conservation and more productive and more efficient water use." See Gleick et al. (2003, 2011) for a discussion of these terms.

and floods. Testing previous assumptions, developing new ones, and testing them against various alternative management scenarios is necessary to provide an informed basis for future public investments and will be an essential part of future water resources and environmental planning. The results of such analyses might be that water supplies will be reduced, and the magnitude of scarcity increased.

A more uncertain and variable water future will require water planning and management for the delta that is anticipatory as well as adaptive. It will require plans and operations that include suites of techniques and technologies designed to manage a highly variable and uncertain waterscape. Most important, the future will require planning and management that specifically acknowledge and take into account that *there is not enough water to meet all desired uses in California with the required degree of reliability everywhere and all the time*.

DIMENSIONS OF SCARCITY

The standard economic definition of scarcity is an insufficient quantity of some resource or commodity to satisfy all wants for it (Baumol and Blinder 2011), and it is used by the committee here. These wants include water for urban, agricultural, and industrial water use and for the aquatic environment. They can change as we gain better understanding of natural processes, multiple stressors, and changes in climate, and in response to changes in public priorities regarding environmental investments, changes in technology, and changing economic, regulatory, and legal conditions. Water scarcity has long existed in much of California, save, perhaps, for exceptionally wet years. The magnitude or intensity of scarcity has grown over time and it continues to grow. Symptoms of this scarcity include legal rulings that require increased allocation of water to support fisheries and environmental flows, demands for more reliability of water supplies from agricultural and domestic diverters, and concerns about the ecological condition of the delta itself and differing positions about how delta waters should be allocated.

While some Californians have increasingly recognized the scarcity of water, not everyone has. The failure of plans for water management in the delta to acknowledge scarcity has greatly hindered the ability of agencies to craft and implement water plans and policies that will be widely accepted. The management of delta water by court decisions reflects in part the lack of adequate water resource planning that takes scarcity into account.

Historically, scarcity has been acknowledged mainly during times of drought. The primary means of coping with scarcity has been the rationing of supplies, and through penalties as well as short- and long-term increasing block rates—rates that increase as use increases. A drought water bank was established and functioned effectively in the later stages of the drought of 1987-1992. It had the advantage of allocating water from lower- to higher-valued uses. It served to mitigate potentially disastrous impacts and also allowed the state to develop carryover supplies to help mitigate the effects of a continuation of the drought (Carter et al. 1994). These measures were short-term, one-time efforts to manage supplies that were temporarily short. Thus, beyond the occasional drought, the concept of long-term scarcity has not figured prominently in delta water plans, or water-management regimes, or the state's approach to water transfers.

Evidence for the existence of water scarcity in California can also be found through an examination of the extent to which the waters of California have already been legally allocated by California water law. Under Water Code §§ 1205-1207 (2012), the State Water Resources Control Board has designated numerous stream systems "fully appropriated" year-round or during specific months including many stream segments in the bay-delta region. This means that the state has approved a total volume of water rights that equals (or even exceeds) the surface supplies available in an average year, although there is no mathematically precise calculation for this allocation. The California Water Code simply required the State Water Resources Control Board to determine that the "supply of water in the stream system is being fully applied to beneficial uses" and that "no water remains available for appropriation."

Under limited circumstances the board may continue to grant water rights, even if the source is fully appropriated. Indeed, some degree of overappropriation is common in the western states. In the case of agricultural projects, for example, the Water Board's historic practices called for approving new water rights as long as water was available in at least some of the years (in low-water years appropriative water rights in California are satisfied on a first-come first-served basis in order of application priority until the supply runs out). This practice, together with other current and historic factors, has caused some stream systems to be overappropriated, at least in dry years. In such cases, according to the State Water Resources Control Board, the face value of *legal* water rights exceeds the volume of water *hydrologically* available for use. According to the Water Board's 2008 estimate for the Central Valley Watershed, for example, appropriative water rights in the watershed have a face value of 245 million acre-feet, as compared to an average annual runoff of 29 million acre-feet. In other words, in some basins, the Water Board has overallocated available supply by more than 800 percent (measuring supply as average annual runoff) (SWRCB 2008). In evaluating the significance of overappropriation, sequential return flows and reuse of both agricultural and urban right holders' waters must be considered. Overappropriation is mitigated by reusing water as it flows downstream from the source toward the ocean (agricultural runoff is added to the downstream users' supply), and water is increasingly intentionally reused (double use) for agricultural and urban purposes. Although the specific amounts needed and diverted for agricultural use are not generally accurately measured, they probably should be in the future.

These calculations consider only human water users and do not incorporate estimates of the volume of water necessary to sustain the natural environment (which itself raises difficult questions concerning the meaning of "to sustain" and "natural environment"). If environmental needs are added to the sum of other allocations, then the volume of water necessary to fully satisfy all water rights and environmental needs would exceed supply by an even greater multiplier. In 2009, the Sacramento-San Joaquin Delta Reform Act required the State Water Board to develop new "flow criteria" to protect public trust resources of the delta ecosystem (Cal. Water Code § 85086). On August 3, 2010, the State Water Board issued its final report, *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem*. The report concluded "the best available science suggests that current flows are insufficient to protect public trust resources" and "[r]estoring environmental variability in the Delta is fundamentally inconsistent with continuing to move large volumes of water through the Delta for export."

The Water Board noted that its recommendations lack binding legal effect unless they are implemented through adjudicative or regulatory proceedings. The recommendations were intended, in part, to inform the development of the Bay Delta Conservation Plan (BDCP) (see Chapter 1).

The presence of intensifying scarcity of delta water means that the planning for and the management of the delta's water resources in the future must differ from the planning and management of the past. The changes required respond not only to scarcity but also to the fact that many of the extensive human-caused changes to the delta's physical and aquatic environment are essentially irreversible. Such irreversibility must also be accommodated in future water planning and management regimes. The improvement of the bay-delta ecosystem must recognize the limits imposed by and variations represented in historical, current, and likely future conditions. But at the same time, the maintenance of current channel configurations and island uses should be reconsidered if planning is to be comprehensive.

It should be widely understood that recovering ecosystems to historical conditions is highly problematic because baselines have shifted in response to significant changes in the larger landscape itself, in climate, and in ecological conditions. Indeed, restoration of ecosystems to a historical baseline is no longer possible in many areas—almost certainly including the delta—and is constrained in most areas by human pressures on the environment (NRC 1996). Given the dramatic declines in salmon and smelt populations, the fundamental shifts that have already occurred in the delta ecosystem, current policies and societal values, and the projected changes for the system, including rising sea level, levee failure, and changes in the timing and volumes of runoff, realistic visions for the future of the delta will not directly match or may not even closely resemble any specified historical baselines (Nichols et al. 1986, NRC 1996).

California's "Two Co-equal Goals"

Contemporary planning for water management in the bay-delta region is directed at two co-equal goals: providing a more reliable water supply for California and protecting, restoring, and enhancing the delta ecosystem. "The co-equal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the delta as an evolving place" (Cal. Water Code § 85054). There are positive attributes of having established these goals. Any planning exercise needs to have clear goals. Making environmental protection a co-equal goal, instead of its more historical position as an afterthought, has the potential to change the way people plan for and manage water use. Making the goals co-equal from the outset should force planners to consider trade-offs between water supply and environmental protection. Specifying the co-equal goals in legislation is educational because the goals necessarily become part of the public discourse about water.

But despite the positive attributes of specifying the co-equal goals, their potential value cannot be fully realized until some additional conditions are met. For example, in practice, it is not clear what co-equal means. Does it mean that any additional water will be allocated half-and-half to support each goal? Or does co-equal imply some proportional allocation? Or does it mean that water for support of one goal should not be available at the expense of water to support attainment of the other? Yet if the attainment of either or both goals requires more water than is currently available, and additional water is unavailable because of scarcity, then the co-equal goals cannot be attained. Even though California has adopted the policy of *decreasing* reliance on the delta,[2] in practice the evidence suggests that demand for the delta's water has been increasing, and it might well continue to increase. For example, as Isenberg (2011) pointed out, major urban water users are required by the 2009 legislative package to reduce

[2] "The policy of the State of California is to reduce reliance on the Delta in meeting California's future water supply needs through a statewide strategy of investing in improved regional supplies, conservation, and water use efficiency. Each region that depends on water from the Delta watershed shall improve its regional self-reliance for water through investment in water use efficiency, water recycling, advanced water technologies, local and regional water supply projects, and improved regional coordination of local and regional water supply efforts" (Cal. Water Code § 85021).

their water use by 20 percent by the year 2020, while agriculture—which uses three times as much water as all other human users in California—is not required to achieve any specified reduction in water use. In short, the lack of a specific definition of "co-equal" means that the co-equal goals have not been operationalized in a fashion that would permit an objective assessment of how well different water management alternatives for the delta would attain them.

Current planning efforts for the bay-delta region and the studies they are based on do little more than assert that the goals are co-equal. Efforts are needed to address different degrees of goal achievement so that resources committed to achieving each goal can be balanced; otherwise, how can the constitutional requirement of reasonable beneficial use be met? Without such efforts how can the best action alternatives be selected?

A fundamental problem is how to allocate scarce water. By positing the co-equal goals without specifically defining them, the legislature has given planners the opportunity to create the necessary balance. Yet, this has not been the focus of planning so far. It appears to be assumed that additional water will have to be found to serve the co-equal goals. When water is scarce, it is not possible to allocate water to support one without reducing the allocation for the other. Of course additional water can always be found by reallocating water from some other use that is independent of the uses envisioned by the co-equal goals, but in California, that simply moves the problem of scarcity to another locus.

The first public (November 2010) draft of the BDCP reviewed by the National Research Council (NRC 2011) and other planning documents do not adequately—and certainly do not explicitly—address the degree to which allocated water is available to support the co-equal goals. Background documents and the goal in legislation of reducing reliance on delta water implicitly acknowledge water scarcity, but the details need to be addressed, clarified, and made specific, because they are at the heart of the planning process. Only when the goals are made specific and operational will the trade-offs required become apparent, and the trade-offs will require policy judgments about priorities, acceptable risks, and acceptable costs. Such judgments should be informed by science.

Future water planning requires that estimates of water availability based on past hydrologic patterns be augmented with anticipated variability in the location, magnitude, timing, and type (e.g., rain versus snow) of precipitation (see Chapter 4). As scarcity intensifies, alternative scenarios of restoration and reliability should be created to ameliorate environmental damage and rehabilitate habitats. Restoring aquatic habitats to some previous baseline condition will rarely if ever be practical, especially if that condition is far in the past, because of all the changes that have already occurred and the likely cost (Chapter 4). In the face of all of these ecological and environmental constraints, an effective system of planning and management will need to consider a broader array of alternatives and options for managing water than has been characteristic of the past. Perhaps more importantly, all delta and export water users will need to more generally acknowledge that water scarcity is a fact of life.

Water Planning to Manage Scarcity

As the effects of water scarcity become more pronounced, successful water planning and management will require widespread public acceptance of a set of principles to avoid the struggles to achieve consensus among competing interests in the past. In addition, the NRC's review of the first public (November 2010) draft of California's BDCP suggests that improvements are needed in the planning process itself, including specifying responsibilities and improving organization. Possible approaches to developing these improvements are discussed in Chapter 5. In addition, regulatory improvements and principles are needed to ensure more robust, comprehensive, and accountable planning. They include application of constitutional provisions and the public trust doctrine, more comprehensive water conservation, inclusion of groundwater in statewide planning, and formalizing a long-term water-market system.

Among these new principles are the following:

- **Recognize that not all uses of water are always compatible with each other.** It is not always possible, for example, to provide reliable and high-quality water supplies while simultaneously protecting all aquatic species and aquatic ecosystems. The current planning objective that all listed species will be protected, that levees and land use will be maintained, and that the reliability and volume of water supplies will be maintained, all while maintaining flood protection, is not tenable or even realistic in an era of varying and hard-to-predict water scarcity. Therefore, planning efforts that acknowledge these difficulties are more likely to lead to lasting and effective outcomes than those that pretend the difficulties do not exist.
- **Provide better definition of competing uses; acknowledge, specify, and account for trade-offs in planning and decision making.** With competing uses, more water for one use implies less for another. Trade-offs normally require a balancing of uses, but frequently the need to balance, the terms of the trade-offs, and the implications for different uses are obscure. For instance not all delta islands can survive in the future; a variety of circumstances (Chapter 3) may cause smelt numbers to continue to decline; delta drinking water may require more treatment to protect public health, reduce undesir-

able taste and odor, and meet EPA water-quality standards; regulated and future contaminants of concern in upstream municipal waste discharges must be removed; and agricultural drainage may require remanagement. If the trade-offs and alternatives are addressed specifically and transparently, outcomes are likely to be more effective and agreements more long-lasting.

- **Modify practices that do not reflect the scarcity value of water.** They include pricing that is determined only by the costs of capture, storage, transport, and treatment of water, which implies that water is not scarce at all. By assigning to water a scarcity value of zero, many current policies signal consumers that water is available without limit, even while the limits imposed by scarcity are intensifying. As a result, more water is used than would be the case if its price reflected scarcity. Although they do not include an actual scarcity value for water, many California water utilities such as the East Bay Municipal Utility District and the Marin Municipal Water District use increasing block rates (higher prices at higher use rates) in an effort to mimic marginal cost pricing. Careful consideration should be given to proposals to include a scarcity premium in the price of water to signal users that water is not freely available (Zilberman and Schoengold 2005). Such values can be estimated with some accuracy and they can also be determined on a trial-and-error basis if prices are established and imposed administratively (Baumol and Oates 1979). They can be determined as part of contract negotiations or renegotiations, or they can be altered from time to time, as appropriate, by water wholesalers. One method of achieving this is through a continuing state market for transferring supplemental water, which would establish a scarcity premium. This premium could be projected into the future for varying climate conditions. ***The cost of water to users should reflect its scarcity, and allocation should be based on analysis that allows for informed decision making.***

In pricing water it is important to recognize that costs are not always paid in terms of dollars and cents. The concept of opportunity cost (e.g., Stiglitz 1986) is both pertinent and important. Simply, an opportunity cost is the value of the most desirable opportunity forgone as a consequence of a specific allocative decision. A decision to divert water for some consumptive use entails an opportunity cost in terms of the environmental services and amenities forgone by not continuing to allocate water to instream environmental purposes. Historically, such opportunity costs were either low or perceived to be low. However, there is evidence, some of it controversial, that environmental opportunity costs may no longer always be small or negligible (Costanza et al. 1997, Safriel 2011). The growth in the real value (i.e., adjusted for inflation) of water in alternative uses is a symptom of growing scarcity. As the population of California grows and as the state continues to develop economically it seems likely (although not inevitable; Hanak et al. 2011) that water scarcity will continue to grow. This should be reflected in an analysis of alternatives, including improvements in water-use technology, reuse technology, economizing on water use, and various degrees of long-term species protection.

The magnitude and intensity of future scarcity will make allocative decisions harder as the values of all uses grow and as the opportunity costs of uses forgone also grow. This means that decisions to reallocate water away from one use to another will intend to involve higher and higher stakes. Paralysis in the face of these high stakes will enhance the prevailing tendency to lock water into existing uses. The danger in such paralysis will likely be that Californians will be using their water less efficiently and productively—and maybe substantially less—than could be the case if water were reallocated from existing low-valued uses to higher-valued ones. Consequently, it will be important to develop new, innovative institutions to develop the tools that will facilitate the reallocation of water among uses as a response to intensifying scarcity.

Some uses are not monetized in terms of dollars and cents. Environmental goods and services [e.g., the provision by the environment of food, fiber, and shelter for humans; see Constanza et al. (1997) and Daily (1997)] and environmental amenities are examples. These uses tend to be public goods in the sense that the services and amenities cannot be withheld from persons who refuse to pay for them. They have value nevertheless, and because of their public-good nature they complicate the allocation process. They can be protected in several ways, including making administrative allocations of water to service environmental uses, taxing water trades and water consumption, and the use of environmental water accounts. [See Booher and Innes (2010) and Appendix F of this report for discussions of California's Environmental Water Account.] That does not mean it could not be improved. A forward-looking plan for managing environmental scarcity should consider alternative ways to protect environmental services and other water-based public goods.

A number of measures to address scarcity are already available. They are either weakly enforced or not enforced at all in California, although they are incorporated into California water law. Use of these measures is consistent with the principles enunciated above. They are consistent with the proposition that exclusive reliance on supply augmentation measures "encourages a simplistic and sometimes counter productive attitude" that we have to "get more" (Hanak et al. 2010). ***The fact of water scarcity does not means that the state is "running out of water." Although most surface flows have been fully allocated or overallocated, the state can use a num-***

ber of tools that optimize the use of existing supplies. As described below there are several tools currently available for use within existing legal authority. Other tools, which could be combined in a prioritized program to increase net benefits from public and private investments, may require additional legislative authorization.

- **Enforce the constitutional prohibition against nonbeneficial, unreasonable, and wasteful water use.** The California Constitution, article 10, § 2, limits all water rights to "such water as shall be reasonably required for the beneficial use to be served, and such right does not and shall not extend to the waste or unreasonable use or unreasonable method of use or unreasonable method of diversion of water." The ideal way to implement this fundamental tenet is through sound water planning of the type recommended in this report. That will require significant changes in responsibilities, organizations, and commitment to a traditional but not recently applied principal of independent objective planning.

This constitutional provision restricts the *types* of uses allowed to those that are deemed "beneficial," a determination that depends on the facts and circumstance of each case, and that may change over time to reflect societal values. For example, in 1935 some farmers claimed that winter irrigation constituted a beneficial use because it simultaneously benefitted their alfalfa crops and drowned gophers living in their fields. The California Supreme Court rejected the argument because it was "self-evident" that the use of water solely to eradicate pests was not a beneficial use (*Tulare Irrigation District v. Lindsay-Strathmore Irrigation District*, 1935). Today recognized beneficial uses include domestic uses, fire protection, fish and wildlife, industrial uses, irrigation, mining, municipal uses, power production, recreation, and other uses (SWRCB 2010).

The constitutional provision also restricts the *amount* of water that can be applied for a specified beneficial use, such as irrigation. One California court, for example, allowed a lawsuit to go forward claiming that direct diversion of water from the Napa River to protect vineyards from frost was an unreasonable use or unreasonable method of diversion (*State Water Resources Control Board v. Forni*, 1976). More recently (2011), the State Water Resources Control Board restricted use of Russian River water for the purpose of frost protection and ruled that diversion outside their demand management program was an unreasonable use of the water (SWRCB 2011).

Thus, although water rights are a protected form of property in California, the scope of the right does not include nonbeneficial, unreasonable, or wasteful uses of water (Gray 2002). The California Water Code § 275 authorizes the department and board to "take all appropriate proceedings or actions . . . to prevent waste, unreasonable use, unreasonable method of use, or unreasonable method of diversion of water in this state." Under this provision, the constitutional prohibitions can be enforced through several mechanisms. First, before approving an application for water rights, the Water Board must determine that the proposed use will be reasonable and beneficial (*Central Delta Water Agency v. State Water Resources Control Board*, 2004). Moreover, even after water rights have been issued, water users and citizens can challenge existing water uses as unreasonable. Hanak et al. (2010) suggest that the state has a wide range of authority:

> A property right in water wholly depends on its reasonable use. The state has authority to declare a variety of water practices unreasonable, even if they were considered acceptable in the past. These may include excessive evaporative and conveyances losses, inefficient irrigation techniques, failure to adopt or to implement best management practices, and perhaps other profligate uses such as the irrigation of water-intensive crops and landscaping, failure to install low-flow water appliances, and continued reliance on imported water, instead of using cost-effective alternatives such as demand reduction, use of recharged groundwater, and recycling reclaimed wastewater.

- **Protect values recognized under the public trust doctrine.** California water rights are inherently limited by the public trust doctrine. In its seminal decision of 1983, the California Supreme Court made clear that the state's navigable lakes and streams are subject to the public trust to protect navigation, commerce, fishing, recreational, ecological, and other public values (*National Audubon Society v. Superior Court*, 1983). According to the court, the state possesses both the power and the duty to protect trust assets. In the case of water rights, the Supreme Court explained: "the state has an affirmative duty to take the public trust into account in the planning and allocation of water resources and to protect public trust uses whenever feasible." Even after the Water Board issues water rights, according to the court, the state retains "the power to reconsider allocation decisions" and in some cases that power "extends to the revocation of previously granted [water] rights." If state agencies fail to act, members of the public can bring a court action to enforce the public trust (*Center for Biological Diversity, Inc. v. FPL Group, Inc.*, 2008).
- **Improve water conservation (including using water more efficiently and productively).** In 2009, the California legislature set new conservation requirements for urban water use requiring a 20 percent reduction in per capita use by December 31, 2020 (Water Code

> 10608.16(a), 2009). Urban water suppliers have a suite of options that can be used to achieve targeted reductions. They include (1) water recycling and reuse; (2) appropriate pricing structures in which prices reflect the scarcity value of water as well as delivery costs and feature tiers which are constructed so that the price of water rises as the volumes used by consumers increase; (3) water rationing, where appropriate; (4) restrictions on outdoor uses of water; and (5) educational programs [see Gleick et al. (2003, 2011) for discussion of examples].

The legislature did not establish a parallel requirement for agricultural uses even though such uses account for 77 percent of consumptive use statewide in California (Hanak et al. 2010). Instead, the legislature required agricultural water users to implement "efficient water management practices by July 31, 2012," but generally limited them to measures that are "locally cost effective and technically feasible" (Water Code 10608.48, 2009). Agricultural water users also have an array of options for reducing and economizing on the use of water. The options include (1) irrigation scheduling and management of soil moisture in which the timing and volume of irrigation applications are linked to the moisture requirements of the crop (Eching 2002); (2) tiered pricing structures similar to those available to urban users but tailored for agriculture; (3) the substitution of closed-conduit irrigation systems—drip, micro, and sprinkler—which may allow more precise management of irrigation water (Heermann and Solomon 2007); (4) tailwater (excess irrigation water) recycling; and (5) regulated deficit irrigation in which the timing of moisture stress is carefully controlled so as to reduce water applications with minimized impacts on yield (Fereres and Soriano 2006).

These techniques cannot be effectively used to economize on water everywhere all the time. Thus, for example, the careful timing of irrigation applications and active management of soil moisture, as well as tiered pricing, are difficult to use when water deliveries are not available on demand. Similar conclusions hold for regulated deficit irrigation. Closed-conduit irrigation systems work best in circumstances where the infiltration properties of the soil are highly variable. Recycling of surface runoff from agriculture is most effective on soils with low infiltration rates.

The result is that conservation techniques must be applied and operated on a local basis and account for local circumstances. Blanket prescriptions for achieving agricultural water conservation on a statewide basis are unlikely to be successful (Gleick et al. 2011, Hanak et al. 2011). One exception to the inapplicability of blanket prescriptions is the need to measure water deliveries and applications and devise consistent procedures for accounting for water deliveries and use. Water deliveries and applications are not widely or consistently measured in California agriculture, and accounting practices are not consistent either. Thus, while it may be inappropriate to require the agricultural sector to reduce water use by some fixed volume or proportion, the availability of conservation opportunities and the need to measure and account for water use suggest that there are opportunities to improve water management in agriculture and achieve significant water savings (Cooley et al. 2008). Christian-Smith et al. (2010) document through case studies a number of successful efforts by California growers to increase the productive and efficient use of water. These documented successes underscore the possibilities and opportunities for further improvements in water use in agriculture.

- **Groundwater monitoring and regulation.** There is no comprehensive permit system for the regulation of groundwater in California, although groundwater accounts for approximately one-third of the state's water usage in an average year. However, there are local and regional avenues for management (Nelson 2011). Of the 431 groundwater basins in California, 22 have been adjudicated through the court system and are the subject of management under court supervision (CDWR 2009). In most other areas, overlying landowners can freely withdraw the percolating groundwater (that is, groundwater that does not flow as an underground stream) beneath their property for reasonable and beneficial use. There is no state regulation of such withdrawals and there is no comprehensive requirement for groundwater management. One result of this situation is that groundwater underlying the southern Central Valley of California has almost certainly been persistently overdrawn (Faunt 2009, Famiglietti et al. 2011). Continuation of unsustainable, persistent overdraft would likely have serious consequences for the economic and food and water security of the United States (Famiglietti et al. 2011).

"Rights" to extract groundwater are subject only to the "correlative" rights of other overlying landowners withdrawing from the same source. As one California court complained in 2006: "California is the only western state that still treats surface water and groundwater under separate and distinct legal regimes" (*North Galilee Water Co. v. State Water Resources Control Board*, 43 Cal. Rper 3d 821, 831 [Cal. App. 2006]). Rather than acknowledge the connection between surface and subsurface supplies, the court explained, California depends on water classifications "that bear little or no relationship to hydrological realities." In 2009, the legislature enacted modest reform by requiring the monitoring and reporting of groundwater elevations (Water Code § 10920). However, the legislature could provide additional tools to address water scarcity by joining other western states in recognizing the interconnection of surface and groundwater [see, for example, Thompson (2011) and a 2006 congressional hearing on this topic (U.S. Congress 2006)]; by enacting more stringent water-use measurement and reporting requirements; and by considering mechanisms to extend the surface-water permit system to groundwater withdrawals. These mechanisms would likely be politically unpopular, but they would provide the state with a comprehensive mechanism to ensure that extracted groundwater meets the constitution's reasonable and beneficial use standard.

Water Markets

Under some circumstances, water markets can be helpful in allocating water among competing uses to achieve economically efficient use. Markets have the advantage of being strictly voluntary because they rely on the willing participation of buyers and sellers. In market transactions, the buyer will typically be motivated because the water is available through market exchange more cheaply than through any other method. Similarly the seller is motivated because the water can be sold for more money than could be realized by using it in any other available opportunity. This means that successful exchanges benefit both seller and buyer. Markets are simple and straightforward and lead to economically efficient allocations so long as there are not significant adverse third-party impacts and as long as environmental uses are appropriately accounted for. Exchanges that involve agricultural-to-urban short-term transfers in the delta have been increasing in recent years (Macaulay 2009). Virtually any water-market scheme will need to accommodate environmental uses and other instream uses. Examples of techniques for accommodating environmental uses of water include funding mechanisms such as taxes to buy water for environmental purposes and administrative allocations that ensure that some level of environmental flow is protected (NRC 1991). Accommodating environmental uses and accounting for third-party impacts may entail large transaction costs in connection with management of delta waters. A principal example is the state of Oregon, which uses a combination of implicit taxes on water trades and administrative allocations to ensure that appropriate quantities of water are left in place for environmental purposes. Such transaction costs should be assessed in any consideration of the desirability of adopting market or market-like arrangements to resolve delta water problems.

There are different types of water markets. There are markets in water rights in which the right to use some specified amount of water in perpetuity is exchanged. There are lease-like markets in which specified quantities of water are exchanged for use over a specified period of time with no transfer of rights. This type of market exchange was used for a 2-year period during the drought of 1987-1992 in California to mitigate shortages that would have had very high cost impact. The resulting exchanges had large net benefits and averted severe drought impacts (Carter et al. 1994). There are also spot markets where water can be purchased in some specified amount for use immediately. This kind of market tends to be informal. Finally there are markets for options wherein a potential buyer pays a potential seller for the right to take a specified amount of water in a dry year. The buyer also pays for the water if and when it is transferred. Where water markets have been used extensively, they illustrate a common pattern in that the vast majority of exchanges do not entail the trade of water rights. ***Long-term transfer of water from willing agricultural sellers to the state that in turn could make it available for instream uses or supplemental supplies, particularly south of the delta, offer a significant opportunity for better management of California's waters consistent with the state constitutional provision.***

Water markets are but one tool that can be used to manage scarcity. Given that they are particularly suited to managing scarcity, they should be given careful consideration in the development of future water plans. The need to acknowledge scarcity in planning for the delta's water future encompasses the need to include in the array of alternatives some consideration of institutional arrangements that are particularly well adapted to managing scarcity. The methods should include information about changes in the degree of scarcity that users could respond to, should encourage water conservation (i.e., discourage excessive use), and if possible should include information about the value of water. Prices and markets are two examples.

Care must be taken in designing and regulating water markets. Where markets have been used successfully, the market arrangements in question did not involve "free-market" transactions (Dellapenna 2000, Sinden 2007). The transfer of water rights, for example, almost always entails a change in the place of use, the season of use, the type of use, or the pattern of return flows. Moreover, almost every type of water exchange has the potential to impose adverse impacts on third parties other than the buyer or the seller. For transfers in excess of 1 year, the California Water Resources Control Board provides public notice and opportunity for comments and evaluates petitions for transfer to ensure that they "would not result in substantial injury to any legal use of water and would not unreasonably affect fish, wildlife or other instream beneficial uses (Cal. Water Code §§ 480-84, 1825-1745).

The potential for third-party effects underscores that markets, whatever their type, may not work in all situations. Some regulation of such markets is required. Indeed, the best documented market arrangement in recent history, which entailed the development of the California Drought Water Bank, involved a clear and transparent set of rules and was carefully supervised by the state which acted, in effect, as a water broker. The resulting short-term or lease market, administered by the California Department of Water Resources, led to large monetary benefits for those who purchased water and also resulted in positive impacts on statewide employment. Even in that case there were adverse third-party impacts, although the costs of those impacts amounted to only a small fraction of the total benefits that accrued from the Drought Water Bank (Carter et al. 1994).

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3

Stressors: Environmental Factors and Their Effects on the Bay-Delta Ecosystem

THE CHALLENGE: IDENTIFYING, DISTINGUISHING, AND RANKING INTERACTING ENVIRONMENTAL FACTORS AFFECTING THE BAY-DELTA ECOSYSTEM

Many environmental factors, including water diversions, affect the structure and functioning of biotic communities in the delta. Although it would be convenient if one or only a few of these factors could be identified as the source of the "problem," or even ranked with some certainty, it is not possible to do that, for at least three reasons: the "problem" is not easily definable, the suite of stressors is complex and interactive, and the ecosystem and its components do not react to any stressor as a single unit.

"The Problem" of the Delta Is Not a Single, Easily Definable Problem

Although the ecosystem has been radically altered over the past 150 years, it nonetheless remains a biologically diverse and productive ecosystem. Some species have thrived, but others, including some listed as threatened or endangered under the federal Endangered Species Act and California's Endangered Species Act, have declined dramatically. In addition, species composition and environmental conditions in the delta have undergone large changes over the period. Therefore, while an immediate difficulty for some is that concern over some listed species has affected water diversions, "the problem" is harder to define biologically, and is perceived differently by various stakeholder groups, institutions, and other interests.

The Suite of Stressors Affecting Water Quality, Habitat, and Sustainability of the San Francisco Bay Delta Is Complex and Interactive

Interactions among stressors and between stressors and ecosystem processes are common. Nutrient enrichment, toxic chemicals, and temperature, for example, are affected by hydrology and hydrodynamics, that is, the way tides and freshwater flow interact to determine the temporal and spatial variability of the physical environment of the estuary. This complicates the interpretation and evaluation as to positive, negative, or neutral overall effects of any single stressor on the ecosystem and its attributes. Furthermore, species differ in their individual responses to most types of stress. The result is a complex biological, spatial, and temporal mosaic of impacts from this combination of influences.

To some extent, the evaluation of the impacts of these effects also depends on which ecosystem services and needs are of interest or concern, for example, safe and usable water supplies, recreational and commercial fisheries, habitat condition, or public use of the delta. Thus, while it is politically attractive to attempt to rank stressors so as to prioritize societal investments in their amelioration, that task is much more complex than it might at first seem. To some degree, priorities can be defined if the stress, species, place, and time are first prioritized or defined. The stressors discussed below and shown in Figure 3-1 are highly dynamic; that is, they can quantitatively change in time and space depending on changes in human activities (including future management actions), climate, and combinations thereof.

The Ecosystem and Its Components Do Not Necessarily Respond as a Single Unit to Most Environmental Factors

For example, Chinook salmon (*Oncorhynchus tshawytscha*) spend several years at sea and then return to pass through the delta as adults to spawn; their eggs and young spend time in delta tributaries before passing through the delta on their way to the ocean to mature. Returning adult Chinook salmon always die after spawning, and so they are not susceptible to chronic environmental factors, because they die before such factors can affect them. They also are strong swimmers and therefore most changes in flow patterns in the delta are reasonably small challenges for them. The eggs and young are susceptible to conditions in the tributaries and are exposed to them for considerable periods, and the outmigrating smolts are not as strong swimmers as are the returning adults, and so probably are more susceptible to changes in flow patterns. By contrast, delta smelt (*Hypomesus transpacificus*) spend their entire (short) lives in the delta and so they can be chronically exposed to contaminants in the water; being smaller and

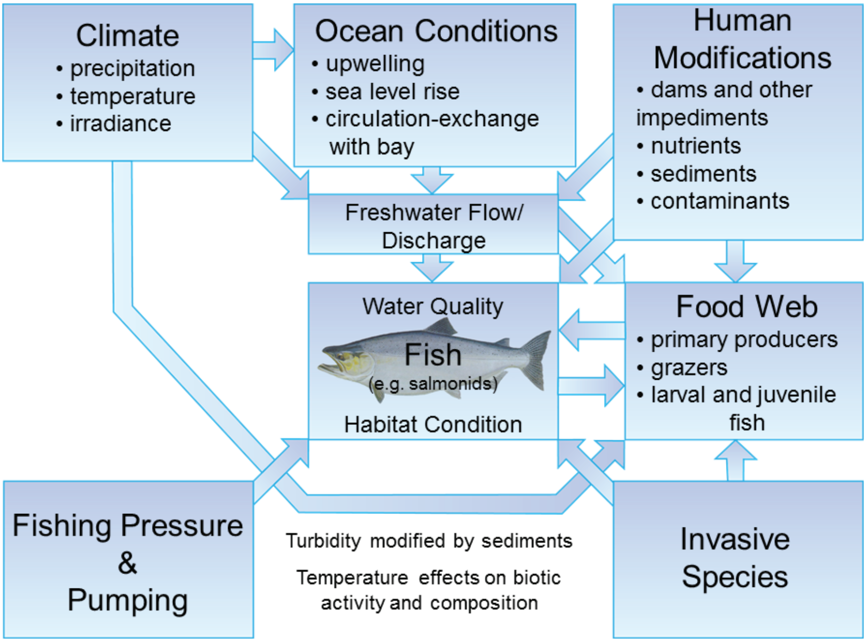

FIGURE 3-1 Conceptual diagram showing the interactive stressors affecting San Francisco Bay Delta water quality, habitat condition, and overall ecosystem structure and functioning. While this figure is focused on key fish species (e.g., salmonids), these are intimately linked to other biotic components of the ecosystem, including planktonic and benthic primary producers, grazers, larval, and juvenile and mature invertebrate and fish species.
SOURCE: Courtesy of A. Joyner, University of North Carolina.

weaker swimmers than even salmon smolts, they likely are more susceptible to changes in flow than salmon are. In addition, the behaviors, food, distribution in the water column, and physiologies of salmon and smelt are different, so even if they are exposed for a time to the same adverse environmental conditions, their responses to them almost certainly are different.

The above discussion compared only two species, but other species are important as well, including those that are not listed. Other biotic components, ranging from phytoplankton to fish, are part of the ecological community and yet they, too, differ in behavior, distribution, physiology, and susceptibility to a wide variety of environmental conditions, including contaminants. Thus most attempts to identify and rank single environmental factors as stressors are very likely to fail, unless the factors can be specifically related to a particular aspect of a species' life history. Even such factors as dams, which would appear at first glance to adversely affect only or mainly migratory species like salmon, steelhead *(Oncorhynchus mykiss*), and green sturgeon (*Acipenser medirostris*), also affect flow patterns, water temperature and quality, food availability, and so on, and they differentially affect many species, even those that do not migrate. There is a complex interplay between key water quality, habitat, and sustainability issues and the drivers affecting them. Furthermore, uncertainties and scientific gaps exist that further compound the problem (Table 3-1). Indeed, the delta problem is a "wicked" problem in the sense of Rittel and Webber (1973) and Conklin (2005): the problem is hard to define objectively and the nature of the problem depends on the values of those who define it.

For all the above reasons, the committee concludes that only a synthetic, integrated, analytical approach to understanding the effects of suites of environmental factors on the ecosystem and its components is likely to provide important and useful insights that can lead to enhancement of the delta ecosystem and its species.

ECOSYSTEM STRESSORS

Although the committee recommends a synthetic, integrated approach to assessing environmental factors, such an approach first requires a description of the individual factors separately. Therefore, we provide such descriptions, covering a variety of environmental factors that are important or potentially important in the following sections. The current set of stressors discussed is not an exhaustive list; rather, they are the most prominent stressors in the delta system in the committee's judgment. Following this, the committee provides its assessment of each stressor individually.

Physical Environment: Geomorphology and Delta Geometry

Changes in geomorphology of the delta in the last 150 years have been dramatic. Alteration of tidal channels and drainage of wetlands within the delta began for agricultural purposes, but eventually, as new centers of commerce and shipping developed, the drained lands supported urban development. Levees surrounding delta islands isolate most land in the delta from tidal or riverine flooding. Historically, periodic flooding of floodplains and wetlands provided habitat for many species and reduced the risk of downstream flooding. The delta absorbed flood flows to become a vast shallow lake. At its greatest extent prior to the transition to agriculture, the delta covered 1,931 square miles of tidally influenced open water, intertidal flat, and marsh. By 1930, however, 35 percent of the delta had been converted (Thompson 1957), leading a trend of land conversion that established the channel geometry and variability that is present today.

TABLE 3-1 Examples of the Interplay Among Ecosystem Processes (Drivers), Stressors, Science Needs, and Policy

Drivers[a]	Stressors	Water Policy Issues	Uncertainties and Science Needs
Anthropogenic infrastructure changes resulting in changes in freshwater flow and turbidity	Canals. Removing more water from the system. Reservoirs.	Effects: benefits vs. adverse implications for ecosystems	Predicting influences of new water routing? Implications of population growth, water use or conservation? Impediments and benefits to fish passage.
Climate change	Temperature: Changing ocean conditions. Changing hydrology.	Will future habitats be suitable for species of concern? Can we save and manage sensitive species?	Can we manage habitats to create refuges and sustain optimal carbon, nutrient, and oxygen cycling?
Exports	Entrainment. Indirect effects on hydrodynamics. Nutrient and carbon loadings. Upstream diversions.	How to balance supply reliability with ecosystem requirements.	Effects on fish populations vs. individuals? Quantifying indirect effects? Quantifying effects of upstream diversions?
Food quality	Nutrients: N,P,C. Flow. Grazing.	Declining quality of food for grazers and higher trophic levels.	Relative importance of bottom-up vs. top-down controls on food web. Influence of habitat changes. Feasibility of management?
Habitat loss	Nutrients. Freshwater flows. Light, turbidity. Physical disturbance and elimination.	Can restoration of habitat facilitate recovery of key processes and native species?	Restoration uncertainties: What is manageable against a changing baseline [climate change, invasive species, declining sediment inputs]?
Harvest and fishing	Top-down	Implications for fisheries.	How to manage harvest for sustainable populations and to avoid top-down effects on ecosystems [sustainable production, desirable water quality, and habitat].
Introduced species	Alteration of food webs and nutrient cycling. Alteration of food availability. Changes in predation. Change in physical habitat from macroflora.	Survival and management of native species. Fate of restoration actions.	Predicting success of invaders and their ecological implications? Life cycle of invasive species: can vulnerabilities be found? Controlling inputs and managing habitat for optimal production of native species.

continued

TABLE 3-1 Continued

Drivers[a]	Stressors	Water Policy Issues	Uncertainties and Science Needs
Nutrients (nitrogen and phosphorus)	Nitrogen/phosphorus loads. Flows. Temperature.	Nutrient input reductions.	Determine nutrient input and flow thresholds for eutrophication and algal bloom formation and macroflora. Roles of ratios and forms of nutrients in determining community composition.
Passage impediments	Dams. Migration barriers. Water diversions.	Inability of species to utilize former habitats.	What species most affected by diversions? Feasibililty of management?
Toxic chemicals	Inputs of selenium, mercury, pesticides.	Concentrations not declining and could increase.	Selenium: San Joaquin River inputs to the Bay? Mercury: methylation increase from wetland restoration? Pesticides: How many areas of high concentration and where? Improved management.

[a]Drivers listed in alphabetical order.
SOURCE: Modified from Healey et al. (2008a).

The Bay Delta Conservation Plan (BDCP) Independent Science Advisors (BDCP 2007) identified two fundamental environmental gradients that control physical characteristics of habitat for various species (Figure 3-2). While the salinity gradient has always been oriented along the axes of the major rivers flowing through the delta, elevation gradients existed at a number of spatial scales. At the largest scale, there is a decrease in elevation and slope along the river channels and banks from upstream as they enter the delta, toward the bay. At the reach scale, the high natural river levees resulted in a decrease in elevation away from the channel into floodplain (upstream) and tidal marsh (downstream), and these "cross-channel" gradients were multiplied by the complex system of river and tidal drainage channels that previously occupied the delta.

Today, the network of delta levees has substantially reduced the area exposed to the tides to about 618 square miles (Culberson et al. 2008). The drainage density within the delta has been reduced and is restricted to deep subtidal channels, resulting in a limited array of environmental gradients within the delta. Natural high land (e.g., river levees) has been essentially eliminated, as have shallow channels. Tidal and riverine flow,

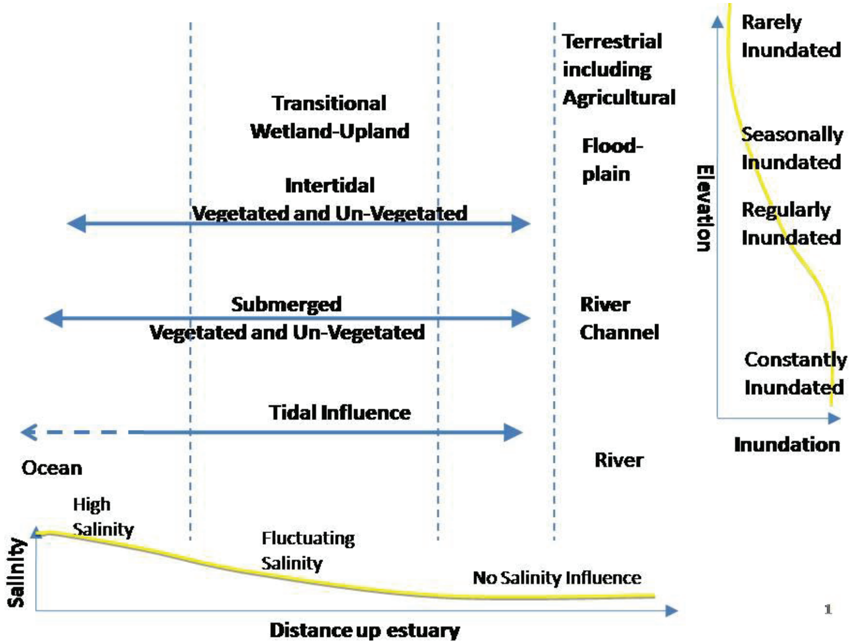

FIGURE 3-2 Horizontal and vertical gradients that control environmental conditions in the delta.
SOURCE: BDCP (2007).

across the salinity gradient, is confined to channels that do not drain at low tide. Flooded delta islands (e.g., Franks Tract, Mildred Island, and Liberty Island) are now lower than the marshes and channels in those areas would have been prior to drainage.

Isolated areas of naturally inundated wetland still exist in the delta (most of the wetlands in Suisun marsh are actually semi-impounded and their inundation regime does not therefore reflect the environmental conditions of naturally inundated wetlands). Forested floodplain with natural inundation regime is now limited to the Cosumnes River, and Rush Ranch in Suisun Bay is remnant salt marsh at the lower end of the system. Because tules (*Schaoenoplectus* spp.) do not require substrate drainage and can grow at elevations as low as ~0.5 m mean lower low water, tule patches exist in remnant midchannels islands and around the margins of some flooded islands. Tules have a low salt tolerance, but current water management that keeps the delta fresh for conveyance purposes allows tule wetlands to extend to the margins of Suisun Bay. Their ability to colonize into the subtidal zone means that bare intertidal flats, which may have historically existed throughout the delta in areas periodically influenced by salinity incursion, have essentially been eliminated except in Suisun Bay. Tules can effectively dampen wave action (e.g., Augustin et al. 2009) and thus limit resuspension of sediment in shallow subtidal areas within the delta. Accordingly, the only areas where wind waves routinely resuspend sediments and provide high turbidity levels are in Suisun Bay. Ruhl and Schoelhammer (2004) found that this effect was accentuated by the storage of highly erodible sediments on mudflats in Honker Bay. If such sediments are deposited in areas colonized by tules, resuspension would be limited. Thus, the changes in elevation gradients within the delta have limited the occurrence of wetlands of various types and shallow turbid subtidal environments.

Physical Environment: Flows and Salinity

The committee's first report, *A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta* (NRC 2010), dealt with aspects of flows, notably Old and Middle River (OMR) flows and X_2[1] positioning that are specific to two biological opinions issued by the Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) to protect listed fish species, the delta smelt, and Chinook salmon. In what follows, we discuss flow effects on the aquatic resources of the bay delta more generally, aiming to set existing knowledge about these flow effects in the same framework as other stressors such as contaminants, nutrient inputs, and invasive species. To do so requires that one consider first how flow affects organisms and processes, in which cases it is anthropogenic changes to flows, volumes, timing, and paths that are the stressor(s). As discussed below, flow volumes and timing (i.e., the hydrograph) affect the temporal and spatial variability of the physical environment, a term we use to mean environmental variables like salinity, turbidity, turbulence level, as well as elements of habitat connectivity associated with horizontal transport (Cloern 2007, Cowen et al. 2006) and vertical turbulent mixing (Lucas et al. 1998). By flow paths we mean transport of organisms and materials through various regions of the bay delta, including the entrainment of listed species by the water project pumps. The issue of entrainment is dealt with below.

The distinction between these two types of flow effects on organisms, the food web, and thus on the ecosystem more generally is important in that sustainable approaches to reducing the effects of flow stressors may be quite different. In particular, the issue of flow paths appears amenable to engineering solutions: With the correct water engineering, entrainment

[1] See page 20 for a definition of X_2.

effects might be eliminated, allowing the maintenance of current diversion volumes, or possibly even permitting increased diversions. In a similar fashion, the problem some fish species have because of altered flow paths might be solved via strategies such as using information about when specific fish species (at various life stages) are at risk of entrainment and, with the aid of modeling, modify pump operations to reduce entrainment.

In contrast, the effects of flow on the physical-chemical environment, most notably the salinity field and its concomitant influences on circulation and transport (Monismith et al. 2002, MacCready and Geyer 2010), do not appear amenable to engineering solutions other than to use specific flow standards tied to water year type and variability, that is, standards like the X_2 standard developed by the Environmental Protection Agency in 1995,[2] which has subsequently been used as a basis for developing a variety of standards, including the recently proposed and litigated Fall X_2 standard as well as X_2 rules as described in State Water Resources Control Board (SWRCB) decision 1641.[3] In this case, the development of regulations to maintain salinity gradients relies on the central hypothesis that the environmentally optimum approach is to try and mimic the shape of the natural hydrograph albeit at a lower level—in other words, to make the system slightly drier than it would be naturally, but maintain the overall pattern of flow. The key conceptual model on which this hypothesis is based is that the current ecosystem is adapted to the presence of a particular seasonal variability in flow, which certainly has varied on evolutionary time scales (Ingram et al. 1996), as discussed by Moyle et al. (2010). As a consequence, many species have life strategies that depend on particular features of flow variability, such as the transport of eggs into suitable habitat at the correct time or the aggregation of ichthyoplankton into regions of higher food availability by gravitational circulation (Arthur and Ball 1979, Kimmerer et al. 1998).

Also, the California SWRCB has recently been actively engaged in developing regulations for various aspects of flows and diversions,[4] an effort that has been backed up by a detailed examination of the manifold ways in which flows affect bay-delta biota discussed in the technical report presented by Fleenor et al. (2010) to the SWRCB.

[2] Federal Register, Volume 60, Number 244.

[3] D1641 was finalized in March 2001.

[4] *Development of Flow Criteria for the Sacramento-San Joaquin Delta Ecosystem*, August 3, 2010.

Hydrologic Factors

The term "flow" encompasses a broad range of effects in the bay-delta estuary. We define flow here as freshwater flow, something that has multiple components and in the context of the delta can best be thought of in terms of four major components:[5] Sacramento River inflow; San Joaquin River inflow; net delta outflow, the total time averaged flow past Chipps Island at the western edge of the delta; and in-delta diversions, most notably the state and federal water projects. These four are not independent and are represented in an average sense (to a good degree of approximation):[6]

Net delta outflow = Sacramento River inflow
+ San Joaquin River inflow – In-delta diversions

Both of the river flows include the effects of reservoir operations (storage and releases) and diversions in and upstream of the delta, for example, the Hetch Hetchy Aqueduct, which transports Tuolumne River water to the San Francisco Bay Area. Because tidal flows at the eastern end of Suisun Bay are generally an order of magnitude larger than are mean flows (e.g., Walters et al. 1985, Monsen 2000), net delta outflow is a calculated rather than measured quantity.

One can look at anthropogenic changes in the hydrology of the bay delta by comparing measured hydrographs with the "unimpaired" hydrograph, that is, the hydrograph that would have been observed in the absence of the water projects, but including the present delta configuration. For example, in their presentation to the SWRCB, Chung and Ejeta (2011) more generally note that, as currently calculated, unimpaired flow is based on the hydrologic behavior of the system at present, rather than the system as it existed before dams, flood control levees, and so on were built. For this reason, the calculated unimpaired flow might actually be significantly different from what actually took place prior to development. Consequently, unimpaired flow should be treated as an approximate upper bound on the natural flow. To our knowledge, an appropriate lower bound has yet to be defined.

Finally, besides a reduction in the overall volume of freshwater entering the bay, the timing of flows has also been altered, with peak flows now occurring earlier in the year (February and March) than they would in the absence of water resources development. Here too, the change is not unequivocally due to water resources development: rather, it also appears

[5] Besides these flows there are also the East Side streams; see http://www.water.ca.gov/dayflow/.

[6] A full water balance for the delta includes groundwater–surface water exchanges as well as evapotranspiration by delta vegetation (see, e.g., Fox 1987).

that precipitation in the Central Valley watersheds is increasingly taking the form of rain rather than snow (Dettinger and Cayan 1995, Cloern et al. 2011), a pattern that also tends to shift the hydrograph peak earlier in the year. Thus, to a first approximation, the flow stressor is defined by changes in hydrology, both in volumes and timing.

Flow Effects on the Physical Environment

In conjunction with mixing from the tides, freshwater flow determines the spatial structure of the salinity field, via the relationship between flow and the position of X_2. (The position of X_2 is a distance scale—kilometers upstream, or east of the Golden Gate Bridge—for salinity intrusion. Thus, if X_2 is at 70 km, it is 70 km east of the Golden Gate Bridge.) The reason is that at steady state the tendency for freshwater flow to carry salt out of the estuary is balanced by the tendency for gravitational circulation and tidal dispersion to carry salt upstream toward the delta. As a result of this balance, the mean position of X_2 is proportional to the net delta outflow raised to the minus one-seventh power (Monismith et al. 2002), meaning that it takes much higher flows to move X_2 when X_2 is farther to the west, or nearer the Golden Gate Bridge, than when it is farther to the east (Figure 3-3). For example, to position X_2 at 72 km (opposite Honker Bay), a flow

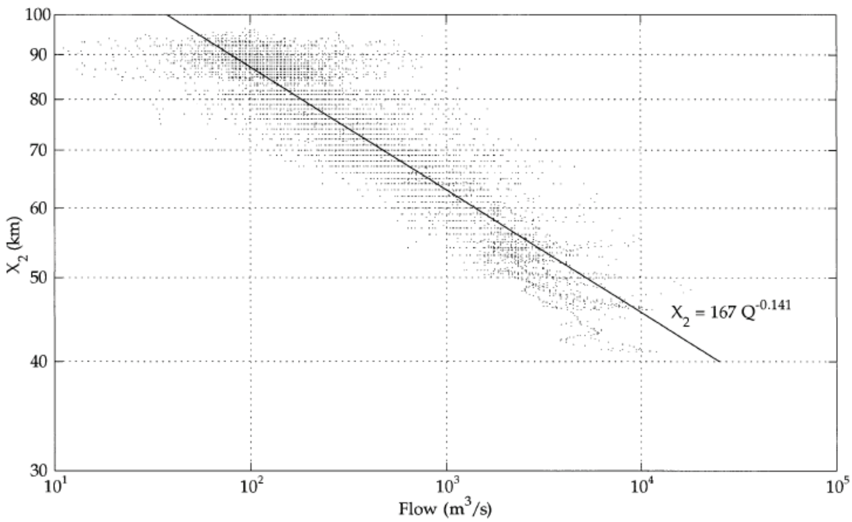

FIGURE 3-3 The position of X_2 in kilometers east of the Golden Gate Bridge as a function of flow.
SOURCE: Monismith et al. (2002).

of approximately 14,000 cubic feet per second (cfs) is required, whereas to position X_2 at 82 km (at the confluence of the Sacramento and San Joaquin rivers) requires 5,500 cfs. The difference in the total volume of outflow between these two positions for 1 month amounts to 500,000 acre-ft. When the position of X_2 is at 72 km, it requires 1,350 cfs to move X_2 1 km downstream, whereas when the position of X_2 is at 82 km, it requires 470 cfs to do so. As context, the tidal excursion in Suisun Bay and the western delta is of the order of 10 km.

The location of X_2 affects several key aspects of the physical environment. First, as reported by Jassby et al. (1995), the local depth-averaged salinity at any distance, x, from the Golden Gate can be estimated approximately as the product of the salinity at the Golden Gate and a function of the ratio of x to the position of X_2 (Figure 3-4). Thus, a given value of the distance of X_2 from the bridge will determine the salinities in a wide variety of habitats (i.e., the channels of the estuarine portions of the Sacramento

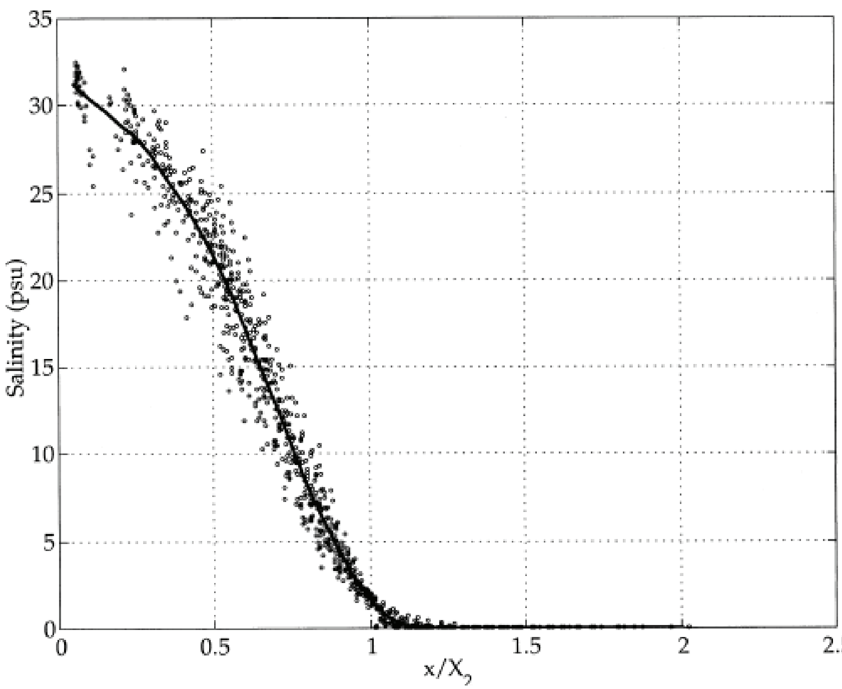

FIGURE 3-4 Depth-averaged salinity as a function of the ratio x/X_2.
SOURCE: Monismith et al. (2002).

and San Joaquin rivers, or the shallows of Grizzly and Honker Bay). This relationship was considered by Kimmerer et al. (2009), who used a 3D circulation model to look at the volume of habitat at a given salinity and depth that might be expected on statistical bases to be used by various species at different life stages.

Second, the position of X_2 also specifies the strength of the salinity gradient and the strength of gravitational circulation and the intensity and persistence of vertical density stratification (Monismith et al. 2002). Upstream of X_2, gravitational circulation is absent, whereas downstream of X_2 it varies both tidally and subtidally (Stacey et al. 2001). As suggested by a number of studies (e.g., Laprise and Dodson 1994, North and Houde 2001), gravitational circulation can play an important role in the retention of estuarine species that otherwise might be swept out of the estuary by tidally averaged flows (e.g., Orsi 1986). Indeed as described by Arthur and Ball (1979), because it is the boundary between the presence and absence of gravitational circulation, the low-salinity zone (LSZ) near X_2 may be a region of concentration of zooplankton as well as larval fish. However, this conceptual model may be applicable only to conditions existing when X_2 is sufficiently far upstream to keep the LSZ in the more channelized sections of the Sacramento and San Joaquin rivers. When the LSZ is in Suisun Bay, energetic horizontal mixing associated with tidal motions over the highly variable bathymetry (Ridderinkhof and Zimmerman 1992, Burau et al. 1993) may weaken the tendency to accumulate organisms in the LSZ. This remains to be evaluated with 3D modeling. Moreover, particle tracking calculations of model zooplankton in the St. Lawrence estuary reported by Simons et al. (2007) show that swimming behavior can substantially increase retention of organisms in an energetic LSZ (see also Bennett et al. 2002).

The vertical structure of the water column is also related to the position of X_2. Upstream of X_2, the water column is generally unstratified, whereas downstream it stratifies and destratifies tidally, with stratification lasting through the tidal cycle when X_2 is sufficiently far downstream and/or at neap tides (Stacey et al. 2001). Moreover, the strength and persistence of stratification varies inversely with the position of X_2, such that the estuary is less stratified when X_2 is in the delta than when it is in Suisun Bay (Monismith et al. 2002). This is important because stratification strongly weakens vertical, turbulent mixing, potentially decoupling the benthos, and benthic grazing (Cloern 1982) from the rest of the water column, and enabling motile phytoplankton to remain in the near-surface photic zone (Koseff et al. 1993) rather than being mixed into the deeper parts of the water column where respiratory losses of biomass can be larger than gains from photosynthesis. In this way, the physical environment of the bay delta is fundamentally affected by flow in ways that may significantly affect primary production and food-web dynamics in regions downstream of X_2 (whether or not X_2 is found in the delta or downstream in Suisun or San Pablo bays).

Finally, the position of X_2 may be important to the likelihood of entrainment of organisms in that when X_2 is upstream of the confluence of the two rivers, organisms that associate with the LSZ (e.g., larval fish), are more likely to be within the region of influence of the pumps (Kimmerer 2004). However, the positioning of X_2 far upstream may also occur with large exports as well as small outflows.

Flow Effects on Aquatic Resources: Primary Production in the Delta

Net delta outflow is thought to influence the residence time of materials in various regions of the delta (Monsen 2000, Monsen et al. 2007), and so should influence primary production in the delta (Jassby and Powell 1994, Jassby 2008). The concept of residence time in the delta is complicated by two factors. With the exception of Mildred and Liberty islands and Franks Tract, water is not well mixed on the scale of the delta and so no single residence time can be defined, and mixing by the tides is energetic, especially on the Sacramento side of the delta (Monsen 2000, Monismith et al. 2009) so that, even without any freshwater flow, there would be exchange between the delta and San Francisco Bay. The only examination of the effect of inflow on residence time that we are aware of is that by Kimmerer and Nobriga (2008). Using the particle tracking capability of DSM2, a 1D network model, they found that, in the northern delta, computed residence times matched or were shorter than the overall hydraulic replacement time of the delta (the delta volume divided by total inflow). Pointing to the complex nature of transport processes in the delta, computed residence times in the central and southern delta were larger than the hydraulic replacement time, did not vary monotonically with flow, and were affected by exports as well as inflow.

The connection between physical transport and primary production was examined by Jassby et al. (2002), who found that, as expected, increased inflow decreased phytoplankton biomass in the delta (as measured by chlorophyll *a*). Note that inflow is the correct flow metric since all the water that enters the delta must leave, mostly via outflow to the bay or by export from the pumps. Jassby (2008) extended these results showing a dramatic shift downward in the biomass-flow relation between 1980 and 2000. Besides flow, geometry of the delta can also influence residence time. For example, Monsen et al. (2007) found that placement of the Head of Old River Barrier, a temporary barrier designed to reduce entrainment of outmigrating salmon smolts in the San Joaquin system, significantly reduced residence time in the San Joaquin ship channel.

A more subtle effect of transport on primary production is that transport can couple regions of high productivity with regions that are strong sinks for primary production due to benthic grazing (Lucas et al. 2002), such that increasing residence time can *reduce* the accumulation of phytoplankton biomass. As an aside, this points to a possible problem with proposals (e.g., in the BDCP) to increase primary production in the system by increasing shallow water habitat: if that shallow water habitat includes a significant biomass of benthic grazers, it may become a net sink for primary production and so will decrease the total phytoplankton biomass available for pelagic grazers like zooplankton. Finally, mixing and transport may not act equally on all types of phytoplankton. In particular, grazing may have a much smaller effect on positively buoyant cyanobacterial genera like *Microcystis* than it does on negatively buoyant species such as the various diatoms that are thought to be good food for zooplankton.

Flow Effects on Aquatic Resources: Effects of the Position of X_2

Evidence demonstrating the effects of flow on bay and delta biota was presented by Jassby et al. (1995), who used Interagency Ecology Program (IEP)[7] data from the period 1968-1991 to show that the abundance (biomass) of a number of organisms, including the total production of particulate organic carbon by phytoplankton in Suisun Bay, the shrimps *Neomysis mercedis* and *Crangon franciscorum*, and several fishes, for example, starry flounder (*Platichthys stellatus*), striped bass (*Morone saxatilis*), and longfin smelt (*Spirinchus thaleicthys*), but notably, not delta smelt nor the key zooplankton *Eurytemora affinis*, was dependent on the values of the position of X_2 averaged over various parts of the year. The averaging periods, which ranged from 4 months to a year (see Table 1 in Jassby et al. 1995), were chosen by considering when flow variations might have an important impact, given known life histories of each organism.

The results of Jassby et al. (1995) do not exclude the importance of entrainment. Indeed they showed that for the particular case of striped bass, a better prediction of population size could be had by including diversions as well as the position of X_2 in the statistical model used to represent spring striped bass survival. Interestingly, the more complicated model had larger uncertainty in terms of determining the position of X_2 that would be required to the median observed level of survival.

Kimmerer et al. (2009) reexamined the results of Jassby et al. (1995), considering separately the period before 1987 and the period from 1987 to 2006, with 1987 chosen as the approximate start of the *Corbula* invasion of San Francisco Bay. For most species considered (but not delta smelt), Kimmerer et al. (2009) found that the slopes of the abundance–X_2-position

[7] See http://www.water.ca.gov/iep/.

relationships were similar for the two periods, although absolute abundances for a given value of the position of X_2 in some cases (e.g., longfin smelt) were reduced. Using modeled salinity fields and observed distributions of each species, Kimmerer et al. (2009) defined habitat indices for each species that also varied with the position of X_2 (Figure 3-5). Using these indices, they found that only for American shad (*Alosa sapidissima*) and striped bass were the abundance–X_2-position and habitat–X_2-position relations consistent, leading them to conclude that only for these species was habitat the means by which X_2 position influenced abundance. For the other species for which a connection to X_2 was inferred, the mechanisms behind observed X_2-position–abundance relations remained to be determined.

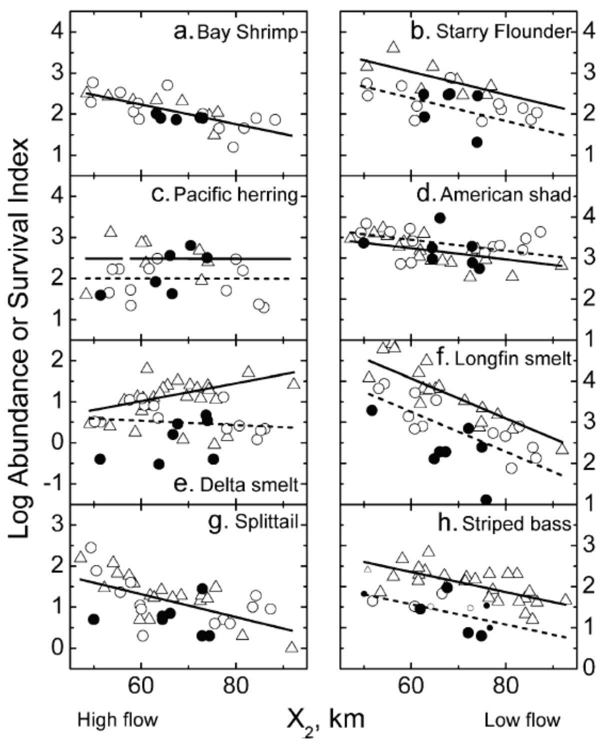

FIGURE 3-5 X_2–abundance relationships for fish and shrimp. Symbols indicate data up to 1987 (triangles and solid lines); 1988-2006 (open circles and dotted lines); and 2000-2007 (solid circles). The panels for striped bass and Pacific herring plot survival indices; all the others show log abundances.
SOURCE: Kimmerer et al. (2009).

For example, for starry flounder and bay shrimp, organisms that "recruit from the coastal ocean along the bottom into the estuary," Kimmerer et al. (2009) suggested that, as the distance upstream of X_2 decreases, gravitational circulation strengthens, and the transit time of organisms from offshore hatching sites to their estuarine rearing grounds would be reduced, presumably increasing survival. For the Sacramento splittail (*Pogonicthys macrolepidotus*), increased abundance when X_2 is downstream may be from an increase in floodplain spawning habitat because high-flow years, when X_2 is farther downstream, tend to involve flooding of the Yolo Bypass (Feyrer et al. 2006). Most recently, in the context of the pelagic organism decline (POD; see further discussion below), Mac Nally et al. (2010) reanalyzed the IEP data for 1967-2006, finding that

1. the position of X_2 in the spring ("spring X_2") strongly influences the abundance of mysids, longfin smelt, and calanoid copepods; fall X_2 (referring to the position of X_2 in the fall, by analogy with spring X_2) strongly affects striped bass; and winter X_2 has a weaker effect on delta smelt; and
2. spring and fall X_2 did not appear to have any statistical relation to delta smelt abundance, although it was related to smelt distribution.

Thus, while the mechanisms behind the influence of position of X_2 on the abundance of a variety of biota remain hypothetical, the statistical relations reported in several papers show that abundance of a number of species at different trophic levels found in the delta and San Francisco Bay is higher when X_2 is farther downstream. This implies that sufficient reductions in outflow due to diversions would tend to reduce the abundance of these organisms.

Physical Environment: Turbidity

Sediment particles, phytoplankton, and other suspended materials in the water column—causing turbidity—affect light penetration in the waters of the bay delta, as do colored dissolved materials. The degree of light penetration limits primary production by phytoplankton (e.g., Cole and Cloern 1984) and submerged aquatic vegetation (SAV) (e.g., Carr et al. 1997) and may shape a wide range of fish behaviors such as feeding (Baskerville-Bridges et al. 2002), since small fish or fish larvae are at risk to predation by visual predators.

On tidal time scales, sediment concentrations in the bay and delta generally reflect a local balance between erosion, settling, vertical turbulent mixing, and horizontal advection (Krone 1979; McDonald and Cheng 1997). In the deeper channels, turbulent processes (i.e., erosion and vertical mixing) are largely due to tides, whereas in the shallow shoals, wind-driven waves are dominant (May et al. 2003). In many estuaries a turbidity maximum (estuarine turbidity maximum or ETM) forms in the LSZ where near-bottom upstream transport by gravitational circulation leads to particle retention (e.g., Geyer 1993), a mechanism thought for some time to be important in the bay delta (Arthur and Ball 1979), although more recently it has become clear that there are multiple ETMs in Suisun Bay, all tied to local bathymetric features rather than to the structure of the salinity field (Schoellhamer 2000). This distinction is important because much of the initial basis for an X_2-flow standard was based on positioning of such an ETM in Suisun Bay (Williams and Hollibaugh 1987).

Given the high turbidity of much of the bay and delta (the Secchi disk depth—a measure of visibility—is typically less than 1 m), planktonic primary production probably is light limited (Cole and Cloern 1984) such that relatively high levels of nutrients have not resulted in algal blooms. Indeed, the delta is one of the least productive temperate estuarine ecosystems (Jassby et al. 2002). Consequently, physical processes such wind (May et al. 2003), which affect suspended sediment concentration, can limit the formation of algal blooms. Importantly, the dominant paradigm of light limitation, which has been well supported by extensive observation, has meant that until recently (Dugdale et al. 2007) little attention has been given to the role of nutrients in primary production. Primary production is discussed in detail below.

Analyzing 36 years' of data, Feyrer et al. (2007) inferred that delta smelt, and age-0 striped bass, were more likely to be found in turbid water, although turbidity explained only 13 percent of the variance in delta smelt occurrence (not abundance). However, Mac Nally et al. (2010) found that delta smelt abundance was not related to turbidity, although the effect of turbidity on occurrence and abundance may be different if the amount of appropriately turbid (and saline) habitat does not limit current delta smelt populations. The effect of turbidity on delta smelt populations may take other forms. Grimaldo et al. (2009b) argue that the appearance of significant numbers of delta smelt at the export pumps is related to the appearance of the first flush of turbid water through the delta and that, accordingly, monitoring of turbidity could be used as a basis for guiding pump operations. On the other hand, the evidence for this behavior presented in their paper (e.g., Figure 6) appears rather weak in contrast to observed relationships between delta smelt salvage and zooplankton abundance or negative OMR flows (Grimaldo et al. 2009b, Figures 7 and 8).

To cast turbidity as a stressor, it is necessary to examine changes and trends in turbidity, namely the fact that turbidity is decreasing with time (Schoellhamer 2011; Wright and Schoellhamer 2004). This has been hypothesized to be a result of decreased sediment supply to the estuary because a significant fraction of sediments that would enter the system naturally are now trapped in upstream reservoirs (Schoellhamer 2011) and in stabilized floodplains. This hypothesis is reinforced by the fact that changes in bathymetry over the past 100+ years (Jaffe et al. 1998) indicate that the system is now net erosive, indicating that the sediment supply into the estuary is exceeded by net exports to the ocean.

These changes are perceived as a stress to pelagic organisms, although the importance of current practices and water project operations (aside from storage of sediments) is less clear because much of the suspended sediment that determines turbidity today was originally deposited in the system in the 19th century through now-banned mining practices (Schoellhamer 2011).

In summary, like salinity, turbidity is a fundamental aspect of the physical environment of the delta, and so systematic, long-term changes in turbidity appear to be important to the ecosystem. Increased clarity should result in increased primary production by both phytoplankton and by SAV. For phytoplankton, this might mean a shift away from dominance by light limitation, toward more nutrient-limited conditions. Given that the connection between turbidity and primary production by phytoplankton is well known, this response of the system should be straightforward to predict. However, in situ it is probably a highly variable trade-off between periods of higher and lower turbidity, leading to highly variable light versus nutrient-limited conditions.

Increasing clarity might also favor negatively buoyant species like diatoms over positively buoyant cyanobacteria like *Microcystis* that can do well in turbid environments, and so it could act to reduce the production of cyanobacteria. For SAV, it appears that increasing clarity may yield increases in nonnative species, most notably *Egeria*. This trend may play an important role when attempting habitat restoration.

Increasing clarity will also act to decrease the amount of suitable habitat for small fish that favor shallow, turbid waters, and make those fish (albeit to an unknown extent) more vulnerable to predation. This effect may be more pronounced in the deeper delta channels rather than in the wave-mixed shallows of Suisun Bay. However, while there are compelling biological reasons to conclude that turbidity is important to fish, the statistical evidence connecting turbidity to abundance is somewhat weaker than that connecting flow to abundance. Thus, at present there is insufficient evidence to conclude that turbidity can be used or manipulated to lessen impacts of diversions on fish.

Physical Environment: Temperature

Water temperatures at any point and time in the delta are determined by heat exchanges with the atmosphere, by long- and shortwave radiation, by horizontal advection by currents (tidal and nontidal), and by vertical, turbulent mixing (Fischer et al. 1979, Wagner et al. 2011. The overall setting of the bay delta involves cold temperatures at the ocean end (particularly during upwelling) and at the riverine end, with warmer temperatures in between. Like salinity, temperature is affected by flow (i.e., net delta outflow for the bay, and inflows and net delta outflow for the delta). For example, modeling and observations reported by Monismith et al. (2009) show that, for the San Joaquin system, net flow through the system acts to push the region of maximum temperature downstream toward the ocean. Regulation of temperature primarily is focused on river sections downstream of dams, where selective withdrawal of cold water can be used to help keep instream temperatures sufficiently cold for salmonids. Further discussion of temperature is in Chapter 4.

Physical Environment Conclusions: The Management Dilemma of Habitat Versus "Plumbing"

The structure of the bay-delta ecosystem is related to the structure and variability of its physical environment. This physical environment has been significantly altered by the development of California's water resources, most notably by changes in flows into and through the system. However, in practical terms, some elements of these alterations are more amenable than others to actions aimed at improving ecological rehabilitation of the ecosystem. For example, other than in riverine regions close to dams, we have little ability to affect temperatures, except through flow. Aside from the fundamental issue of storage of sediments in reservoirs, turbidity (and its variation) is primarily a result of natural forces. Importantly, given that diversions in very wet years constitute a small fraction of the unimpaired flow in winter and spring, it appears that important aspects of variability of flow are outside the control of water project operations. Nonetheless, human use of water does have significant influence on freshwater flow much of the time. Thus, some form of flow management is of paramount importance for ecological rehabilitation.

In considering flow management, it is critical to recognize that the issues raised by the relationship between the position of X_2 and abundance of many species are fundamentally different than those associated with entrainment of fish. In principle, entrainment of fish is a problem localized to the delta that can (optimistically) be solved by changing the water engineering of the delta. In effect, the fish salvage facilities at the State Water

Project (SWP) and Central Valley Project (CVP) pumps represent the first attempts at eliminating direct entrainment effects; indeed, if the facilities were perfect and predation near the pumping facilities were negligible, 100 percent of the fish that find their way to the pumps would be saved. In reality, salvage is quite inefficient, and only a small fraction of the entrained fish survive salvage (Brown et al. 2009). A second example is the gate on the Delta Cross Channel (DCC), which can be closed to improve survival of salmon smolts on the Sacramento River side. However, closure of the DCC tends to increase salinities in the western delta, affecting water quality at the Contra Costa Water District water intake (Monsen et al. 2007). A similar alteration to the plumbing is the Head of Old River Barrier (see above). It too may have collateral negative effects by possibly increasing the entrainment of delta smelt resident in the south delta (Kimmerer and Nobriga 2008). The most radical effort of this type was a proposal by the Metropolitan Water District to build and operate two sets of gates on Old and Middle rivers, with operations tied to turbidity variations that may affect delta smelt.[8]

The largest alteration to the flow-path engineering, one originally contemplated in the planning of the SWP, is one designed to avoid entrainment directly by separating the diversion of Sacramento River water from the rest of the delta. If used by itself, and if screening on the intake is successful, such a facility might reduce entrainment as well as reverse mean flows in the delta that might affect fish migration.

However, the utility of these plumbing measures depends on two factors: the importance of entrainment to fish populations (see stressor section below) and the degree to which outflow from the delta into San Francisco Bay itself does not influence species abundance or other ecosystem attributes. The advantage of changes to the flow paths is that these active, engineering measures might support human use of freshwater entering the delta, while also providing some degree of environmental protection.

In contrast, flow effects that affect San Francisco Bay downstream of the delta, as might be represented in the relations between the position of X_2 and abundance, are not amenable to direct engineering intervention in that the only things that can be controlled are timing and volume of flow out of the delta. Given that the position of X_2 for different periods of time appears to be important for different species, one can argue that water operations should be designed to preserve as much of both the volume of outflow and the timing of that volume that would be observed in the absence of diversions (Moyle et al. 2010, SWRCB 2010). In light of the nature of the connection between flow and the position of X_2, this may necessitate limiting available water supply, especially in dry years.

[8]See http://www.usbr.gov/mp/2gates/docs/index.html.

Nutrient Enrichment

Macronutrients (nitrogen, phosphorus, silicon) and micronutrients (trace metals and iron) are essential for supporting and sustaining primary and secondary production in aquatic ecosystems, including the delta. Microalgae, specifically phytoplankton, are dominant primary producers in the delta and lower bay systems; hence, this section focuses on them. High nutrient inputs can lead to altered community structure and proliferation of phytoplankton that may have undesirable effects on biogeochemical cycling, food-web dynamics, habitat conditions, and human health. There are numerous examples of the negative effects of nutrient overenrichment, or "too much of a good thing" (D'Elia 1987) worldwide (Schindler 1971; Smetacek et al. 1991; Vollenweider et al. 1992; Nixon 1995; Paerl 1997, 2008; Boesch et al. 2001; Cloern 2001; Elmgren and Larsson 2001; Conley et al. 2009) and in the delta (Dugdale et al. 2007, Lehman et al. 2008, Meyer et al. 2009). These include (1) increased primary production, (2) selective stimulation of harmful (i.e., toxic) algal bloom species, and (3) shifts in phytoplankton community structure to more opportunistic species that (4) induce changes in food-web structure and trophic transfer and (5) enhance the potential for bottom-water hypoxia and anoxia due to increased sedimentation of autochthonous (indigenous) organic matter.

High inputs of both nitrogen (N) and phosphorus (P) can accelerate estuarine eutrophication (Nixon 1995, Boesch et al. 2001, Elmgren and Larsson 2001, Conley et al. 2009, Paerl 2009), with P playing a more important role in the freshwater regions and N playing a more dominant role in marine systems (Nixon 1995, Paerl 2009). However, in transitional environments like estuaries, both N and P play interactive controlling roles (Fisher et al. 1992, Paerl 2009). Both the *amounts* and *ratios* of N and P inputs and resultant concentrations can determine the structure and functioning of primary producers. The various *chemical forms* of these nutrients can play additional roles in modulating community responses. Finally, there are synergistic and antagonistic interactions among limiting nutrients. For example, N and P co-enrichment often leads to greater degrees of biostimulation than N or P alone (i.e., they may be co-limiting) and the effects of N enrichment may be amplified by parallel iron (Fe) enrichment, since N assimilatory enzymes require Fe as a structural component, and energy yielding biosynthetic pathways requires Fe as a cofactor.

Alpine and Cloern (1992), Cloern and Dufford (2005), and Jassby (2008) pointed out that in turbid, highly tidally mixed, well-flushed, nutrient-enriched estuaries like San Francsico Bay and the delta, light availability, flushing rates (i.e, water residence time), and filter feeding assume important, and at times dominant, roles in limiting phytoplankton production. In well-flushed regions of the bay and delta, both N and P are often plentiful (i.e., exceeding the half-saturation constants[9] for growth), and N:P supply ratios or different chemical forms have little effect on shaping phytoplankton community structure and function. However, in some regions of the bay delta where tides are weaker (e.g., the southernmost reach of South San Francisco Bay or the southern interior delta) water residence time may be long enough (especially during low-flow periods) for nutrients to be thoroughly assimilated (Cloern 2001), leading to biomass increases (unless grazing exerts a strong control). Under these conditions, nutrient limitation is most likely to occur, and nutrient enrichment could impact the species composition and functioning of primary producers and consumers. Given that water residence times can vary on short- (diel) and longer-term (seasonal, interannual) time scales, nutrient limitation might be intermittent rather than continual. This possibility should be investigated for the delta.

Additionally, in many parts of the delta, where flows are weaker and water withdrawals and diversions have taken place, flow and residence time have been altered (Lucas 2009). Recent studies in these habitats (Frank's Tract, Mildred Island) have shown that such hydrologic alterations can affect phytoplankton community structure (Lucas 2009, Lucas et al. 2009). In addition, delta geomorphology, and human changes therein, can affect flow, residence time, and potentially nutrient assimilation, primary production, and phytoplankton growth and composition. Monsen et al. (2007) provided an example of how the placement of a barrier in the south delta radically changed flushing times and water quality.

When flow and flushing are reduced and water residence increases, phytoplankton will have more time to assimilate nutrients and build up biomass (as blooms) before being transported out of the system. This scenario benefits phytoplankton in general, and more specifically those species that have generally slow growth rates, since under the influence of reduced flushing (longer residence time) these species will more effectively compete with faster-growing species for nutrients and other resources. Most cyanobacteria (blue-green algae), including harmful bloom–forming types, exhibit relatively slow growth rates (Paerl and Huisman 2009, Paerl et al. 2011). Hence, reduced flow and flushing conditions tend to favor cyanobacteria, especially if nutrient supplies are adequate to sustain blooms (Paerl 2008, Paerl and Huisman 2009). In recent years, the non-N_2 fixing, potentially toxic bloom–forming cyanobacterium *Microcystis* spp. has increased in dominance in slow-moving fresh to oligohaline waters of the upper delta (Lehman et al. 2008). This genus appears to have benefitted from the combined effect of reduced flushing (increased residence time), possibly warmer

[9] In algal physiology, the half-saturation constant is used to describe the general affinity of an enzyme for a substrate or nutrient, which allows one to estimate whether an organism is operating under nutrient-limiting or nutrient-saturating conditions.

water conditions (which would enhance growth rates), more intense stratification, and increases in nutrient loading. *Microcystis* is indicative of nutrient-enriched conditions worldwide (Reynolds 1987, Paerl 2008). In particular, this genus tends to dominate in waters that are receiving excess N, since it is a non-N_2 fixer and hence relies on externally supplied forms of N. Their recent increase appears to be due to the combined effect of increased residence time and excessive N loading (possibly combined with a warming trend), which is conducive to *Microcystis* bloom formation. In addition, colony-forming cyanobacterial bloom genera like *Microcystis* are not readily grazed by crustacean zooplankton or benthic infauna because they cannot be effectively filtered, and they produce toxic compounds that can deter grazers and they form surface scums, which cannot be accessed by benthic and subsurface planktonic filter feeders (copepods, cladocerans, invertebrates, and fish larvae).

There are geographically diverse examples that point to excessive N inputs as a factor promoting *Microcystis* blooms (Paerl et al. 2011). While excessive N inputs may help stimulate bloom formation, P supplies must also be available. Therefore, while there is evidence for N overenrichment, P inputs should also be examined as a possible secondary nutrient stressor that affects ecosystem structure and functioning.

Cloern (presentation to the NRC committee, July 2010) pointed out that excessive N loading may also be problematic in South San Francisco Bay, which can have dry weather residence times of several weeks (Gross et al. 1999) and is prone to harmful (i.e., potentially toxic) dinoflagellate blooms, which have recently appeared in this part of the bay.

With respect to the influence of different *chemical forms* of nutrients as possible stressors on the delta system, it has been proposed that the reduced form of N, ammonium, may play a selective role by inhibiting nitrate utilization and growth of diatoms in mesohaline to full-salinity regions of the delta and downstream bay regions (Dugdale et al. 2007). This scenario would depend on whether N is even limiting in this region, which has been questioned by Cloern and colleagues (e.g., as opposed to light availability, flushing and transport, and grazing as potential factors controlling phytoplankton growth) (Cloern 2001, Cloern and Dufford 2005). The ammonium inhibition argument is based on mostly oceanic observations of a strong preference for nitrate as the N source in diatom populations, and on laboratory observations that relatively high levels of ammonium (>4 μM) can inhibit the uptake of nitrate in diatoms. These observations have led Dugdale and colleagues (2007) to propose that ammonium discharge from upstream wastewater treatment plants (specifically the Sacramento Waste Water Treatment Plant or SWWTP) may be high enough to cause inhibition of nitrate uptake by diatoms in downstream waters (e.g., Suisun Bay) (Dugdale et al. 2007). If common and widespread, this type of inhibition affects the food web and nutrient and carbon cycling, since diatoms are considered a good food source for most zooplankton, planktivorous fish, and shellfish species. In this regard, there has been a general decline in diatom biomass since the mid-1990s (Dugdale et al. 2007), and the amount of ammonium discharged by the SWWTP (and possibly other wastewater treatment plants) has shown a parallel increase. This too would give a flow effect since increased delta inflow would tend to dilute SWWTP discharges into the Sacramento River and lower ammonium concentrations in Suisun Bay.

However, Jassby (2008), Jassby et al. (2002), Thompson et al. (2008), and Cloern et al. (2010) all pointed out that the decline in diatom biomass in Suisun Bay and other locations took place shortly after the introduction of the Asian clam *Corbula*, a voracious grazer capable of removing vast amounts of phytoplankton biomass. Therefore, several environmental factors correlate with the decrease in diatom biomass starting in the mid-1990s. Also, in addition to decreases in diatom biomass, other phytoplankton taxa decreased in biomass at this time, at similar locations. This latter observation would tend to support the argument that "top-down" grazing exerted by invasive benthic bivalve grazers is a major control of phytoplankton biomass at these locations. Finally, it is exceedingly difficult to attribute specific ammonium supplies and concentrations in the lower delta and San Francisco Bay to the SWWTP, which is more than 100 km upstream from these locations. It is likely that ammonium, as well as other bioreactive N compounds released from the plant, go through numerous biogeochemical transformations during their travel time in the river and upper bay delta. Therefore, *total* biologically available N (ammonium, nitrate/nitrite, dissolved organic N) discharged from SWWTP and other anthropogenic sources should be included when considering N input reductions aimed at stemming unwanted symptoms of eutrophication (e.g., cyanobacterial blooms in the upper delta and other nutrient-sensitive regions of the San Francisco Bay, e.g., South San Francisco Bay). The role of ammonium in favoring an invasive species and thus structuring the pelagic community (Glibert 2010, Glibert et al. 2011) is discussed further below with other effects of nonnative species.

Conclusions

When physical conditions permit (i.e., increased residence time, adequate clarity, elevated temperatures, and enhanced vertical stratification), nutrients can play a role in the control of phytoplankton production and in bloom formation and persistence in parts of the delta system. Nitrogen appears to be the nutrient most likely to influence bloom formation, although a potential secondary role of P should not be ignored. Therefore, there is agreement that N input reductions will help ensure optimal water quality conditions in the delta and possibly parts of San Francisco Bay (South Bay). There appears to be less certainty as to whether reducing one form of biologically available N is preferred over another (e.g., nitrate vs. ammonium vs. dissolved organic N). Because different forms of N are biologically available and readily cycled between the water column and sediments, **the prudent approach is to reduce the impacts of all forms of organic and inorganic N**, which will ensure that undesirable algal bloom formation in regions prone to such events is minimized. There is less certainty as to the role P inputs play in the control of algal production and bloom formation. If P plays a role as a limiting nutrient, it is likely to be during freshwater blooms, but this has not been established. The degree to which N reductions should be practiced is at present uncertain and requires field and laboratory research (i.e., establishing nutrient-bloom thresholds using bioassays, stoichiometric analyses, N transport, and fate and cycling studies) and modeling that takes both physical and chemical forcing features, as well as the interactive effects of grazing, into consideration.

Food Quality and Quantity: Linking Environmental Stressors to Changes at Base of the Food Web

The drastic alteration of the Sacramento–San Joaquin Delta and San Francisco Bay since at least the mid-1800s has led to multiple and interacting physical, chemical, and biological changes (Healy et al. 2008b). Among the most potentially problematic changes (from biogeochemical cycling and trophic perspectives) are those at the base of the food web, namely significant changes in the structure and functioning of phytoplankton communities, the key food source supporting higher trophic levels (Cloern 1982, Cole et al. 1992, Jassby 2008). These changes have cascaded up the food web (Healy 2008, Kimmerer et al. 2008a). Filter feeders, grazers (zooplankton and invertebrate larvae), and planktonic herbivorous fish species appear to be particularly sensitive to changes in food quantity and quality. For example, growth of delta zooplankton is limited at chlorophyll *a* levels of < 10 µg/L (Mueller-Solger et al. 2002). There is also evidence of similar thresholds for clams. This, combined with the data of Jassby (2008) showing median chlorophyll *a* concentrations in the delta much less than 10 µg/L and overall declining over time, suggests that primary consumers are, at times, food limited.

Changes in the food web were among a suite of factors examined as possible causes of the recent declines in four fish species, collectively termed the "pelagic organism decline" or "POD." The four POD species were delta smelt, longfin smelt, threadfin shad (*Dorosoma petenense*), and juvenile striped bass. There were several related drivers or causative factors that caused changes in the food web that were considered. These include a decline in diatoms (preferred food source for grazers) in the Susin Bay and other areas (Dugdale et al. 2007, Cloern et al. 2010), increasing prevalence of potentially toxic and cyanobacterial bloom species, which also are of low nutritional value, in the delta region (Lehman et al. 2005, 2008, 2010), trophodynamic changes (phytoplankton and zooplankton) in the delta and bay caused by the proliferation of exotic species, most notably the overbite clam (*Corbula amurensis*) and Asian clam (*Corbicula fluminea*), and the expansion of invasive aquatic macrophytes (e.g., Brazilian waterweed, *Egeria densa*) affecting phytoplankton in some regions of the delta. The decline in diatoms has been attributed to excessive ammonium (Dugdale et al. 2007) and *Corbula* grazing (Alpine and Cloern 1992, Jassby et al. 2002, Greene et al. 2011).

Blooms of the colonial cyanobacteria *Microcystis* are problematic from a food-web perspective, because even though these blooms can produce large amounts of biomass, they are either avoided or not captured and assimilated by key crustacean (copepods, cladocerans) zooplankton species and invertebrate larvae that serve as a food source for numerous ecologically and recreationally important fish species (Paerl et al. 2001, Lehman et al. 2008, 2010).

Corbula amurensis, an aggressive invader, has populated the benthic regions of San Francisco Bay and the western delta to the extent where its density has reached 10,000 per m^2. Its grazing capabilities are such that it is capable of quantitatively "grazing down" phytoplankton populations (Cole et al. 1992, Thompson and Nichols 1996), which appears to have led to a state change in segments of the northern bay where phytoplankton biomass exhibited a precipitous and sustained decline coincident with the proliferation of these bivalves (Alpine and Cloern 1992, Jassby 2008; J. Cloern, presentation to the NRC, July, 2010). Finally, the expansion of invasive aquatic macrophytes (e.g., Brazilian waterweed, *Egeria*) may also play a role in the declining dominance of phytoplankton in some regions of the delta.

The same drivers that affected the phytoplankton also affected the zooplankton. In some cases, these drivers (e.g., introduced species) directly affected the zooplankton. In other cases, the driver effects were indirect, through their direct effects on the phytoplankton that support the zooplankton. The major changes in the zooplankton are described by Kimmerer in Appendix E. Nutrients, optical properties, residence time, and invasive species also affect aquatic macrophytes, such as Brazilian waterweed; these macrophytes have large ecosystem effects, as described in the next section. Changes in nutrients affect their growth (e.g., Feijoo et al. 1996, 2002).

When taken all together, the changes in the food base from top-down grazing and macrophyte competition (above) can be viewed as alternative hypotheses to the "ammonium inhibition" and more general N overenrichment hypotheses (see nutrient-enrichment section). Most likely, there are interacting environmental drivers at play in controlling the qualitative and quantitative makeup of food supplies at the base of the delta and bay food webs.

Conclusions

There is a need to distinguish changes in physical drivers such as freshwater discharge, turbidity, temperature, and vertical mixing as well as circulation, from chemical factors, such as nutrient enrichment and changes in nutrient supply ratios, and biological factors, including top-down grazing, as causative agents for changes at the base of the food web and the POD. All of these factors affect rates of primary production, standing stock, and composition of primary producers along the freshwater-to-marine continuum representing the bay-delta system. These diverse but often interacting drivers have been illustrated in the conceptual diagram presented by Meyer et al. (2009) in their evaluation of the role of ammonia/ammonium in food-web and biogeochemical dynamics of this complex system (Figure 3-6).

Drivers of quantity and quality of primary production of the bay-delta ecosystem include climate, hydrology "(including upstream water withdrawals and other flow modifications), human activity, loadings and types of nutrients (mainly N and P, from anthropogenic and natural sources), loadings and types of contaminants (including NH_3/NH_4^+, NO_2^-, metals, pesticides and algal toxins), sediment loadings, light, and food web processes (including trophic interactions, with special emphasis on invasive species)" (Meyer et al. 2009). Because they co-occur in space and time, these drivers are highly interactive, synergistically and antagonistically, and hence should be portrayed this way. These interactions are conceptualized in Figure 3-6. Meyer et al. (2009) aptly summed up the interactive nature of these environmental controls on food source and type as follows:

> These factors are interrelated in a complex web of physical, chemical and biological processes. . . . Climate and hydrologic variability are closely related factors that, in conjunction with human activity, influence and to varying degrees control many of the other drivers (e.g., delivery of nutrients and contaminants, changes in residence time). Therefore, climate/hydrologic variability and human activity are placed on the left in [Figure 3-6], with consequences of those factors cascading from left to right through all the other drivers and ecosystem components. The endpoints of major concern in this framework are changes in the Bay-Delta food web and populations of the POD organisms, as shown on the right in [Figure 3-6].

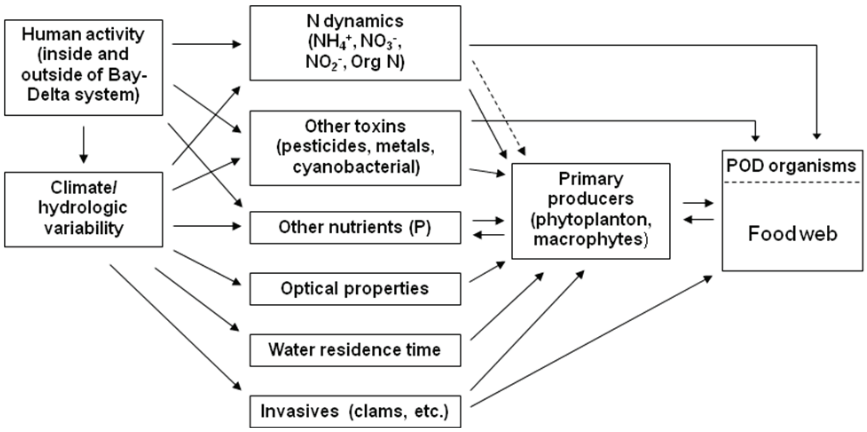

FIGURE 3-6 Conceptual framework of major drivers of water quality and ecosystem structure and function, and their relationships to the food web and POD organisms, in the Sacramento-San Joaquin Delta and Suisun Bay ecosystem. The solid arrow from the N dynamics box to the primary producers box indicates traditional processes associated with nutrient supply and uptake; the dashed arrow indicates the proposed inhibitory/competitive effect of NH_4^+ on uptake of NO_3^- by diatoms. SOURCE: Meyer et al. (2009).

Introduced Species

The bay delta has been referred to as "the most invaded estuary in the world" (Cohen and Carlton 1995). This statement focuses on rates of invasions, i.e., "one new species every 24 weeks since 1990" (Cohen and Carlton 1995). Many ecosystems have been subjected to introductions and invasions, although attention to estuaries has been relatively recent compared to freshwater and terrestrial ecosystems (Ruiz et al. 1997). Introduced and invasive species are a global problem (Lodge et al. 2006). There have been about 50,000 nonnative species introduced into the United States thus far; some have been beneficial.

The many species invasions into the bay and delta are not a new problem, but their effects on the ecosystem seem to be increasing. Before 1870, most nonnative species arrived as fouling organisms attached to ships, which is no longer a major problem. Striped bass, which include delta smelt and juvenile salmonids in their diet, were brought by train from the eastern United States and deliberately introduced in the 1870s (Lampman 1946). From 1870 to the early 1900s, other Atlantic species were brought from eastern North America by train and planted in San Francisco Bay; they include oysters, American eels (*Anguilla rostrata*), lobsters (*Homarus americanus*), and American shad (*Alosa sapidissima*) (Lampman 1946).

Although the oysters, lobsters, and eels did not become established, many nonnative species associated with the oysters did become established (Ruiz et al. 1997). Since then, nonnative species have been largely introduced from ballast water. There was a rapid increase in introduced species beginning in the 1940s when ships converted from dry ballast to wet ballast (Thompson 2005). Some invasive[10] species arrived, appeared to be increasing, and have since disappeared; *Sinocalanus* spp. was introduced in 1978 and reached high levels (Orsi et al. 1983) but had dropped in abundance by about 1990 (Winder and Jassby 2011).

Other invasive species have persisted and some have become dominant in the bay and delta. Nearly all common macroinvertebrates present in inner shallows of the bay are introduced species (Nichols et al. 1986). The Asiatic freshwater clam is prevalent in the freshwater areas of the upper delta (Jassby 2008), and the green crab (*Carcinus maenas*) invaded the bay in 1989-1990 (Cohen et al. 1995). Other examples include Brazilian waterweed, whose areal coverage increased more than 10 percent per year from 2004 to 2006 (Baxter et al. 2010), and largemouth bass (*Micropterus salmoides*), whose abundance followed that of Brazilian waterweed (Brown and Michniuk 2007). In addition, the frequency of *Microcystis aeruginosa* blooms (native to the bay and delta) have increased since 1999, concentrated in the freshwater of the central delta during summer (Lehman 2010), and also have affected community composition.

A series of studies has documented the high degree of establishment of nonnative species within the fish community. Feyrer (2004) examined larval fish composition during 1990-1995 in the south delta region and captured 15 species or taxonomic groups, with 3 comprising 98 percent of the total catch by number. The three most abundant species were the alien Asian shimofuri goby (*Tridentiger bifasciatus*) (71 percent), nonnative eastern and central U.S. threadfin shad (15 percent), and the native prickly sculpin (*Cottus asper*) (12 percent). Grimaldo et al. (2004) also sampled fish larvae but in four marsh sites in the central delta. They also found that nonnative species dominated the catch, with threadfin shad, members of the sunfish family (Centrarchidae), and inland silversides (*Menidia beryllina*[11]) accounting for about 60 percent of the catch. They suggested that the extensive colonization by the nonnative Brazilian waterweed provided good habitat for Centrarchidae (fishes of the sunfish family). Brown and May (2006) examined juvenile and adult fishes through the Sacramento–San Joaquin Delta and found that the overall catch was 59 percent nonnative

[10] "Invasive" species are nonnative species that not only become established but become major components of the ecosystem.

[11] This species is designated by some as *M. audens*, the Mississippi silverside, but we follow AFS (2004) here, as in other fish names.

species, with 93 percent nonnative in the San Joaquin River and 89 percent in the interior delta.

Corbicula amurensis is an example of an invasive species of clam that subsequently caused major shifts in the bay-delta ecosystem. These shifts then act as stressors on the listed fish species. *C. amurensis* spread in the delta after its introduction in 1986. Nichols et al. (1990) documented how in Suisun Bay the arrival of the clam was correlated with the loss of the dry-period benthic community, despite periods of low flow since the invasion. Winder and Jassby (2011) described how since the invasion chlorophyll *a* decreased in Suisun Bay and shifted from diatoms to a higher proportion of chlorophytes, flagellates, and cyanobacteria.

The effects of *C. amurensis* on zooplankton and fish were not as clear as their effects on benthos and phytoplankton. Zooplankton biomass generally declined in the area from Suisun Bay to the central delta over the 1972-2008 period, with some suggestion of declines in particular zooplankton taxa in the delta subregion during the 1980s with the arrival of *C. amurensis* and an extended drought period (Winder and Jassby 2011). Kimmerer (2002) performed a similar analysis as Winder and Jassby but focused on certain key zooplankton taxa and also included fish. He examined the effects of flow as well, contrasting before and after the *C. amurensis* invasion. Chlorophyll *a* decreased between before and after *C. amurensis*, and there were species substitutions within the zooplankton that offset species-specific losses and thus dampened the decrease at the total biomass level. *Pseudodiaptomus affinis* replaced *Eurytemora affinis*, and introduced mysids partially offset the loss of *Neomysis mercedis*. Despite changes in zooplankton, striped bass survival was not related to the appearance of *C. amurensis*. Kimmerer (2006) further analyzed an expanded version of the data and suggested that the summer decline in northern anchovy in the low-salinity region was due to their movement out of the area in response to lowered food availability. Diets of other fish species have also responded to the invasion of *C. amurensis* (Feyrer et al. 2003, Nobriga and Feyrer 2008, Grimaldo et al. 2009a). How these changes in zooplankton composition and diet, and displacement to other areas, have affected fish at the population level is difficult to quantify.

Recently, Glibert and colleagues (Glibert 2010, Glibert et al. 2011) analyzed the long-term data and concluded that changes in nitrogen (concentrations and ratios) were also coincident with some of the changes in chlorophyll *a* and some key zooplankton species such as *E. affinis*. They interpreted their results as being a more consistent explanation in terms of timing of declines than the invasion of *C. amurensis*. However, the matter is not settled (e.g., Cloern et al. 2012). Nonetheless, the analysis of Glibert and her colleagues illustrates the difficulties in attributing dynamics in a complex food web to single stressors, such as species invasions or changes in a single nutrient.

Conclusions

There is no doubt that nonnative species have affected delta smelt and other fish species listed under the Endangered Species Act. The changes in habitat (e.g., spread of Brazilian waterweed), zooplankton biomass and composition, and predator mix and abundances (e.g., striped bass and largemouth bass are piscivores) have been dramatic, and it is intuitive to look at these changes and infer that such large changes must have had effects at the population level of the fish species. However, such arguments are insufficient for conclusive statements because of the complexity of the linkages between population responses and changes in habitat, food, and predation (Rose 2000). At present, we cannot determine the magnitude of these effects because the relationships among invasives, other stressors, and the listed fish species population responses are complex. Some nonnative species have been present in the ecosystem for more than a century. Some species invasions were localized regionally, preventing easy extrapolation to the fish population level. Also, the invasive species can interact with other stressors, which also are affected by other factors than invasives. The linkage between introduced species and fish species of interest is often due to physical alterations of habitat, shifted food base, or changed predation pressure, and we lack the data or models to make these linkages quantitative. Several analyses have included covariates related to introduced species in the analysis of POD species declines but without definitive conclusions (discussed further below).

Nonnative species as a stressor will continue into the future and likely will become a more prevalent issue. There will be increasing human population and more shipping traffic. Overlaid on these trends are the possibility of large-scale levee failures, sea level rise, and climate change altering the ecosystem and creating new opportunities for invasive species (Moyle 2008).

Nonnative species constitute a stressor that is mostly beyond the control of humans. Prevention is the key but prevention is expensive, requires extensive local, national, and international cooperation, and is risk based. Most introduced species do not become established, but even preventing 95 percent of potential invaders from arriving might be insufficient, because 5 percent could be enough for sufficient inoculations to lead to an invasion. Most legal instruments focus on preventing introductions (Williams and Grosholz 2008). Eradication of some plant species, once they have invaded, is possible, but controlling aquatic animal species, especially mobile species, is not practical. Williams and Grosholz (2008) argue that it is feasible to control invasive species in marine systems. Interestingly, their examples of successful eradication were plants or generally sessile organisms; no zooplankton or fish examples were given. As inexpensive and convenient control measures become available, they should be evaluated. One example is the use of nitrogen gas to kill organisms in ballast water, which is inexpensive and has the additional benefit of reducing corrosion (Tamburri et al. 2002). But for the most part, introductions and invasions will continue to be a feature of the bay-delta ecosystem and likely will interact with existing stressors (e.g., further changes in the zooplankton community) and might lead to the development of new stressors (e.g., disease).

Early detection is critical, because even if we cannot control the outcome, we can at least make adjustments in monitoring and prepare for possible ecological effects. Introductions will continue, and it is very likely that some of these will lead to successful establishment. Furthermore, also it is likely that a few of these establishments will significantly alter the ecosystem. Such changes to the ecosystem can put endangered species at additional risk and reduce or eliminate the positive effects of management actions. Preparation should involve identifying the likely types of invaders and their possible effects on the ecosystem. Methods exist for identifying vulnerabilities to invasions in ecosystems (Lodge et al. 2006), and the long history of introductions and successful invasions of the bay-delta ecosystem can provide a test bed for evaluating the various vulnerability models. If the possible types of likely invaders and subsequent alterations to the bay-delta ecosystem alterations can be grouped and generalized with some confidence, then some form of contingency planning might be appropriate. Planning can include changes to the monitoring program to allow for earlier detection, and adjustments to planned management actions to prepare for possible ecological effects if such changes occur.

Toxic Chemical Contamination

Chemical contamination is recognized in all plans for the future of the bay delta as a stressor, one of the threats to native and listed species and a factor in regional-scale ecological changes (Healey et al. 2008b). Contamination is not a single issue. There are many contaminants, many of which pose risks to different species, in different locations, or at different spatial and temporal scales. Chemical contamination is historically well documented in the San Francisco Bay Delta compared to many coastal environments (e.g., Luoma and Phillips 1988, van Geen and Luoma 1999, Hunt et al. 2001, Kuivila et al. 2008, Weston and Lydy 2010, Davis et al. 2011). Conceptual models describing processes important in the ultimate impacts of some aspects of chemical contamination were developed for the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) process (see p. 128). Nevertheless, recent reviews of the pelagic organism decline concluded either that data are insufficient to demonstrate whether contaminants have adverse impacts in nature (Johnson et al. 2010) or that "ecological effects of contaminants remain unquantified, and are difficult to investigate with standard methods based on acute toxicity" (Brooks et al. 2012).

One problem is that the complexities of the responses of individuals and populations to contamination make it difficult to unambiguously link environmental contamination to specific ecological responses (Luoma and Rainbow 2008, Brooks et al. 2012). Powerful technologies exist to effectively determine concentrations of many potentially toxic chemicals in nature. But because of the limitations of toxicity testing, the complexities of chemical behavior in the environment, and complexities of biological responses, it is difficult to predict with accuracy the concentration thresholds at which local sensitive species will begin to disappear in nature.

A complex combination of considerations determine if chemical contamination is going to be influential in nature:

- the specific chemical's toxicity, persistence, and tendency to enter food webs;
- the concentration and interactions of that chemical in the environment;
- the spatial scale over which concentrations of contaminants are elevated;
    - many localized hot spots can be as important as region-wide contamination;
- the risks to communities and ecosystem functioning, as determined by differences among species in their
    - physiological tolerance,
    - exposure as determined by functional ecology,
    - genetic flexibility,
    - demographic plasticity, and
    - role in the community (keystone species or important prey species); and
- the time it takes for chronic exposures and subtle effects to manifest themselves as ecological change.

Another issue is that studies of contaminants in nature that include adequate chemistry, biology, and ecology to evaluate impacts are difficult, rare, and considered inadequate evidence by some (Luoma and Rainbow 2008). Fragmented regulatory approaches (see Chapter 5) and important fundamental differences among research disciplines contribute to a lack of synthesis between ecology and ecotoxicology (Luoma and Rainbow

2008). For example, correlative analyses designed to address causes of the most dramatic ecological changes or change points in the bay delta did not even consider toxic chemicals (Dugdale et al. 2007, Sommer et al. 2007, Thomson et al. 2010). Thomson et al. (2010) state that "[c]ontaminants are too numerous and dispersed, and effects too sporadic and subtle, for any monitoring program to provide useful information for correlative analyses. Thus, these effects must be investigated through more detailed, mechanistic studies."

Despite these challenges, San Francisco Bay is also one of only a few estuarine locations where site-specific ecological impacts from contaminants have been clearly shown in the field. Most obvious is the general observation that since the 1980s, visible impacts of contamination have declined along with concentrations of chemicals in the environment (as the Clean Water Act was implemented). Fish kills that occurred almost once per day in the bay and its tributaries in the 1980s, despite a lack of eutrophication, are now rare (Luoma and Cloern 1982, Brooks et al. 2012). Top predators (e.g., striped bass), which once commonly contained lesions consistent with organic contaminant effects (Luoma and Cloern 1982), have recovered their health. Finally, spatially broad detection of toxicity in standard toxicity tests in the waters of the delta and the major rivers are less frequent than earlier.

Populations of piscivorous birds that were near local extinction because of reproductive failures are recovering. Several more-specific studies meet the criteria for demonstrating cause and effect with reasonable certainty, including minimization of confounding variables (Brown et al. 2003). Long-term studies of the metals silver and copper began when contaminant concentrations were elevated in the 1970s and followed recovery of benthic species and the associated community as metal concentrations in the organisms declined into the 1990s (Hornberger et al. 2000, Brown et al. 2003). Potentially toxic tissue concentrations of selenium in predatory fish and birds were linked with controlled studies of toxicity to show why selenium affects reproduction in benthic rather than pelagic food webs, and that important benthic predators in San Francisco have sufficient exposure to selenium to produce such effects (Stewart et al. 2004, Presser and Luoma 2006). A well-designed ecological study of multiple stressors showed how mercury impacts reduce shorebird reproduction (Schwarzbach et al. 2006). Careful field applications of sensitive in situ toxicity tests showed that pyrethroid pesticides affect the benthos of stream ecosystems (Weston and Lydy 2010). They also demonstrated the frequency of potential contaminant stress on benthos from contaminated sediments in the bay (Hunt et al. 2001). Careful use of control sites and test sites also showed how polychlorinated biphenyls (PCBs) continue to affect benthic communities (and probably their predators) at an area of high PCB concentration in the bay (Janssen et al. 2011).

These lines of evidence suggest that toxic chemicals, at least at concentrations typical of the 1980s and before, affected individuals and populations of some species, and probably the structure of some communities in the bay delta. Although it is more difficult to identify ongoing effects, it is reasonable to assume recovery from the past is not complete where chemical contamination has declined but not returned to background levels, and that contaminants cannot be eliminated as a stressor of some influence.

It is difficult to rank the importance of contaminants compared to other stressors for the reasons already discussed. But it is possible to be more specific about how contaminant impacts might differ among themselves. If we use specific criteria as defining risk, it is possible to evaluate the degree of that risk, and what contaminant, organism, locality, environmental condition, or season that risk applies to. Similarly, using defined criteria and mechanistic understanding, it is possible to compare how different groups of organisms might respond to different types of contamination risks.

Thus, risks from contaminants must be considered chemical by chemical, with attention paid to the species at risk and the distribution of the contamination. Although it sounds complex, recognizing this principle actually simplifies conclusions about contaminants. Table 3-2, for example, compares risks among different groups of contaminants. Concentrations, toxicity, bioaccumulation potential, spatial distribution, and trends are used as criteria to define the most important issues.

Trends are used as a criterion because the future contamination issues include those that have not been at least partly solved by historical approaches to remediation. Industrial relocation and large investments in waste treatment during the past four decades reduced, but did not eliminate, some of the most serious sources of toxic contamination from the bay delta (e.g., see special issue of *Marine Chemistry* edited by van Geen and Luoma (1999); Squire et al. 2002). While some areas with high concentrations of contamination remain (e.g., Janssen et al. 2011), the number of such problems is also reduced. But risks are not declining for some contaminants and, for others, risks could increase or trends are not understood (Table 3-2). Spatial criteria are used because contaminants affecting only a few areas of high concentration create less ecological risk to the system than contaminants with a wider geographical influence. Using these criteria and the perspective of chemical class, Table 3-2 indicates the highest risks to the bay-delta ecosystem are posed by selenium, mercury, and pesticides.

In the 1980s, deaths and deformations in birds, along with the local extirpation of aquatic species, accompanied the disposal of selenium-rich irrigation drainage from the western San Joaquin Valley into the Kesterson National Wildlife Refuge. The linkage between selenium contamination and

TABLE 3-2 Contaminants That Have the Greatest Potential for Risks to Bay-Delta Ecosystems as Determined from Their Concentrations, Toxicity, Bioaccumulation Potential, and Trends[a]

Contaminant	Trends	Location	Potential measures
Selenium[b]	No trend. Potential upward because of high potential for further inputs from the western San Joaquin Valley.	San Joaquin River through Suisun and San Pablo bays. Effects on sturgeon and waterfowl in Suisun/San Pablo bays	In-valley solutions in western San Joaquin Vally. Consider San Joaquin River inputs to bay when evaluating infrastructure changes.
Methylmercury[b]	No trend. Potential upward if marsh restoration exacerbates methylation.	bay-delta-wide. Effects on birds in South Bay.	Control Hg methylation potential in restored wetlands.
Pesticides/ herbicides[c]	Unknown. High usage continues.	Worst effects in local sloughs and urban streams and rivers. Enough stress points to make this a regional problem? Pesticide squeeze.	Best management practices (orchard pesticide example; Werner et al. 2004).
Emerging chemicals (pharmaceuticals, etc.)[c]	Upward? Little spatial information.	Localities influenced by poorly treated urban wastes.	Waste treatment.
Metals (Ag, Cd, Cu, Pb, Zn, V, Ni, Cr)[d]	Downward: 1970-2000. Stable recently.	Urbanized areas. Mine impacted areas upstream. Perhaps delta islands where Cu is in herbicides.	Sustain point source waste treatment. Remediate mine wastes impacts.
Legacy organic contaminants and PAHs[d]	Downward. No trend for PAHs.	Urbanized areas.	Clean up legacy hot spots, especially in bay.

[a]Locations and food webs at risk are also shown (these differ among contaminants), as are potential measures for managing these risks.
[b]High certainty that this is an important stressor with potential for increased problems in the future. Long-term need for increased management.
[c]Pockets of contamination exist with high certainty of adverse ecological impacts. Uncertainty as to whether enough stress points exist in time and space to make this a regional-scale stress. Need for long-term improved management is certain.
[d]Temporal trends show these potential stressors have declined in recent decades, although concentrations of most remain moderately elevated. Sustained management is essential.
NOTE: PAH, polycyclic aromatic hydrocarbon.

toxicity to wildlife was unambiguous at the Kesterson National Wildlife Refuge.

A very large reservoir of selenium exists in the soils of the western San Joaquin Valley associated with the salts that accumulated there during decades of irrigation (Presser 1994). Irrigation drainage, contaminated by selenium from those soils, is also accumulating in western San Joaquin Valley groundwaters. The problem is exacerbated by the recycling of the San Joaquin River when water is exported from the delta. While control of selenium releases into the San Joaquin River from the valley soils has improved, how long those controls will be effective is not clear because of the selenium reservoir in groundwater.

Some potential solutions could create more problems than they solve. For example, proposals to dispose of the contaminant outside the San Joaquin Valley in the bay or in the oceans could exacerbate ecological risks there (Presser and Luoma 2006). Other aspects of water management also could affect selenium contamination. For example, infrastructure changes in the delta such as construction of an isolated facility could result in the export of more Sacramento River water to the south, which would allow more selenium-rich San Joaquin River water to enter the bay. The solutions to selenium contamination must be found within the Central Valley and the risks from selenium to the bay are an important consideration in any infrastructure changes that affect how San Joaquin River water gets to the bay.

Organochlorine pesticides like DDT were unquestionably a cause for the near extirpation of piscivorous bird populations in the bay delta in the 1970s and 1980s. More recently, pesticide toxicity that was once dominated by water column effects attributable to pesticides like carbamates has switched to contaminated sediments as the dominant class of pesticides has switched to pyrethroids (Weston et al. 2005). Benthic food webs dependent for a part of their life cycle on urban streams, sloughs, as well as floodplains, and streams or rivers that receive direct runoff from cities or agricultural fields, appear to be at risk from the growing use of this class of pesticide. Because sediment-bound pesticides enter aquatic systems with the high sediment concentrations that accompany the first flush of agricultural fields and urban landscapes, species that are mobilized during such a period (e.g., delta smelt) may also be more at risk. The sensitivity to pyrethroids of native species, the spatial distribution of the contamination, its seasonality, its food-web dynamics, and effects on community structure and function are not as well known as they need to be. But pesticides are an important stressor in at least some localities.

Concerns about mercury stem from a historic legacy of widespread mercury contamination north of the delta (Suchanek et al. 2008, Bouse et al. 2010); efficient biomagnification of methylmercury in food webs; high toxicity of methylmercury to reproduction of upper-trophic-level species;

threats to the health of people that consume certain species of fish from the watershed (Greenfield et al. 2005); and the possibility that restoration of wetlands could exacerbate the methylation of mercury in sediments.

Green sturgeon (*Acipenser medirostris*) appears to be the species most at risk from chemical contamination. Sturgeon tissues contain higher concentrations of selenium and mercury than any other fish species, reflecting their position as a top predator in the benthic food web (Stewart et al. 2004). This may also result in greater exposure to bioaccumulative organic contaminants, such as PCBs and perhaps some emerging chemicals of concern. Because green sturgeon is a long-lived, slowly reproducing species, populations are vulnerable to chemical disruption of reproductive processes (typical effects of selenium and mercury). The few analyses of sturgeon populations consistently fail to mention contaminants in the list of sturgeon stressors; an illustration of the scientific disconnect between ecology and ecotoxicology (Luoma and Rainbow 2008).

Risks from mercury provide an example of the complexity of ranking contaminants as a stressor. Schwarzbach et al. (2006) showed that mercury contamination exacerbated low reproduction potential in the endangered California clapper rail (*Rallus longirostris*), a shore bird in the south bay. Loss of habitat is the most important stressor for the clapper rail in the bay. Within the existing habitat, however, Schwarzbach et al. (2006) first considered how nests of the species were affected by predation and flooding. After those effects were accounted for, the nests most contaminated with mercury had the lowest reproductive success rate. Thus, mercury is not the only stressor for clapper rails, but it is one of the stressors holding back recovery of this endangered species. Runoff into South Bay from the historic New Almaden mercury mine is the source of contamination in this ecosystem. More important, a large area of wetlands undergoing restoration in the south bay receives freshwater from the stream that drains the catchment containing this mine. Because methylmercury production is amplified in wetlands, and at least some historic sources continue to release mercury (Suchanek et al. 2008), adding wetland habitat could result in an expansion of the mercury problem in the delta.

Conclusions

Contaminants are not a single ubiquitous stressor in the delta as much as they pose risks that differ among the chemicals, among species, among locations, and among seasons or even years. In no case is it clear that "contaminants" are the sole cause of large-scale ecological change in the delta at present. On the other hand, contaminant stress was likely an important factor in piscivorous birds and benthic communities near outfalls (Hornberger et al. 1999) and fish that were resident in urban streams before the 1990s (Luoma and Cloern 1982). When implementation of the Clean Water Act began to take effect, however, at least some of the most concentrated contamination was reduced and some of these effects were reversed (Hornberger et al. 1999). In addition, contaminants cannot be eliminated as one of the several causes of some of the ongoing changes in today's delta like the apparent continuing decline of white sturgeon populations, poor reproduction in certain shore birds, and simplification of benthic communities in streams affected by urban runoff. In addition, it is not clear that sustainable solutions are in place to reduce the effects of contaminants like selenium, mercury, and pesticides and some proposed changes could even increase risks. Nor are there sufficient data to fully understand the implications of some new classes of emerging contaminants. Ranking contaminants relative to other stressors will vary with the perspective of the ranking body. Given the complexities described above, that is probably not a constructive exercise. However, continuing to better understand and address the most important contaminant issues should remain one of the priorities in managing the delta ecosystem.

Impediments to Fish Passage

Impediments to fish passage take a variety of forms. NMFS (2009a,b) applies the term in a broad sense to include structures and actions that can interfere with fish movement through a migratory corridor. This can include dams, unscreened water diversions or pump intakes, and a variety of anthropogenic actions that can produce thermal barriers or other water-quality problems. For this discussion we define passage impediments as structures (e.g., dams) and actions (e.g., diversion of water and pumping facilities) that block or remove fish from the migratory corridors upstream from the delta. Impediments have a range of effects, from slowing the migration by delaying passage, removing fish from the migration corridor to encounter hazardous conditions, or completely blocking access to productive habitat.

Dams as Absolute Barriers

One prevalent form of passage impediment in the Central Valley is dams that form absolute barriers to migrating fish, in that they have neither ladders for adults nor bypass systems to pass seaward-bound smolts. Dams have been built for a variety of purposes, including hydropower, flood control, irrigation, and municipal uses. Many have permanently blocked or hindered salmonid access to historically productive spawning and rearing grounds and have dramatically truncated the freshwater habitat accessible to anadromous salmonids and sturgeon. These impacts were evident more than 80 years ago when Clark (1929) estimated that 80 percent of this habitat for these species in the Central Valley had been lost by 1928. More recently Yoshiyama et al. (1996) estimated that 82 percent of the historical salmon habitat is now inaccessible. NMFS (2009b) suggests that the extent of habitat loss for steelhead (*Oncorhynchus mykiss*) may be even greater, since they had a broader geographic distribution than Chinook salmon.

As a result, winter-run and spring-run Chinook salmon, and steelhead populations, are confined to lower-elevation portions of many tributaries as well as the mainstem Sacramento and San Joaquin rivers (NMFS 2009a, b). Overall this decrease in the quantity and quality of spawning and rearing habitats has reduced fish abundance (Lindley et al. 2009). The reduction of a habitat type not only limits potential carrying capacity but also negatively affects the population structure of anadromous fish, by reducing the number of independent population units. Lindley et al. (2004) note that only one population of winter-run Chinook now exists, restricted to a confined temperature-regulated zone below Keswick Dam. They suggest that historically four separate populations inhabited the Central Valley. Spring-run Chinook salmon have incurred the same fate, with only 3 of 19 historical independent populations remaining. Lindley et al. (2006) estimate that no fewer than 81 independent steelhead populations once existed in the Central Valley.

The southern distinct population segment (DPS)[12] of green sturgeon incurred a similar fate. One population is currently confined to a single spawning area in the upper mainstem Sacramento River. Historically spawning habitat likely extended upstream from the current site into the Little Sacramento, Pitt, and McCloud rivers (Adams et al. 2007). Green sturgeon may also have spawned in the Feather River, upstream from Oroville Dam.

Viable Salmonid Populations (VSP)

The reduction in population complexity associated with migratory barriers affects not only fish abundance by limiting the quantity of suitable habitat but also ultimately the probability of the species persisting in the Central Valley. The Viable Salmonid Populations (VSP) framework (McElhany et al. 2000) provides a foundation for discussing these impacts. The VSP parameters of productivity, abundance, and population spatial

[12] The Endangered Species Act (ESA) defines the term "species" as including "any subspecies of fish or wildlife or plants, and any distinct population segment of vertebrate fish or wildlife which interbreeds when mature" (Section 3 (15)). A DPS is thus a smaller evolutionary unit than a species or subspecies. (If a DPS is the whole species, then it is called a species and not a DPS.) For more detailed discussion of this term, see NRC (1995).

structure are key indicators of a species' resilience and likely viability. Reduction in the values of these parameters is associated with a loss in genetic or life history variability. Ultimately this results in reduced population resilience to environmental variation at local and basin-wide scales.

The committee concludes that the dams that act as absolute barriers, which have eliminated access to nearly 80 percent of the historical habitat, have been, and continue to be, a major stressor limiting the recovery of ESA-listed anadromous fish species in the Central Valley. The effects include limiting abundance and productivity associated with severe habitat loss, and the pronounced reduction of genetic diversity through extirpation of the vast majority of unique populations once present in the system (e.g., NRC 1996).

Dams as Partial Barriers

The Red Bluff Diversion Dam (RBDD) is owned and operated by the Bureau of Reclamation. It is located 59 miles downstream of Keswick Dam. For decades until 2011, the dam blocked or delayed adult salmonids and sturgeon migrating upstream to various degrees, depending on run timing and configuration of the dam during the different migratory periods (CDFG 1998, Vogel et al. 1988). Dam operations affect both juvenile and adult life stages of salmonids, and sturgeon. The intent is that after May 2012 the gates will be permanently opened and irrigation water will be provided by pumps (USBR 2011).

The Anderson-Cottonwood Irrigation District (ACID) diversion dam spans the Sacramento River 5 miles downstream from Keswick Dam. It is one of the three largest diversions on the Sacramento River, and the ACID has senior water rights of 128,000 acre-feet of water. The diversion dam is operated from April through October. Substantial reductions in water releases from Keswick Dam are required to install or remove the flashboards at the dam. This operation has dewatered redds, and stranded juveniles. However, the reductions in flows usually last for less than 8 hours, but the amount of mortality due to dewatering of incubating eggs and stranding juveniles is uncertain. Even so, this constitutes a risk to early life stages. Based on run timing, the diversion dam operations could affect winter-run, spring-run, and fall-run Chinook and green sturgeon (Table 3-3).

The ACID diversion dam was improved in 2001 with the addition of new fish ladders and fish screens around the diversion (CDFG 2004). Since upstream passage for salmonids was improved, winter-run Chinook spawning shifted upstream with more than half of the winter-run redds typically observed above the ACID diversion dam. The majority of winter-run in recent years (i.e., > 50 percent since 2007) spawn in the 5 miles of river from Keswick Dam downstream to the ACID dam (NMFS 2009b). Nevertheless, the ladders do not accommodate green sturgeon, and thus the migration is completely blocked during a portion of the migratory period (Table 3-3). Newly emerged green sturgeon larvae that hatch upstream of the ACID diversion dam would be forced to remain for 6 months upstream of the dam or pass over it and be subjected to higher velocities and turbulent flow below the dam, thus rendering the larvae and juvenile green sturgeon more susceptible to predation.

Given the paucity of quantitative studies of survival probabilities associated with passing or operating seasonally passable dams, we cannot determine the extent to which they have contributed to the decline of the ESA-listed anadromous species in the Central Valley. Even so, we suspect the effect was historically pronounced, has diminished in the past decade, and may diminish further as new operations are developed.

Smaller Water Diversions

Apart from the larger dams that span the mainstem or major tributaries, a complex of smaller water diversions for irrigated agriculture, municipal and industrial use, and managed wetlands are found throughout the Central Valley. According to NMFS (2009a), thousands of small and medium-size water diversions exist along the Sacramento River, San Joaquin River, and their tributaries. Many remain unscreened. Herren and Kawasaki (2001) reported that 98.5 percent of the 3,356 diversions included in a Central Valley database were either unscreened or inadequately screened.

Unscreened diversions put juvenile fish at risk by removing them from the rivers, thus contributing to mortality during their rearing phase or seaward migration. Although actual entrainment rates are not cited, NMFS (2009a) states that the CVP/SWP operations Biological Assessment (USBR 2008) provided calculations of estimated entrainment of salmonids through unscreened diversions along the Sacramento River. According to the calculations, over 7,000 juvenile winter-run are lost to unscreened diversions annually. Beyond this we have not encountered reliable estimates of population-level effects on any anadromous species, as associated with entrainment by water diversions. NMFS (2009a) notes that estimates of the mortality at unscreened diversions in the Sacramento River are small, but the cumulative impact is likely to affect ESA-listed species at the population level. NMFS (2009a) also notes that most, but not all, large diversions are screened. To guide future fish screening projects, the Anadromous Fish Passage Program is focusing on monitoring losses at smaller unscreened diversion. NMFS (2009a) concludes that the combined mortality from all screened diversions in the Sacramento River is insignificant at the population level for the ESA-listed species. However, Moyle and Israel (2005) note the paucity of information regarding population-level effects of diver-

TABLE 3-3 Life History Timing for Anadromous Fish Species in the Upper Sacramento River

Species	Adult Immigration	Adult Holding	Typical Spawning	Egg Incubation	Juvenile Rearing	Juvenile Emigration
Winter-run Chinook	Dec – Jul	Jan – May	Apr – Aug	Apr – Oct	Jul – Mar	Jul – Mar
Spring-run Chinook	Apr– Jul	May – Sept	Aug – Oct	Aug – Dec	Oct – Apr	Oct – May
Fall-run Chinook	Jul – Dec	n/a	Oct – Dec	Oct – Mar	Dec – Jun	Dec – Jul
Late fall-run Chinook	Oct – Apr	n/a	Jan – Apr	Jan – Jun	Apr – Nov	Apr – Dec
Steelhead Chinook	Aug – Mar	Sept – Dec	Dec – Apr	Dec – Jun	Year round	Jan – Oct
Green sturgeon Chinook	Feb – Jun	Jun – Nov	Mar – Jul	Apr – Jun	May – Aug	May – Dec

SOURCE: Reproduced from Table 5-1 in NMFS (2009a).

sions in the Central Valley and conclude that screen diversions may have population-level effects.

The weight of evidence—or in this case lack thereof—indicates that the impacts of screened and unscreened water diversion on anadromous fish are poorly described and certainly not quantified in any meaningful manner. Given this, the contribution of this class of stressors to the decline of anadromous fish in the Central Valley is unknown. A thorough evaluation of water diversions within the active migratory corridor is warranted.

Delta Pumps and Related Flow Effects

The committee fully appreciates the complexity of mechanisms and negative impacts that the SWP and CVP pumping operations have on juvenile salmonids in the vicinity of the delta. The National Research Council's (NRC's) 2010 report on the delta (NRC 2010) noted that, in addition to direct effects associated with entrainment at the pumps, there are indirect effects associated with predation within the labyrinth of delta channels. The dynamics is further complicated by magnitude and timing of OMR flow (NRC 2010).

The committee accepts the conclusion that pump operations pose a risk to juvenile salmonids. The survival of salmonid smolts migrating through the delta is low. Several studies make this point. Recently, Michel (2010) used acoustic-tagged late-fall Chinook yearling smolts to estimate survival from the upper Sacramento River (Battle Creek) to the mouth of San Francisco Bay. Expressing survival in each segment in terms of survival per 10 km of migration distance, he found low survival in the upper Sacramento River from the release site to near Butte City (92.4 to 96.8 percent/10 km) and through the delta zone (93.7 percent/10 km). The lowest survival occurred through the San Francisco Bay estuary immediately west of the delta (67.0 to 90.2 percent/10 km). Based on these results, survival of yearling Chinook salmon through the delta is estimated to be 52.5 percent (±3 S.E). In support of this estimate, Perry et al. (2010) reported delta survivals of Coleman hatchery-origin late fall–run Chinook salmon smolts of 35 percent (±10 S.E.) and 54 percent (±7 S.E.) in December 2006 and January 2007, respectively. In contrast, Michel estimated total survival from release in the upper Sacramento River to the mouth of the San Francisco Bay was an order of magnitude lower, ranging from 3.1 to 5.5 percent. Michel also noted that this total survival (which includes the delta segment) was substantially lower than published values for other west coast yearling Chinook. Notably, it is an order of magnitude less than that typically reported for yearling Chinook smolts migrating past eight dams in the Snake Columbia River system.

It was not possible to ascertain from these data the magnitude of direct and indirect effects associated with pump operations as smolts migrated through the delta. Nevertheless, visual inspection of the survivorship curve by Michel (2010) suggests that on average perhaps 20 to 30 percent of the smolts died while migrating through the delta zone as delineated in that study. These losses are substantive and are at least in part attributable to pump operations that alter current patterns into and through the channel complex, drawing smolts into the interior waterways and toward the pumps.

Statistical analysis of tagged hatchery releases recovered at Chipps Island or the ocean fishery have shown negative associations between pump export volume and relative survival. However, the variation in relative survival was very large (Newman and Rice 2002; Newman 2003, 2008).

The mortality of smolts migrating out of the San Joaquin River drainage and through the delta is also pronounced. Recent studies using San Joaquin River fall Chinook salmon smolts estimated survival between 5 and 8 percent as smolts migrated through the south delta, Old River, and reaches leading to the pumps (San Joaquin River Group Authority 2010). Furthermore, preliminary survival information has suggested that San Joaquin fish collected at the south delta pumps and transported out of the delta had higher, but still very low, survival than fish that migrated through the San Joaquin River (R. Buchannan, personal communication to J. Anderson). The committee recognizes that these estimates are for one salmon species only and others may exhibit different responses. However, at this juncture these estimates provide the best available population-level index of impacts associated with passage past and through the delta during periods of pump operations.

Strategies for mitigating the impacts of mortality of juvenile salmon passage through the delta are likely to differ for Sacramento and San Joaquin runs because of the differing routes through the delta. The Sacramento fish can avoid the higher mortality of the central delta altogether by entering the Yolo Bypass when it floods (Figure 3-7, ❶) or by passing through the lower Sacramento when the Delta Cross Channel is closed (Figure 3-7, ❷). In contrast, juvenile fish migrating through the San Joaquin are either routed directly through the delta (Figure 3-7, ❸) or toward the south delta pumps (Figure 3-7,). It has been generally believed that routing fish away from the pumps is undesirable (route ❸ preferred over ❹), which has been the main justification for closing the barrier at the head of the Old River. However, recent studies have suggested that survival through Old River with collection at the pumps and transport out of the delta may provide better, although still low, survival than when routing fish through the main channel (route ❸). Possible reasons for this surprising conjecture may involve differences in predator densities in the routes as well as differences in tidal influences on passage. Juveniles may experience multiple encounters

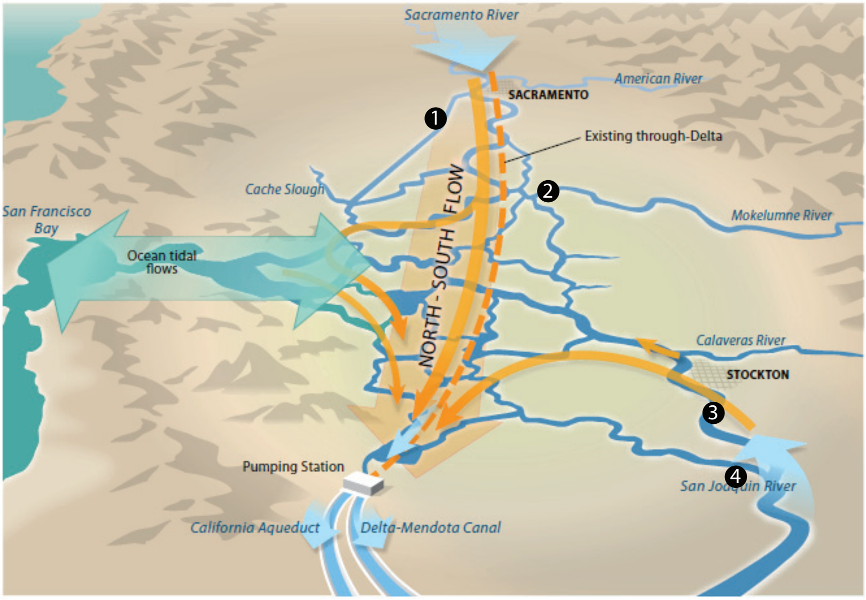

FIGURE 3-7 Alternative routes of passage of Sacramento and San Joaquin salmon through the delta. Sacramento River fish diverted into Yolo Bypass avoid the central delta ❶, while those not entering Yolo are susceptible to entering the delta ❷. San Joaquin fish either pass through the delta in the main stem of the river ❸, or enter the Old River to be drawn to the pumps where the survivors are collected and transported out of the delta ❹.
SOURCE: California Natural Resources Agency (2010).

with predators as they migrate through the delta and are displaced back and forth by the tides. In contrast, fish moving with the flow toward the pumps may experience weaker tides and thus fewer multiple encounters with predators (Anderson et al. 2006). The salient point is that survival of fish through the San Joaquin system is complex and further survival studies are needed to evaluate what actions might be most effective in improving their passage through the delta.

The available data based largely on Michel's (2010) and the San Joaquin River Group Authority (2010) studies suggest that delta-specific management actions may not yield the large survival benefits some might expect. Migrating smolts incur substantial levels of mortality outside of passage through the delta, including mortality directly and indirectly associated with SWP and CVP pump operations. The take of fish at the pumps represents a fraction of the total population that is drawn toward the pumps through the various delta reaches. Mitigating the effects of pumping involves routing fish thought the delta segments with the lowest mortalities as well as mitigating the take directly at the pumps. Thus, control over fish passage routes and improved collection and transport of salmonids at the pumps both need to be considered as mitigation actions. However, at this time the data and understanding of mortality processes within the delta are insufficient to identify a course of action. Increasing passage through Yolo Bypass may be a viable action for Sacramento runs. However, actions for San Joaquin fish appear less certain. Should actions divert fish through the tidally dominated central delta or should fish be diverted, collected, and transported at the pumps? Information is insufficient to evaluate such alternatives.

Delta Smelt

The entire life cycle of the delta smelt is confined to the delta region, which includes the area where the pumps are situated. Population-level effects of entrainment from pump operations have been described by Kimmerer (2008b), and subsequently critiqued by Miller (2011), which led to a reevaluation by Kimmerer (2011). In the initial Kimmerer (2008b) analysis, estimated overall impacts were generally small to moderate in most years (< 20 percent), but were high (> 30 percent) in some of the years analyzed. Kimmerer (2008b) noted that the estimates have large confidence limits and have index values varied widely across years, with large proportional losses of some delta smelt life stages evident in some years. He suggests that these highly variable annual loss estimates reflect episodic effects and therefore their annual magnitude should be empirically calculated rather than inferred from correlations.

Subsequent to Kimmerer's (2008b) analysis, Miller (2011) systematically laid out the assumptions and data issues in the Kimmerer (2008b) analysis. He then inferred that because most of the assumptions made by Kimmerer (2008b) would lead to an upward bias in the estimated population-level impacts, Kimmerer's estimates of impacts were therefore high. Kimmerer (2011), in his reanalysis, addressed some but not all of the issues and uncertainties raised by Miller (2011). Kimmerer (2011) concluded that, while the new estimates were slightly lower, the initial conclusion that entrainment by the pumps was large on an episodic basis remained valid.

The difficulties in estimating population-level impacts from entrainment are illustrated by the many assumptions and the complexity of the analyses detailed in all three of these papers. Continued critiques and constructive exchanges will enable further refinement of the estimated impacts and clear identification of the key uncertainties that need to be addressed with additional modeling and data collection.

Based largely on Kimmerer (2008b, 2011), Miller (2011), and the NRC's previous conclusion on pumping operations (NRC 2010), we conclude that in some years the population-level impacts on delta smelt are large and thus is a significant factor affecting delta smelt population dynamics. The committee does note that the status and knowledge of delta smelt have changed substantially in the last 5 years. Take at the pumps has been low and the seasonal sampling programs have suggested that the population levels are extremely low. However, an experimental sampling protocol coordinated with tidal cycles recently found unexpected concentrations of adult delta smelt. We therefore conclude that, in general, significant uncertainty exists on the condition and prospects for recovery of the delta smelt.

Model Analyses of Pump and Flow Effects

In an earlier report (NRC 2010), the assessment of the modeling framework required to adequately assess effects among pump and flow treatment noted some significant deficiencies that will impede informed decision making. The report emphasized the need for a more comprehensive life-cycle modeling approach that is more realistic and better matches the scale of processes at the population level (NRC 2010, pp. 40-41). This committee concludes that population-level effects analysis is required in order to rank this class of stressor against the others identified in this report. Absent that solid quantitative perspective, we are left to rely on qualitative assessments (e.g., Delphi process) in ranking entrainment (or any stressor) among all of the possible stressors. We note that this deficiency is not specific to the pump/flow mechanisms in the delta; all the stressors we discuss suffer in this regard.

There is recent accelerating activity in the area of life-cycle modeling of salmon and delta smelt. Several models are under development but not yet published. Maunder and Deriso (2011) recently published a life-cycle model of delta smelt. This model includes some assumptions that need further additional evaluation (e.g., role of density-dependent survival). However, the model is noteworthy because it illustrates that there is increasing activity in the important area of life-cycle modeling. The committee knows of several other life-cycle models that are in various stages of completion and is encouraged by this upsurge in activity. We further encourage continued development of models, within a collaborative regional process. A collaborative process is needed to minimize the paralysis that can occur from dueling models that are difficult to compare after their development and analyses are completed.

Conclusion

The committee concludes that the dams that act as absolute barriers, which have eliminated access to nearly 80 percent of the historical habitat, have been and continue to be a major stressor adversely affecting ESA-listed anadromous fish species in the Central Valley. The effects include drastically limiting abundance and productivity associated with severe habitat truncation, and the pronounced reduction of genetic diversity through extirpation of the vast majority of unique populations once present in the system.

Passage impediments at the RBDD and ACID diversion dam contributed to the decline of the ESA-listed anadromous species in the Central Valley. However, improvements in passage at both facilities, ACID in 2001 and RBDD in 2011, appear to have significantly improved passage in the Sacramento River.

The effects of water diversions on anadromous fish are poorly described, inadequately evaluated, and remain unquantified in any meaningful manner. Given this, the contribution of this class of stressors to the decline of anadromous fish in the Central Valley is unknown. We recommend a thorough evaluation of screened and unscreened water diversions within the active migratory corridor.

Based on smolt survival studies (Michel 2010, SJRGA 2010) and export–flow–survival relationships, the committee concludes that mortality incurred while migrating through the delta is substantial and in part attributable to pump operations. However, we cannot determine the extent to which altering pump operations, or providing alternative passage options, might affect population-level responses (e.g., population growth rate) relative to other stressor agents. The limited studies do indicate that significant mortality occurs prior to smolts reaching the delta pumps. For the delta smelt we conclude that in some years pumping operations pose a high risk to smelt, but in other years the impacts appear low. It is difficult to assess the current impact on the total population because it appears few delta smelt are found in the central delta. On balance we judge that across years this stressor poses a moderate impact to smelt at the population level.

There seems to be an expectation in the region that alleviating or minimizing pump effects in the delta will lead to robust populations of the ESA-listed salmon populations in the Central Valley. Assessing the likely effectiveness of doing this would be helped by developing a comprehensive, life-cycle model that is capable of exploring a variety of passage alternatives in combination with effects from other stressors. Several salmonid models are under development and we encourage their development and cross-comparisons and cross-fertilization. Furthermore, assessing the impacts of pumping on salmon populations will also require further studies to assess the impacts of pumping on the passage routes of smolts through the delta complex and their survival through the routes. The NRC noted this in an earlier report (NRC 2010).

The committee concludes that an integrated quantitative analysis is fundamental and required in order to rank the SWP and CVP pump operations on fish routing and direct take against the other stressors identified in this report. Absent that solid quantitative perspective we are left to rely on qualitative assessments in ranking among other stressors. This holds not only for anadromous salmonids, but also delta smelt and other species of concern. This deficiency is not peculiar to the pump/flow mechanisms in the delta; many if not all the stressors we discuss suffer in this regard.

Fishing

The potential negative effects of fisheries on individual species (Myers et al. 1996), on ecosystem services (Worm et al. 2006), and on coastal and estuarine ecosystems generally (Jackson et al. 2001) is widely acknowledged. For individual species, fisheries are known to have a range of effects on exploited population beyond the obvious decreases in abundance. Fisheries are highly selective agents of mortality that can cause rapid changes in phenotypic (Rjinsdorp 1993) and genetic traits (Policansky 1993, Conover et al. 2005). Beyond their direct effects on individual species, fisheries can alter community structure (Yemane et al. 2005, Kitchell et al. 2006) and disrupt habitats (Collie et al. 2000). It is not only industrial, commercial fisheries that have the potential to produce these changes; recreational fisheries can also contribute substantially to mortality in exploited species and may influence community structure (NRC 1999, 2006, Ihde et al. 2011). Moreover, even when fisheries occur in restricted geographical regions, their impacts can be felt over a broader geographic range because many species are highly mobile and often undertake long migrations. This is particularly true for estuarine-dependent diadromous species such as the salmonids (e.g., Chinook salmon and steelhead) and temperate sea basses (e.g., striped bass).

The bay and delta supported sizeable fisheries in the past. Historical reports indicate the first commercial fisheries in the bay-delta system developed in the mid-1800s and targeted Chinook salmon in the Sacramento and San Joaquin rivers and in Suisun Bay (Scofield 1956, cited in Smith and Kato 1979). Rapid expansion of these fisheries, in combination with reduced water quality and impediments to stream passage, led to substantial reductions in salmon numbers. However, both commercial and recreational fisheries continued until 2008, when all salmon fisheries in state waters were closed following dramatic declines in Sacramento fall-run Chinook. The closure continued in 2009. It has been estimated that these closures led to economic losses of more than $250 million and more than 2,000 jobs annually (Morse and Manji 2009). Today, the only commercial fisheries that remain in the delta proper are for threadfin shad, armed box crab (*Platymera gaudichaudii*), and crayfish (CA Fish and Game).[13]

During this time, commercial fisheries also developed in San Francisco Bay proper. These fisheries targeted a diverse assemblage of species including Pacific herring (*Clupea pallasii*), striped bass, both white (*Acipenser transmontanus*) and green sturgeon, and Chinook salmon. Several of these fisheries followed the same pattern of expansion and retraction exhibited in the salmon fisheries (Figure 3-8). Fisheries for other species have had longer histories, including those for anchovy (*Engraulis mordax*) and Pacific herring. Fisheries for herring harvested as much as 4,000 metric tons (mt) as late as 1975. Although much smaller than at its peak, in 2009, the last year this fishery operated, the California Department of Fish and Game report a harvest of 459 mt landed in the port of San Francisco.[14] In many ways the fishery for herring in San Francisco Bay was the last reminder of once sizeable estuarine fisheries. Indeed, inspection of current commercial landings for the Port of San Francisco reveal fisheries dominated by nonestuarine species such as Dungeness crab (*Metacarcinus magister*) and Pacific sardine (*Sardinops sagax*).

Today the bay and delta support recreational fisheries for striped bass, largemouth black bass, white sturgeon, Chinook salmon, steelhead, catfishes (family Ictaluridae), and American shad. In 2004, the state of California mandated that any anglers wishing to fish within the estuarine system purchase a Bay-Delta Sport Fishing Enhancement Stamp (California Fish and Game Code § 7361(b)). The funds from this program were invested in research and restoration activities to enhance and sustain recreational fisheries in the region. This program provides the basis for estimates of angler participation. From 2004 to 2009, when the program was closed, 1.81 million anglers purchased more than $9 million worth of stamps (CDFG 2009), suggesting that perhaps 300,000 anglers fished the San Francisco Bay-Delta system annually.

We may identify direct (removal of target species or removal as bycatch) and indirect (removal of potential prey or predators) impacts of fisheries. Elsewhere fisheries have been shown to have important direct (Myers et al. 1996) and indirect effects (Kitchell et al. 2006). Thus, the central question before us is, “Given this pattern of commercial and recreational fisheries, what impact may these fisheries have on the bay-delta ecosystem?”

Considering direct impacts first, the minimum requirement for their assessment are annual estimates of the size of the targeted fish population and an estimate of the total removals by fishing for that population. Often

[13] Available at http://www.dfg.ca.gov/marine/landings09.asp. Accessed May 12, 2011.
[14] Available at http://www.dfg.ca.gov/marine/landings09.asp. Accessed May 12, 2011.

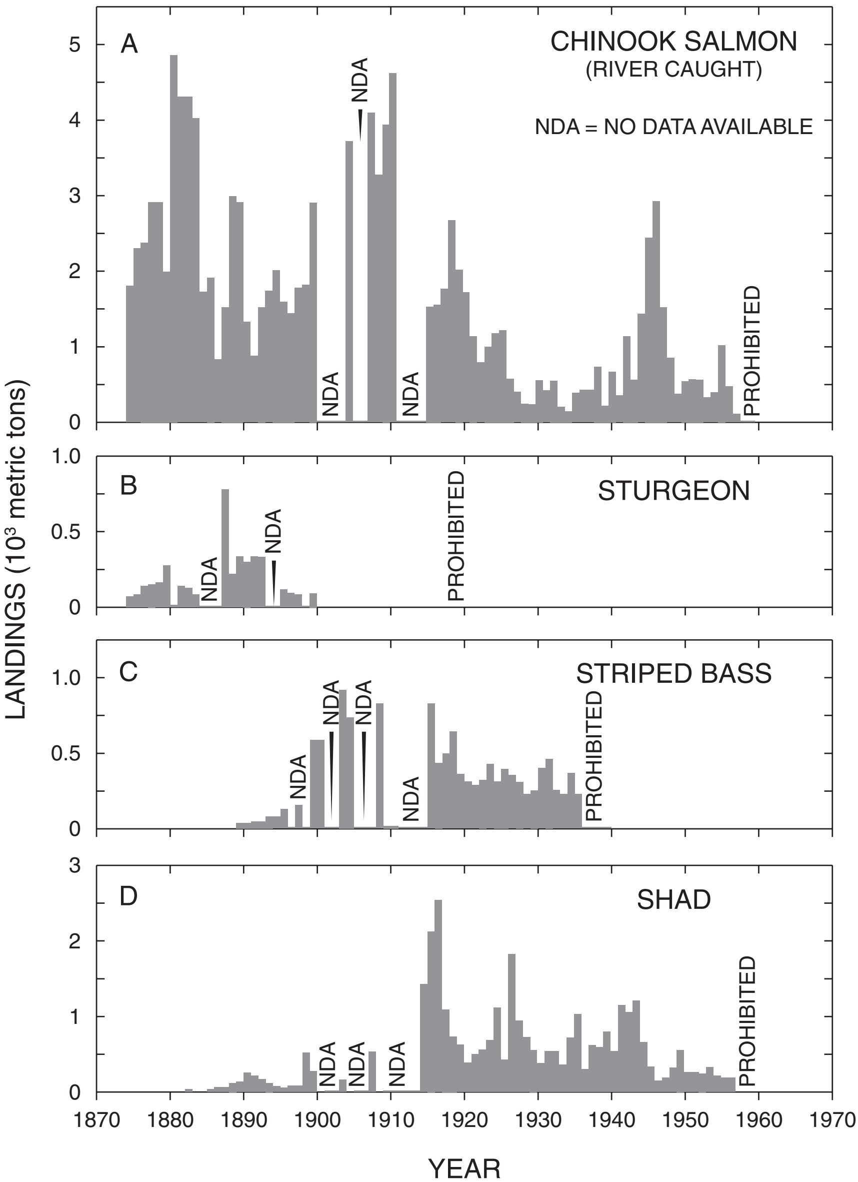

FIGURE 3-8 Commercial fish catches from the San Francisco Bay Delta for (A) Chinook salmon (Sacramento and San Joaquin rivers only), (B) sturgeon, (C) striped bass, and (D) American shad.
SOURCE: Smith and Kato (1979).

these estimates are derived from sampling programs that estimate relative abundance and catch levels, and stock assessment modeling that translates these empirical estimates to absolute impacts. For many species of interest in the bay-delta system, sampling programs are available to estimate trends in abundance (e.g., Fall Mid Water Trawl Survey[15]) and harvest [e.g., Recreational Fisheries Information Network (RecFIN)[16]].

However, population models that combine these data streams to provide an integrated picture of trends in absolute abundance and exploitation are lacking for all principal species, a point made also by the NRC (2010). This lack precludes provision of absolute estimates of the impact of harvest on any of the principal species. Despite this shortcoming, it is possible to estimate trends in the relative impact of exploitation on the dynamics of any targeted species.

As an example we consider striped bass in the bay delta and note that similar calculations could be undertaken for other species. The annual salvage estimate at the Tracy Fish Collection Facility (TFCF) may provide an estimate of the relative abundance of striped bass in the system (Aasen 2011; Figure 3-9A). We recognize that the number of striped bass salvaged will be affected by the amount of water conveyed by the system, but as a first approximation inter- and intra-annual variability in the volume of water conveyed will be ignored. It would be equally possible to use other indices of abundance, such as the California Department of Fish and Game tag-recapture. The RecFIN program provides an estimate of the total number of striped bass harvested in inland waters in northern California (Figure 3-9B[17]). Finally, the ratio of the estimates of harvest and abundance provide a measure of relative exploitation, U (Figure 3-9C). These relative exploitation estimates may provide an indication of the years in which exploitation was relatively more important. For example, the pattern in Figure 3-9C suggests that exploitation was almost twice as large in 1996 and 2003 (U ~ 3500) as in 1993 (U ~ 1700). But importantly, these data cannot be scaled to absolute impacts. Thus, their utility in comparing the importance of exploitation as a stressor among species or among stressors is limited.

Further complicating estimation of relative exploitation rates is the fact that many species of interest in the San Francisco Bay-Delta system are diadromous (migrate between saltwater and freshwater) and have broad distributions. As a consequence, the principal exploitation stress may not be from harvests within the bay-delta system, but rather from harvests outside the system. For example, green sturgeon tagged in the bay-delta

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[15] See http://www.dfg.ca.gov/delta/projects.asp?ProjectID=FMWT. Accessed July 16, 2012.
[16] See http://www.recfin.org. Accessed July 17, 2012.
[17] See http://www.recfin.org/data/estimates/download-estimates-data-files. Accessed July 17, 2012.

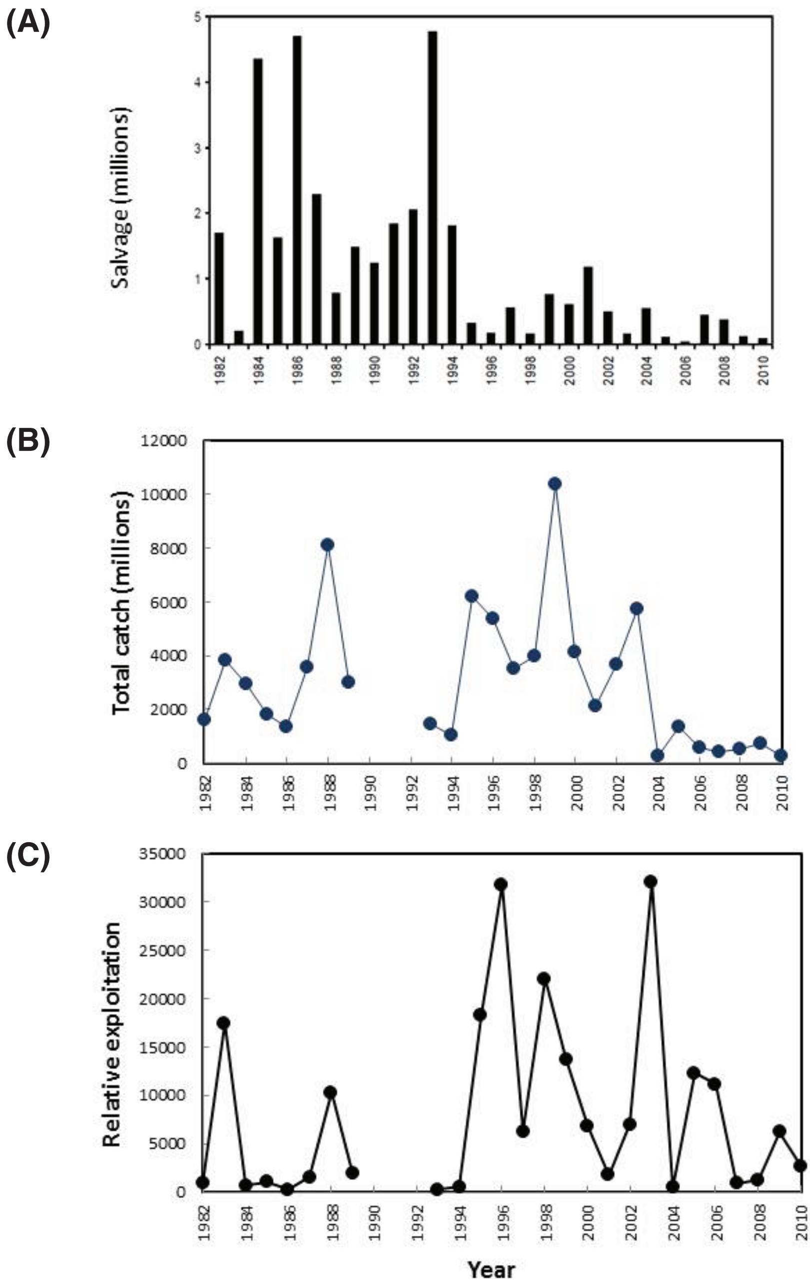

FIGURE 3-9 Patterns in (A) relative abundance (salvage numbers at the TCFC in millions), (B) catch (from the RecFIN survey), and (C) relative exploitation (catch/abundance) for striped bass in the San Francisco Bay-Delta system.

system have been recaptured off Oregon. The catch of these species outside the bay-delta system, whether in targeted fisheries such as for salmon or as incidental catch such as the case for green sturgeon, may be an important additional stress.

Estimating the indirect effects of fishing on an ecosystem presents a greater challenge than estimating the direct effects of exploitation. Most often these impacts are observed after the fact rather than forecast a priori (Baum and Myers 2004). Attempts to quantify indirect effects have usually relied on ecosystem-based models of fishery ecosystems using tools such as EcoPath with EcoSim. Such a model is available for the delta system (Bauer 2010). Ecosystem models have a high demand for data, including time series of relative abundance, catch data, and diet information, to quantify the composition and quantity of prey items for each species. Bauer's model involves 40 functional groups (both trophic groups, individual species, and age classes of individual species). Represented in the model are three age classes of striped bass, Chinook salmon, splittail, delta smelt, and largemouth bass as well as different categories of zooplankton, phytoplankton, and detritus. The level of resolution of such models depends on the availability of data. It would be possible to use such a model to trace the indirect dependencies of harvest in the bay-delta ecosystem, although Bauer did not report such results.

Models such as Bauer's (2010), however, cannot account for evolutionary and behavioral changes in response to stressors. For example, Pine et al. (2009) report several examples of fishery ecosystems that exhibited fundamentally different responses to management perturbations than those predicted by ecosystem models. In two examples cited by Pine and colleagues, managers took action to increase the prey abundance for piscivorous fish in an effort to increase harvests of the piscivorous fish to anglers. However, increased prey abundance actually led to decreased abundance of the desired predators because of competition between the juvenile stages of the predator and the prey for a shared zooplankton response. The central message in these studies is that ecosystems are highly nonlinear systems that are sensitive to multiple inputs such that simple dependencies of A gives B gives C may fail.

Conclusion

Exploitation is a significant structuring agent in a diverse range of ecosystems from small freshwater ponds to ocean basins. However, we lack definitive evidence that exploitation is a major stressor in the San Francisco Bay-Delta system, especially since the harvest of Chinook salmon and steelhead in California has been tightly controlled recently (green sturgeon, as a listed endangered species, may not be taken). That is not to say that exploitation could not be a principal stressor, but simply that we lack the empirical collection programs and integrated modeling programs to determine the importance of exploitation in this system.

Hatchery-Related Effects on Anadromous Salmonids in the Central Valley

In the 2009 draft Recovery Plan for Central Valley Chinook salmon and steelhead, NMFS (2009b) identified hatchery effects as a stressor contributing to, or implicated in, the decline of ESA-listed anadromous salmonid species in the Central Valley. Even so, they acknowledge the positive roles that hatcheries have provided in certain circumstances. The current status of wild populations is a critical consideration when assessing benefits and risks associated with hatchery production. For the three ESA-listed salmonids, population structure today is greatly diminished compared to their historical status. According to NMFS (2009b), historically the Sacramento River winter-run Chinook salmon evolutionary significant unit (ESU[18]) was composed of four populations. It now consists of a single population, which depends on hatchery production. The Central Valley spring-run Chinook salmon ESU had as many as 18 or 19 total populations. Today there are three. NMFS (2009b) hypothesized that historically 81 independent populations of steelhead were dispersed throughout the region; today there are perhaps 26 populations.

Winter-Run Chinook Salmon

Given the depressed state of this ESU, NMFS recognizes the need to rely on the Livingston Stone National Fish Hatchery (LSNFH) near Red Bluff, California, as part of the overall conservation strategy. The population declined from nearly 100,000 returning adults per year in the late 1960s to fewer than 200 in the early 1990s (Good et al. 2005). In the past two decades the number of returning adults have ranged from 2,542 in 2007 to a high of 17,153 in 2006 (NMFS 2009b).

NMFS considers LSNFH to be a good example of a conservation hatchery whose intent is to increase genetic diversity and minimize domestication of the hatchery progeny. Even so, Lindley et al. (2007) identify hatchery influence on the wild population as a potential concern with regard to genetic diversity. Even a small contribution of hatchery fish to the natural spawning

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[18] NMFS uses the term "ESU" as a basis for identifying a "distinct population segment" as specified in the Endangered Species Act, under which a DPS of vertebrates is included in the definition of "species for the purposes of the act." The Endangered Species Act does not define a "distinct population segment," but both it and the ESU are smaller evolutionary units than species or subspecies.

population could compromise the long-term viability of the population and increase the probability of extinction. Furthermore, Lindley et al. (2007) concluded that the winter-run population "is at moderate extinction risk according to the PVA [population viability analysis]," and at low risk according to other criteria (i.e., population size, population decline, and the risk of wide ranging environmental catastrophe).

Although in the recovery plan NMFS did not explicitly indentify hatchery effects as a key stressor for this species, it expressed concerns as the proportion of hatchery fish on spawning grounds increases. Lindley et al. (2007) reported, based on unpublished data from NMFS, that since 2001, the hatchery-origin winter-run Chinook salmon from LSNFH "made up more than 5 percent of the natural spawning run," and in 2005 it was more than 18 percent. As the percent hatchery contribution on the spawning grounds rise, so will concerns regarding the potential for negative genetic impacts, given there is only one wild population unit remaining.

Spring Chinook Salmon

NMFS estimates that historically there were up to 600,000 wild spring Chinook adults returning to the Central Valley and its tributaries. Since 1970, the number of hatchery and wild fish returning has generally ranged from 3,000 to 30,000 individuals each year. Hatchery fish are a substantial component of this run. The Feather River Fish Hatchery (FRFH), the only spring Chinook hatchery, was established in 1967. The target production is 2 million smolts released annually.

The release strategy at FRFH appears to have promoted excessive straying (that is, adults returning to a different stream from where they hatched). Up to 1 million smolts have been regularly released in San Pablo Bay, increasing the probability of returning fish straying throughout the Central Valley. In fact there is direct evidence of pronounced straying of spring-run Chinook salmon. The NMFS Recovery Plan (NMFS 2009b) reported that up to 20 percent of the sport catch in the American River are of FRFH origin. Cramer and Demko (1997) estimated that half of the hatchery-reared spring-run Chinook salmon returning to the Feather River did not return to the hatchery but spawned naturally in the river. The committee found no information on the spawning success and productivity of that population component.

Whether these observed distributions reflect true straying or wandering, i.e., detouring but eventually ending up in the natal stream, has not been determined. Straying has more negative implications since fish do not return to their natal streams. A wandering fish could eventually return to its natal stream following attraction to localized favorable water conditions, unless of course it is intercepted in a fishery. Furthermore, in the past, outdated hatchery practices likely promoted the unintended mixing of two Chinook salmon races at the hatchery, resulting in hybridization (CDWR and PSMFC 2004). At times, both populations were together in the hatchery complex due to periodic temporal overlap of returning spring and fall-run populations at the hatchery. Current practices strive to minimize such mixing.

Central Valley Steelhead

For steelhead, the increase in Central Valley hatchery production has reversed the wild-to-hatchery ratio of the steelhead population since the 1950s. McEwan (2001) quoted Hallock et al. (1961) as estimating that historically, 1 to 2 million adult steelhead returned to the Central Valley. In the 1960s those numbers dropped to near 40,000 (CDFG 1996). And by 1996, fewer than 10,000 returned to the system. In the 1950s, 88 percent of the population was composed of naturally produced fish (McEwan 2001), decreasing to an estimated 23 to 37 percent naturally produced[19] fish in recent times (Nobriga and Cadrett 2003).

The NMFS recovery plan explicitly identifies hatchery effects as a major stressor contributing to the decline of Central Valley steelhead. It notes that hatcheries relied on nonlocal populations of steelhead in some of the hatchery programs. Early on, the Nimbus Hatchery on the American River imported fish from the Eel River, a coastal stream in northern California, and transferred that stock to hatcheries in the Central Valley. In the 1970s, the FRFH imported steelhead from Washington State and incorporated those into the breeding program. For these reasons NMFS judges the original gene pool has likely been compromised. Today such practices are generally avoided. One of the recommendations in the Joint Hatchery Review Report (CDFG and NMFS 2001) was to identify and designate new sources of steelhead brood stock to replace the current brood stock of Eel River origin.

Hatcheries—Benefit or Risk?

In the Central Valley, hatcheries have been established to offset the loss of wild production associated with dams that prevent access to 80 percent or more of the historical spawning and rearing habitat. The role of hatcheries in fisheries management has been a continuing topic of debate,

[19] Naturally produced fish are the progeny of fish that spawned in the wild, whatever the origin of the parents.

particularly regarding anadromous salmonids. Do perceived benefits outweigh risks to wild populations?[20]

The extent to which hatcheries or hatchery fish have contributed and will continue to contribute to the decline of wild populations is difficult, if not impossible, to ascertain. There are often-cited benefits and risks associated with reliance on hatchery programs to satisfy fishery demands and supplement production of depressed wild populations. Devising strategies to achieve an acceptable balance among the risks and benefits is a constant source of debate. Waples (1991) stressed hatchery risks and argued that releasing large numbers of hatchery fish could adversely affect wild Chinook salmon and steelhead through various mechanisms such as hybridization, competition between hatchery and wild fish for food and other resources, predation by hatchery fish on juvenile wild fish, and the effects on wild fish of increased fishing pressure as a result of increased hatchery production.

Brannon et al. (2004) concluded that hatchery fish have an important role in recovery and supplementation of wild stocks. Riley et al. (2004) reported that small-scale releases of hatchery-reared smolts of Chinook or coho (*Oncorhynchus kisutch*) salmon had few significant ecological effects (density, group size, and microhabitat use) on wild salmonid fry in small, coastal Washington streams, particularly when the densities of wild salmonids are relatively low. They acknowledged the numbers of fish released was considerably smaller than most hatcheries release. More than two decades ago Hillman and Mullan (1989) observed that the release of numerous hatchery fish was associated with a decrease in abundance of wild salmonids in the Wenatchee River, Washington.

More recently, Araki et al. (2008) and Christie et al. (2012) reviewed and analyzed information on genetic effects on salmonids of hatchery rearing. They concluded that domestication selection can produce significant reductions in fitness in steelhead, Atlantic salmon (*Salmo salar*), and coho salmon. The declines can occur surprisingly rapidly, in as little as one or two generations, even in hatchery stocks derived only locally, that is, derived from the stream into which their progeny will be released. The National Research Council (2004) concluded that even with the best possible hatchery practice, domestication selection cannot be entirely eliminated. In addition, it is almost impossible to avoid selection for changes in run timing, especially in the diversity of run timing within populations (NRC 2004).

[20] "Wild" fish often are defined as being the second generation of naturally produced fish (e.g., NRC 2004, McElhany et al. 2000). It is difficult or impossible to identify pristine populations of anadromous salmonids in the continental United States, that is, populations that have never been altered by introduction of genes from hatchery fish or fish from other populations. Such populations likely are rare, if they exist at all (NRC 2004).

From an ecological perspective, Mobrand et al. (2005) concluded that hatcheries must be considered part of the ecosystem in terms of biomass input, effluent, and predation-competition dynamics involving wild fish. Ecological and genetic interactions involving wild and hatchery anadromous salmonids are of concern in terms of competition for habitat and resources, predation on smaller life stages, interbreeding, and reproductive success.

Fishery managers regularly confront the dilemma of satisfying commercial and sport fisheries with abundant hatchery production, while simultaneously attempting to conserve threatened and endangered wild populations. An important consideration is the often unintended consequence of harvesting depressed wild stocks in a mixed-stock fishery fueled by abundant hatchery fish. Such a "mixed-stock" fishery tends to further depress less-productive stocks at the expense of the more-productive, often hatchery-based, stocks. This matter was discussed in detail by the NRC in an earlier report (NRC 1996). Since the goals of producing large numbers of fish for exploitation and conserving the genetic variability of wild populations conflict, and because relatively little harvest of steelhead and salmon in California is currently permitted, decisions will need to be made about the purposes of the national fish hatcheries. This, indeed, echoes a recommendation of the Hatchery Scientific Review Group (2009) (see below).

More than a decade ago, Congress recognized the inherent conflict between boosting hatchery production to supply fisheries and the obligation to protect and conserve depressed wild stocks, and thereby funded a hatchery reform project in Washington State in the year 2000. The ensuing Hatchery Scientific Review Group (HSRG) formulated guidelines for balancing the needs of both hatchery-produced and wild salmonids in the Columbia River system.[21] In particular, the HSRG concluded that "[h]atchery fish cannot replace lost habitat or the natural populations that rely on that habitat. Therefore, hatchery programs must not be viewed as surrogates or replacements for lost habitat, but as tools that can be managed as part of a coordinated strategy to meet watershed or regional resource goals" (HSRG 2009).

But even in light of these numerous concerns regarding risks and negative effects associated with hatcheries, NMFS (2009a) sees the need to continue reliance on them in the broader recovery strategy and recommends that a hatchery supplementation plan be formulated. The Biological Opinion (NMFS 2009a) notes (LF 2.2),

> In consultation with the NMFS Southwest Fishery Science Center, Reclamation shall develop and implement a long-term population supplementa-

[21] The HSRG's reports are at http://hatcheryreform.us/hrp/welcome_show.action. (The HSRG began a review of the Klamath River and Central Valley systems in 2010; reports were not yet available in early 2012.)

> tion plan for each species and fish passage location identified in V. *Fish Passage Program*, with adult recruitment and collection criteria developed with consideration for source population location, genetic and life history diversity, abundance and production. . . . The plan shall identify wild and/ or hatchery sources for adult reintroductions and long-term supplementation, and the specific NMFS-approved hatchery management practices that qualify a hatchery for conservation purposes. Species-specific conservation hatchery programs may be developed to supplement reintroductions and maintain long-term performance standards for abundance and viability.

Conclusion

The committee recognizes the risks that have been imposed on wild salmonid populations by hatchery programs to date, and shares the concerns voiced by the scientific community and in the NMFS recovery plan. However, because negative effects of hatcheries are difficult to observe, the committee cannot reach a conclusion as to whether and how much hatcheries have contributed to the decline in wild populations in the Central Valley. In fact, the NMFS recovery plan asserts that for winter-run Chinook the LSNFH is one of the most important reasons the winter run persists. Importantly, the committee sees the need to follow recommendations of the NMFS Recovery Plan to formulate a new comprehensive hatchery program, and adopt the Viable Salmonid Population guidelines (McElhany et al. 2000) as guiding principles for long-term recovery. The committee expects continued reliance on hatcheries in the future, given the limited amount of productive spawning and rearing habitat that will likely be available.

Araki et al. (2008) concluded that the "general finding of low relative fitness of hatchery fish, combined with studies that have found broad scale negative associations between the presence of hatchery fish and wild population performance (e.g., Hoekstra et al. 2007), should give fishery managers pause as they consider whether to include hatchery production in their conservation toolbox." The NRC (2004) concluded that despite a more than 130-year history of stocking,

> [t]he available information is not sufficient to conclude whether hatcheries in Maine can actually help to rehabilitate [Atlantic] salmon populations, whether they might even be harming them, or whether other factors are affecting salmon so strongly that they overwhelm any good that hatcheries might do.

How do those conclusions apply to the steelhead and Chinook salmon of the Central Valley? Atlantic salmon in Maine, for example, have had fewer than 2,000 adult returns in recent years, including hatchery fish, at least an order of magnitude fewer than the number of returning Chinook salmon in the Central Valley, but more comparable to the number of steelhead returns. In addition, steelhead, Atlantic salmon, and coho salmon typically spend a year or more as juveniles in freshwater before migrating to the ocean, whereas Central Valley Chinook juveniles typically spend less than a year. The committee cautions against applying results from one species to another without careful consideration of potential differences between them, and reiterates the difficulty of confidently ascribing observed changes in salmonid populations to hatchery effects. Nonetheless, the committee concludes that the cautionary notes developed from studies of Atlantic salmon in Maine and coho and steelhead in the western United States are generally applicable to all of the anadromous Central Valley salmonids; for Chinook, especially, more specific information would be valuable. The committee judges that adoption of HSRG guidelines under a unified hatchery management plan will reduce (but not eliminate) risk to wild populations from hatcheries, and probably represents the most viable option for maintaining populations of salmonids in the Central Valley unless or until other methods are found to increase the productivity of wild populations.

Ocean Conditions

Ocean conditions have a significant impact on all fish that pass through the delta and reside in the ocean during part of their life cycle. Particularly affected are salmon, steelhead, and sturgeon, which are anadromous. Their adult stages occur in saltwater, they pass through the delta to spawn in streams, and the juveniles pass through the delta on their migration to the ocean. The major mechanism by which the ocean affects anadromous fish, and in particular salmon, is known as bottom-up forcing, in which patterns in atmospheric temperature, wind, and precipitation drive ocean temperatures, mixing, and currents, which in turn control growth and advection of plankton that provide food for salmon (Batchelder and Kashiwai 2007).

Year-to-year variability in coastal conditions affects early ocean survival of delta salmon (Williams 2006b, Williams in press) and variability in ocean indices appears to be increasing (N. Mantua, U. Washington, unpublished data cited in Lindley et al. 2009). Such variability appears to have contributed to a collapse of the 2004 and 2005 brood years of Central Valley fall Chinook. When in 2005 and 2006 the broods passed though San Francisco Bay and into the Gulf of the Farrallones, conditions were poor. The juveniles experienced periods of weak upwelling, warm sea surface temperature, and low density of prey (Lindley et al. 2009). The estimated survival from hatchery release to age 2 was only 3 percent of the survival of the 2000 brood. Lindley et al. (2009) proposed that the impacts of year-to-year variations in coastal conditions are amplified because releases of juvenile hatchery fall Chinook salmon are correlated among nearby hatcheries.

Thus, the combined effects of hatchery-synchronized juvenile outmigration and a possible increase in ocean variability may lead to more booms and busts in the fisheries.

The longer-term effects of bottom-up forcing are more difficult to assess, but this is an active area of research under the coordination of the North Pacific Marine Science Organization (PICES 2010). The problem is being considered across several temporal and spatial scales. The Pacific Decadal Oscillation (PDOs), which characterizes the decadal scale variations in ocean temperature and currents, has a significant impact on the coastal habitat of west coast salmon. During the warm phase of the PDO, there is less advection of cold-water zooplankton species from the north and strong advection of warmer-water species from the west (DiLorenzo and Minobe 2010). The cold-water species have higher lipid content and are thus more nutritious for salmon, which is thought to improve early ocean survival of the salmon (Peterson and Tadokoro 2010). PICES studies also are focusing on the effect of large-scale climate variability on the lower trophic levels (see also Cloern et al. 2010). While the PDO is correlated with many west coast salmon stocks, a clear correlation with Central Valley Chinook salmon has not been found (Botsford and Lawrence 2002). The lack of correlation might involve unique oceanic conditions in the Gulf of the Farallones (Williams 2006b). San Francisco Bay and the Gulf of the Farallones lie at the southern boundary of the ocean habitat of salmon. Furthermore, the boundary is predicted to shift north with climate change (Irvine 2010).

In any case, studies to identify the effects of ocean changes on fisheries are in their initial stages (DiLorenzo et al. 2010). Studies are identifying detailed mechanisms that relate past changes in ecosystems to climate forcing (Lluch-Coat et al. 2010). While they are focused on the ocean boundary ecosystem, there is no emphasis on the southern boundary where Central Valley salmon and steelhead first enter the ocean. Furthermore, little information is available on climate impacts on the high seas habitat of steelhead and some runs of Chinook. The effects of climate warming and CO_2 on ocean chemistry and the resulting effects on marine life are of concern, but it is too early to draw conclusions as to the likely responses of ecosystems (Denman et al. 2010).

In conclusion, despite wide-ranging and international research on the effects of changes in ocean conditions on fish and fisheries, there is little focus on the Central Valley stocks. This is unfortunate because these stocks enter the ocean at the southern boundary of the habitat and so it is plausible that ocean changes will have a significant impact on them.

Disease

Fish are constantly exposed to bacterial, fungal, protozoan, and viral pathogens but are generally protected from disease by a series of defense systems. The first line of defenses are the skin, scales, and mucus layers that trap and inhibit growth of pathogens. Pathogens that breach these systems are attacked by specific and nonspecific immune systems (Iwama and Nakanishi 1996). The ability of pathogens to overcome these defense systems and cause disease depends on abiotic, biotic, and genetic factors (Snieszko 1973). Disease may be enzootic, persisting in the population without significant impacts, or occur as short-term epizootic disease, which may have a significant impact on a population. Furthermore, fish exposure to pollutants and contaminants can lead to immunosuppression and increased susceptibility to infection (Arkoosh et al. 1998). Disease spread within a population also depends on the proximity of noninfected to infected individuals, for example, as occurs in hatcheries and at passage facilities where fish densities are high. Disease is also spread to offspring through inbreeding of infected and noninfected fish (NMFS 2009a). Analyses of threats to delta fish species typically mention disease as a cofactor with biotic and abiotic stress (e.g., NMFS 2009a, Baxter et al. 2008). In these situations, disease may occur as a result of reduced immunocompetence (i.e., the ability to ward off disease).

Generally, immunocompetence is lowest in young and old fish. Additionally, immunocompetence decreases during periods of hormonal stress, e.g., parr-smolt transformation of salmon and sexual maturation (Tatner 1996). Xenobiotic stressors such as metals, aromatic hydrocarbons, and pesticides reduce immunocompetence (see discussion of contaminants). Elevated temperature can have a major effect on stress response (Schreck 1996), which affects immunocompetence, and NMFS (2009a) notes that elevated temperature associated with climate warming may lead to increased disease in salmon.

In spite of the great potential impact of disease on delta fish populations, evidence for significant direct impacts of disease, or the impacts associated with containments, is mixed. Whirling disease caused by the parasite *Myxobolus cerebralis* is established in California salmonid populations but has been in decline and epizootic infections have only been reported in hatchery populations (Modin 1998). Infectious hematopoietic necrosis virus (IHNV) is common in juvenile hatchery salmonids but horizontal transmission of the Sacramento River strain of IHNV to wild cohorts appears to be a low ecological risk (Foott et al. 2006). High temperatures and fish densities induced an outbreak of disease in Chinook salmon oversummering in Butte Creek and resulted in prespawning mortalities between 20 and 60 percent (NMFS 2009a). However, in general wild salmon tend to be less susceptible to disease than hatchery salmon (NMFS 2009a). Histopathological and viral evaluation of young longfin smelt and threadfin shad indicated no histological abnormalities associated with toxic exposure or disease (Foott et al. 2008). Adult delta smelt collected from the delta exhibited little histopathological evidence for starvation or disease, while there was some evidence of endocrine disruption (Teh et al., unpublished reference called out but not referenced by Baxter et al. 2008). However, studies in Suisun Bay reported fungal infection in yellowfin goby and viral infections in inland silverside and juvenile delta smelt. High occurrence of parasitic infection and inflammation and muscle degeneration were reported for striped bass (Baxter et al. 2008). Evidence suggests these infections may have been associated with the transfer of xenobiotics on larval striped bass in the San Francisco Estuary (Ostrach et al. 2008). Irrespective of these documented instances of pathogens, little information exists to quantify changes in infection and disease-associated mortality effect in Central Valley salmon (NMFS 2009a) and other species.

In short, the studies to date do not suggest that disease by itself or associated with contaminants has a major impact on the population levels of anadromous and estuarine fish that migrate through or inhabit the delta.

Multiple Stressors and the Pelagic Organism Decline

The pelagic organism decline (POD) was the simultaneous decline beginning in 2002 of the abundance indices of delta smelt, longfin smelt, threadfin shad, and juvenile striped bass. The POD study is a major effort at determining the role of the different stressors in causing the fish declines. A POD management team was established in 2005 by the IEP. Roughly every 2 years, the POD management team synthesizes the results of the various research projects to push toward answering the overarching question of what caused the POD (IEP 2006, Baxter et al. 2008, 2010); a final report is due in 2012-2013. In the periodic reports from the POD management team, the POD results were described by stressor (driver) for each life stage and season for each of the four species.

Initially, a single conceptual model was proposed, which was followed by refinement as species-specific models. The conceptual models were organized as life-cycle diagrams, with the definition of life stages and time periods related to the commonly used monitoring data (e.g., fall midwater trawl, summer tow net survey, 20-mm survey). The list of drivers (stressors) has increased during the POD study, paralleling the increasing complexity in the evolving conceptual models. Initially, the POD synthesis reports used a generic life-cycle conceptual model with three drivers (toxic substances, exotic species, and water projects). This was expanded by the IEP's POD Management Team "to species-specific models and nine drivers: (1) mismatch in time and space of larvae and their key prey items; (2) reduced habitat area and volume; (3) adverse water movement/transport; (4) entrainment; (5) toxic effects on fish; (6) toxic effects on fish food items; (7) harmful *M. aeruginosa* blooms; (8) *C. amurensis* effects on food availability; and (9) disease and parasites."

Quickly, it became apparent that a "smoking gun" (i.e., a single driver that was the cause) was not present and the philosophy shifted more toward evaluating the effects of multiple stressors acting together. Two statistical analyses (Mac Nally et al. 2010, Thomson et al. 2010), done partly with funding coordinated by the IEP, concluded that important covariates correlated to the fish abundance indices prior to the POD were no longer related to the abundance indices observed after the POD. Using the results of various studies, the overall POD synthesis efforts by the management team identified some potential drivers that were not strongly related to abundances, which helps to constrain the problem, and illustrates the difficulties in relating drivers to population dynamics of the fish species.

Most recently, the view from the POD management team has evolved with more attention paid to the longer-term declines and the notion of an ecological regime shift superimposed on the effects of the multiple stressors. A regime shift is a relatively sudden, large-scale change in the state of ecosystem from one stable configuration to another due to nonlinear responses to slow changes in drivers (Andersen et al. 2009). The POD is a recent decline within long-term declines for each of delta smelt, juvenile striped bass, and longfin smelt.

The POD study is an excellent example of the type of synthesis that is needed to examine the effects of multiple stressors on fish species declines. The POD study involved many people and used strategic planning with conceptual models to design the study elements and then piece the results together. A logical next step to the POD study is to further evolve from the purely qualitative, conceptual formulations of species life cycles to more-quantitative life-cycle modeling analyses.

The POD effort has contributed to a major shift in the thinking of stressor effects on fish species in the delta. The long-held earlier idea that a single stressor (e.g., entrainment) must be the cause has changed to now examining the simultaneous, and potentially interactive, effects of multiple stressors. This is a landmark change in thinking. Whether the latest idea of an ecological regime shift has a similar impact on the scientific thinking about the declines in fish in the delta community remains to be determined. Some stressors can be eliminated, but the remaining stressors are difficult to rank because their occurrence overlaps and their effects can be nonlinear, episodic, and interactive.

Priority Stressors for ESA-Listed Species

The committee was asked to attempt ranking the importance of various stressors with regard to their importance in affecting survival, productivity, and ultimately recovery of endangered fish species. The following is a discussion and evaluation of stressors for listed species.

Anadromous Salmonids

At least two forums have attempted to characterize and score the importance of various stressors on ESA-listed anadromous salmonids in the Central Valley; the NMFS Draft Recovery Plan and the Delta Conceptual Models[22] for those species. The NMFS approach is very detailed and specific as to species and population unit, life stage, and river locale. Although very thorough and extensive in their treatment, the committee encountered no concise distillation by broader stressor categories. Since the charge of this committee is coarser and broader, the committee could not readily distill their evaluations to align well with our approach to Central Valley stressor impacts.

The Delta Conceptual Models considered stressor impacts at a higher level, more consistent with our charge, and we looked to those for reference, against which to judge our assessments of stressors. However, they had some limitations for our purposes. The stressor scoring focused on ten categories of stressors, for each of four salmon life stages. Each was scored from low (1) to high (4) in terms of three parameters: understanding, importance, and predictability. Although a promising template, many of the cells in the matrix were not scored, leaving the assessment still open ended. Furthermore, many of the environmental and anthropogenic factors considered candidate stressors in this report were not treated in that document. Thus, the committee concludes that in their present form the salmonid conceptual models provided a still incomplete picture with regard to assessing the importance of a broad spectrum of stressors.

The committee treats the anadromous salmonids as a species complex in the ranking discussions. The loss of access to over 80 percent of the historical habitat has led to greatly reduced carrying capacity and simplified population structure. These outcomes limit abundance, productivity and resiliency, even if a variety of other stressors are relaxed.

Unless these fundamental constraints are relaxed, recovery goals will be very difficult to attain and the populations might even be in danger of extinction, especially in the face of expected climate change. Altering pump operations or providing an alternative water conveyance system will do

[22] See http://www.science.calwater.ca.gov/drerip/drerip_index.html. Accessed July 17, 2012.

little to offset the dramatic effects of habitat loss and deficiencies in existing population structure. The successful reintroduction of salmonids to select, expansive, and productive watersheds will provide needed increased carrying capacity, provide access to thermally acceptable areas, and enable the selection for and expression of new life history patterns and accompanying establishment of new population units. NMFS recognizes this as reflected in the draft Recovery Plan and has identified candidate watersheds that are currently inaccessible to salmonids. Feasibility studies for reintroduction remain to be formulated. The strategy of reintroducing anadromous salmonids to drainages upstream from dams lacking fish ladders is being implemented in the Pacific Northwest (PNW), with notable success. Sockeye and coho were successfully reintroduced above two dams on the Baker River in Washington State. On the Lewis River, efforts are under way to reestablish naturally producing salmon populations upstream of Swift Dam. The same type of effort has been ongoing on the Cowlitz River for over a decade. Numerous other sites in the PNW are now being assessed as to feasibility (AECOM and BioAnalysts 2010). The implementation involves collecting adults at the base of the dam and transporting them above the barrier. But the most technically difficult task involves the design of a collection system that can safely and effectively intercept and route smolts around the structure (AECOM and BioAnalysts 2010).

Dam removal can be an effective strategy for increasing the area of habitat for diadromous fishes, but it is not simple or inexpensive, especially for large dams (Heinz Center 2002, NRC 1996, 2004). In a water-short region like the delta watershed, it seems unlikely that any large dams will be removed soon. In addition, large dams can be used to mitigate the adverse effects of increasing temperatures in the waters below them by providing for the release of cold water. Removal of small dams high in the watershed might provide some benefit in combination with other strategies, but the feasibility and desirability of doing so would need to be weighed carefully against the costs and other disadvantages (NRC 2004).

Green Sturgeon

Green sturgeon (*Acipenser medirostris*) is a diadromous species that occupies different Central Valley habitats depending on life stage and season (Figure 3-10). The Central Valley subpopulation is very small. Moyle (2002) estimated that between 140 and 1,600 adults occupy the system each year, while Israel and May (2010), using molecular kinship analysis of various life stages in the upper Sacramento River, estimated that their results could be accounted for by as few as 10 to 28 spawning adults above the Red Bluff Diversion Dam each year. The Central Valley subpopulation

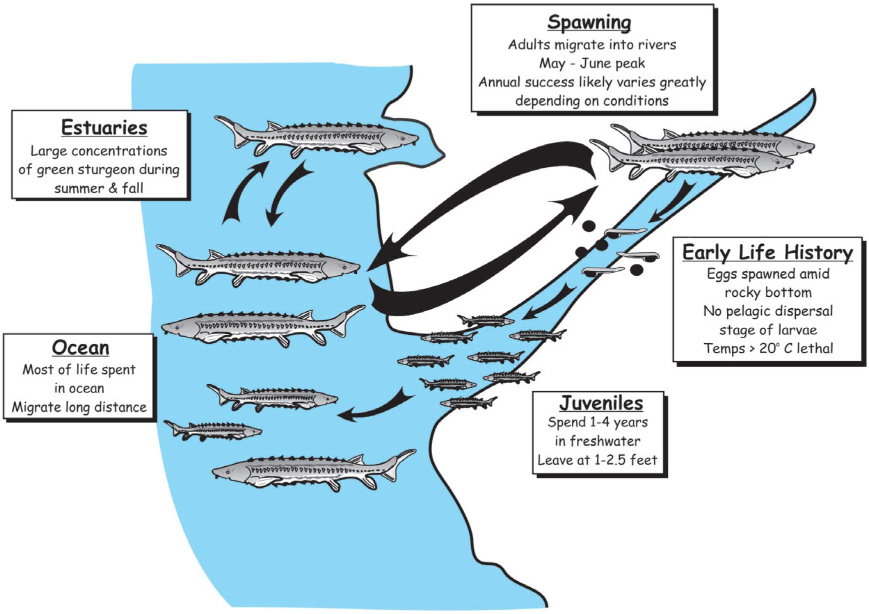

FIGURE 3-10 Schematic of the life cycle of green sturgeon.
SOURCE: Beamesderfer et al. (2007).

is part of a southern population segment that is genetically distinct from a northern population segment (Israel et al. 2009).

Adult green sturgeon (13-16+ years old) migrate into the bay-delta system in winter months. Most adult sturgeon undertake spawning migrations up the Sacramento River beginning in March and reach upriver locations (adjacent to and above Red Bluff Diversion Dam) in late spring and early summer (Beamesderfer et al. 2007, Israel and Klimley 2008, Heublein et al. 2009).

It is believed that sturgeon spawn in this area in stretches of the river with high flow over bedrock. Fertilized eggs hatch in 6-8 days, and then larvae initiate feeding and disperse downstream in a nocturnal diel migration. Following metamorphosis to juveniles, sturgeons adopt a benthic orientation, feeding on invertebrates while they move slowly downstream to lowland and estuarine habitats. By 3 years of age, juveniles move into the coastal ocean (Beamesderfer et al. 2007), where they migrate widely, co-occurring with the northern population segment in the estuaries of the Pacific coast of North America (Lindley et al. 2008).

Green sturgeon populations are susceptible to stressors in several life stages. Israel and Klimley (2008) and the NMFS Biological Opinion (NMFS

2009a) identified critical factors in the larval early life period in the Sacramento River habitat: (1) warm water temperatures, (2) insufficient flows, (3) decreased dissolved oxygen, (4) lack of rearing habitat, and (5) increased predation. Although such studies rarely address the issue, bioaccumulative contaminants like selenium and mercury also pose a particular risk for this species. The risks stem from the sturgeon's high trophic position in the benthic food web, the importance of life stages most at risk from these reproductive toxicants, and the poor demographic compensational abilities of this long-lived, slowly reproducing species. Because the southern distinct population segment is listed under ESA, recovery action may extend beyond the San Francisco Bay Delta. Using elasticity analysis, Heppell (2007) identified sensitive life history stages and concluded that reductions in bycatch would be the most effective way of restoring green sturgeon. Mora et al. (2009) developed a green sturgeon habitat suitability model and concluded that broad reaches of the Sacramento–San Joaquin system now are unavailable because dams block formerly suitable spawning habitat. However, they caution that their conclusions are fraught with uncertainties because of the complex impact of dams on the ecology and hydrology of impounded rivers. In addition, they comment that efforts to regulate flow to benefit endangered salmonids may have had negative effects on sturgeon.

Overall, the committee makes the following points from a review of the green sturgeon literature:

1. Recent genetic and hydroacoustic tagging evidence continues to support the existence of two distinct population segments: a southern DPS that spawns in the bay delta and in particular in the Sacramento River, and a northern DPS that spawns in rivers in Oregon and Washington. However, these same data also clearly show that the two DPSs mix throughout the range at all times except while spawning. This suggests that restoration of the southern DPS in the bay delta must also keep in mind the status of green sturgeon throughout its range.
2. The value of subadult sturgeon to future population growth is substantial and thus efforts to reduce the bycatch and other incidental sources of mortality on this life history stage should continue. There has already been a concerted effort that has reduced bycatch from thousands of fish in the second half of the 20th century to hundreds of fish today.
3. The temporal and spatial distribution of sturgeon in the Sacramento–San Joaquin river system is relatively well described and should inform management efforts to maximize the suitable habitat. However, there are inherent trade-offs in trying to promote maximum habitat quality for different species of concern. What may be good

for salmon may not be beneficial to sturgeon or delta smelt. These trade-offs should be carefully identified and considered when making management decisions for each species.

4. Our knowledge of the distribution and habitat use of larval and juvenile sturgeon is particularly weak. Knowledge would be advanced by development of the kind of geospatial habitat quality model produced by Mora et al. (2009) for adult green sturgeon. This approach uses information for sturgeon throughout their range to inform decision for the bay delta.
5. The vulnerability of both green and white sturgeon to bioaccumulative contaminants like selenium and mercury is well known (see contaminants section). While habitat is clearly crucial in determining the fate of this species, recovery could be slowed by the existing levels of selenium and mercury contamination in the bay delta. Exacerbation of selenium or mercury contamination would increase risks to this species in particular, and with some possibility of the extirpation of the relict populations that currently inhabit the bay.

Delta Smelt

Several analyses have attempted to determine the importance of stressors affecting the population dynamics of delta smelt. While all the analyses generally agree on the list of potential stressors, the relative importance of the different stressors was highly variable across the analyses. These analyses are the DRERIP conceptual model, the POD synthesis study, three statistical analyses, and a life-cycle model. The analyses were not independent. They all used overlapping data sets, and the DRERIP conceptual model and POD synthesis study were qualitative and relied on the results of other analyses.

DRERIP

The Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) was one of four regional plans intended to guide the implementation of the CALFED Ecosystem Restoration Element of CALFED.[23] DRERIP developed a series of conceptual life-cycle models for key species, including delta smelt (Nobriga and Herbold 2009). Primary and secondary drivers were identified as factors affecting habitat, and primary and secondary stressors were identified that affect population abundance but operated through one or more drivers. Drivers determined to be affecting delta smelt abundance were sporadically high adult and larval entrainment, spring water temperatures reducing spawning season duration, warm summer-fall

[23] See www.dfg.ca.gov/delta/erpdeltaplan. Accessed July 17, 2012.

water temperature, decreased summer-fall habitat area based on salinity and water clarity, and suppression of the food (zooplankton) base. A variety of stressors can contribute to each of these drivers. For example, water exports and Delta Cross Channel operations are stressors that affected the driver of entrainment, and introduction of the overbite clam is a stressor related to changes in the driver of food base.

Pelagic Organism Decline (POD)

The POD management team hypothesized that habitat degradation was the fundamental cause of the smelt decline through its effects on growth and reproduction (see Baxter et al. 2010 for details). Warm temperatures and low food quality and quantity during the summer slowed growth; smaller adults produced fewer eggs. Calanoid copepods have shown a long-term decline and the feeding area during the summer has been reduced due to warm temperatures and lower turbidity. Fall habitat, as measured by low salinity and high turbidity being good, has also showed a long-term decline; the specifics of how fall habitat relates to survival (via predation, disease, and food) are unclear. The shrunken fall habitat also places the smelt closer to the pumping facilities, which could increase entrainment in the following winter. High winter entrainment of adults during the POD years was superimposed on a low abundance comprising small individuals with low egg production. Entrainment of juveniles occurs during the spring and is generally higher during dry years (i.e., POD period), which overlapped with the years of high adult entrainment in winter. Blooms of toxic cyanobacteria and contaminants effects likely had less influence.

Statistical Analyses

Two analyses (Mac Nally et al. 2010, Thomson et al. 2010) used almost identical explanatory variables. Mac Nally et al. (2010) used a multispecies approach to examine whether the associations between the target species and other species and between target species and environmental covariates were consistent throughout the historical record. Thomson et al. (2010) focused on individual species and examined whether decreases in delta smelt, longfin smelt, juvenile striped bass, and threadfin shad abundance indices in the early 2000s were the continuation of longer-term trends (since the 1970s) or were more abrupt changes, and whether the covariates important before the changes continued to be important after the changes. The explanatory variables used for analyses of delta smelt included, among other variables, spring and summer biomass of calanoid copepods, chlorophyll *a*, spring X_2, winter and spring exports, summer water temperature, PDO, biomass of *Limnoithona* copepodites and adults during the summer, water clarity, and mean catch rates of inland silverside and largemouth bass during the period July through September. Thomson et al. (2010) inferred that a step change occurred in delta smelt and generally identified water clarity and winter volume of exported water as important, and that the importance of the covariates was not maintained after the step change. Mac Nally et al. documented biological and environmental associations involving delta smelt, but did not find that these associations changed after 2002.

Miller et al. (2012) reported the results of a third statistical analysis of delta smelt abundance indices and similar but not identical explanatory variables as Thomson et al. (2010) and Mac Nally et al. (2010). Miller et al. (2012) used the ratio of delta smelt abundance indices as a measure of survival (fall to summer, summer to fall, and fall to fall) and related these to covariates using a regression model that included density-dependence (i.e., a Ricker relationship) (Ricker 1954). Because of the potential for correlation among many of the covariates, Miller et al. (2012) used a complicated approach of subsetting the covariates and switching them to determine possible redundancies in detected relationships. They found associations between the fall-to-summer survival index and abundance indices in previous years, zooplankton densities, and entrainment. Summer-to-fall and fall-to-fall survival indices were related to previous abundance indices and zooplankton measures.

Life-Cycle Model

Maunder and Deriso (2011) developed a stage-based life-cycle simulation model of delta smelt population dynamics. They assumed possible density-dependent survival between life stages, and fit the model to the long-term monitoring data (summer tow net, fall midwater trawl). They then statistically searched for improved fit by allowing for explanatory variables (covariates) to be included as modifiers of stage survivals, singly and in combinations and either before or after density dependence. Using two of the fitted models, they then examined the importance of the explanatory variables, including entrainment. They concluded density-dependent survival was important for survival from juveniles to adults, and that covariates related to food abundance, water temperature, and predator abundance were most correlated with the interannual population variation. Adult entrainment also played a role in some of the final models selected.

Summary

These analyses used a variety of techniques applied to overlapping data sets, and they produced similar subsets of stressors as being correlated with the variability in delta smelt abundance indices. However, the different analyses did not converge with respect to the relative importance of individual stressors within the subset of generally important stressors.

Conclusions

While there are factors that all analyses agree are not important, there has been little agreement on the ranking among the potentially important factors for delta smelt. These analyses shared, to some extent, the same database but did not all use the same list of potential explanatory variables and sometimes used different numerical versions of the same explanation variable. The analyses identified various mixtures of important covariates, including spring and summer plankton biomasses, predator indices, water and spring exports, and fall water clarity.

OVERALL CONCLUSIONS

Multiple stressors have affected and continue to affect the delta ecosystem and its biota, including the listed species of fishes. While some species have increased in the delta in the past few decades, listed fish species have continued to decline. The committee concludes that while it is possible to identify more-significant and less-significant stressors, a precise ranking of them, even for individual species, is not possible.

First, statistical evidence and models suggest that both flows and flow paths are critical to population abundance of many species in the bay delta. However, none of the statistical flow-abundance relations suggest the existence of thresholds (i.e., that if the position of X_2 were to be allowed to remain far upstream for suitable [species-dependent] periods of time, there would be irreversible declines in fish populations or the near elimination of critical ecosystem processes like primary production of phytoplankton). However, it is clear that very dry periods can alter species composition in more permanent ways (Alpine and Cloern 1992, Jassby et al. 2002, Kimmerer et al. 2009).

Thus, it appears that if the goal is to sustain an ecosystem that resembles the one that appeared to be functional up to the 1986-1993 drought, exports of all types will need to be limited in dry years, to some fraction of unimpaired flows that remains to be determined. Setting this level, as well as flow constraints for wetter years, is well beyond the charge of this committee and accordingly we suggest that this is best done by the SWRCB, which is charged with protecting both water rights holders and the public trust.

The idea of developing operating policies based on statistical models highlights a fundamental challenge inherent to the substantial uncertainty of the observed relationships between flows, the position of X_2, or any other abiotic factor. Design of most engineered systems tends to rely on optimization of performance, given some knowledge of the system, a practice that is known in seismic engineering as performance-based engineering. If critical aspects of flow and flow variability could be identified, for example, a short period of time when a run of salmon moves through the delta or when a critical life stage of delta smelt is vulnerable to entrainment, the timing of pumping or the flow path of the diverted flow could be chosen so as to maximize the amount of water diverted while minimizing the effect of those diversions on at-risk species. Given the diverse set of organisms and processes that constitute the bay-delta ecosystem, the ultimate success of any approach targeted only to particular species seems doubtful. In contrast, broad ecosystem approaches, recognizing substantial uncertainty, are needed, although they might require more water. A risk of any approach is that long-term changes in the food web due to invasions or nutrient inputs or climate change might alter the influence of flow on the ecosystem; thus, continued monitoring is essential.

The hard decisions that will need to be made are ones of balancing different kinds of trade-offs. These will be matters of policy rather than being the result of a straightforward application of "good science." Nonetheless, exactly because statistical correlations are not adequate to fully explain the responses of aquatic species to either flows or flow diversions (paths), continuing the effort to better understand the processes that control the implications of both flows and flow paths is essential into the future.

For migratory salmonids, and probably green sturgeon, significant stressors are the dams. They are impediments to passage, cause the loss of spawning and rearing habitat, change the abundance of predators, and affect temperature and flow. These effects limit abundance and productivity and reduce genetic diversity through extirpation of the vast majority of unique populations once present in the system.

Limited survival studies suggest migrating salmon and steelhead smolts incur substantial mortality during river and delta passage. Increasing passage of smolts through Yolo Bypass may be a viable action for Sacramento salmon populations. However, options for San Joaquin fish are less certain, because studies suggest that passage through the delta main channel and collection and transport at the pumps—the two main passage options—result in equally low survival.

Entrainment effects of SWP and CVP pumping are likely large in some years and, thus, act as an episodic stressor that has a significant adverse effect on delta smelt population dynamics, although it is very difficult to quantify the effects in simple ways. The flow path within the zone of influence of the pumps is especially important as a stressor for this species. Inflows to the bay are clearly important for longfin smelt. A series of papers on estimating entrainment impacts (Kimmerer 2008b, 2011; Miller 2011) provides a good example of careful and constructive critique and response that is desperately needed to further refine these important analyses. The dialog should continue, and the approach also is needed for other controversial analyses. The committee reemphasizes the need for life-cycle modeling and a collaborative process to reduce the paralysis that can occur from the use of dueling models and to encourage cross-comparisons and cross-fertilization. The recent surge in life-cycle modeling for both delta smelt and salmonids is encouraging.

Changes in nutrient loads and concentrations in the delta and bay, especially those for nitrogen and phosphorus, are stressors of increasing concern from water-quality and food-web perspectives. Further simplification of this ecosystem is a serious concern if the impacts of such inputs increase because of failure to better remove nutrients from waste streams, climate change, or human-induced changes in flows. Toxic pollutants such as selenium also appear to be significant stressors, especially for sturgeon, with San Francisco Bay and the San Joaquin River being the areas of greatest concern. With appropriate investments both nutrients and selenium issues can be better managed, probably to the benefit of both functioning and structure in the delta and the bay. Examples of actions with a high likelihood of net benefits for the environment include the following:

1. A nutrient reduction plan that moves toward reducing all biologically available forms of nitrogen (especially) and phosphorus could benefit the delta and regions of the bay by addressing the increasing unwanted symptoms of eutrophication such as harmful algal blooms. However, as in any ecosystem effort, care will need to be taken to ensure that a change in nutrient ratios (e.g., N:P ratio) does not inadvertently favor other unwanted species, such as Brazilian waterweed.
2. A transparent plan for sustaining the effort to improve the in-valley solutions for the selenium issue is essential to ensuring that selenium inputs to the bay will not increase in the future.
3. Continued study is essential, including scenario building, of the ecological risks from water quality changes, especially selenium, of changing flow paths in ways that result in an increase of the ratio of San Joaquin River to Sacramento River water entering the bay.

The above stressors also interact with each other and with changes in salinity, turbidity, and freshwater discharge/flows resulting from hydrologic changes in the delta and its tributaries, changes that have been attributed to water exports, changes in land use, and changes in the morphology of the delta. The latter factor, caused by canalization and the abundance of hardened structures that also have eliminated tidal wetlands, has affected delta smelt by changing the aquatic habitats they occupy. But such physical changes in habitat occurred long before the most recent collapse of delta smelt and other pelagic organisms. Flow-related changes in habitat are more complex to understand and could have a more recent origin. There is evidence that restoration of shallow-water physical habitat could be of value to the growth of POD species (e.g., if it imitates the Yolo Bypass). But care should be taken in assuming that such restoration can reverse the present decline in such species, given the lag between changes in the morphometry of the bay delta and declines in abundance. Again, support for better understanding the processes that link flows, habitat structure, and habitat characteristics such as salinity, turbidity, and temperature should remain a high priority.

Introduced species have caused dramatic changes in habitat, prey, and predators of the listed fish species in the delta. Determining the contribution of introduced species compared with the effects of other stressors to changes in the delta ecosystem is difficult, because some effects are local, multiple stressors vary simultaneously, and the data or models to directly link introduced species to observed ecosystem changes often are lacking. Introductions of nonnative species will continue because management controls that substantially reduce risk are difficult and expensive to implement. Changes in human activities and climate change could exacerbate the problem in the future. If solutions to problems caused by invasive species are possible, they will come from better understanding of the life cycles and vulnerabilities of these species. New technologies offer some possibilities for solutions as well (e.g., sterilization of ballast water with nitrogen gas; Tamburrri et al. 2002), as do adjustments in management designed to reverse the habitat characteristics that favor such species (e.g., varying salinities in the delta). However, all such proposals should be carefully evaluated for their feasibility. Early detection through monitoring is useful to prepare for likely changes to the ecosystem.

Largely because negative effects of hatcheries are difficult to observe, the committee cannot reach a conclusion as to whether and how much hatcheries have contributed to the decline in wild populations in the Central Valley. The committee judges that adoption of recent conservation guidelines under a unified hatchery management plan will reduce (but not eliminate) risk to wild populations from hatcheries, and probably represents the most viable option for maintaining populations of salmonids in the Central Valley unless or until other methods are found to increase the productivity of wild populations.

Coastal ocean productivity is one of the most significant factors determining the ocean survival of juvenile salmon and the number of adult salmon that return to spawn. Increased variability in coastal conditions expected with climate change may increase variability in Central Valley salmon and steelhead recruitment. When ocean conditions are unfavorable, the effects can be partially ameliorated by increasing the diversity of wild and hatchery salmon ocean entrance timing.

Currently, disease does not appear to be a significant stressor factor for juvenile or adult salmon. However, with climate change and increasing river temperatures disease may be become a major factor in salmon mortality.

The real complexities added to the system by these factors, as well as the complexities added by interactions of all the above considerations, mean that ecological changes in response to engineering changes will not necessarily be linear. Policies should be based on more than just the presence or absence of linear, simple relationships between a stressor and its target(s). While we recognize that policies must move forward, a continuing, transparent effort to study, model, and track environmental changes and how they are influenced by those policies, is essential. Given the diversity of the challenges presented by "stressors" to the bay delta, better integration of the governance structures and science-policy dialogue, as suggested in other chapters of this report, is another important ingredient in addressing the stressor issues.

It is clear from consideration of the many stressors and their impacts that eliminating any one is unlikely to reverse declines in the listed species. Nor is it constructive when the advocates of the implications of one stressor use that advocacy to suggest their stressor is not important. Opportunities exist to mitigate or reverse the effects of many of the above stressors. To make it more likely that any actions to rehabilitate the ecosystem are cost effective, continued effects analyses, modeling, and monitoring will be needed.

Models will not eliminate controversy and they will not eliminate the need for information gathering in the field. Indeed, well-designed models should guide data collection. Nonetheless, modeling remains an essential part of scientific endeavors in the delta, especially as a way to test hypotheses and to improve understanding. Three-dimensional models that include salinity, temperature, and flow also would be helpful. While such modeling might not benefit decision making in the immediate future, it would help scientists to understand the complexities of the system better and provide a guide for conducting analyses and perhaps experiments to better understand complex interactions. Finally, hydrologic water-routing models for the entire system, covering the northern tributaries, the delta, and the demand areas in the south, should continue to be developed as a way to understand water budgets and long-term patterns of water use under various alternatives.

The CALSIM model is an example of such a model (e.g., Systech Water Resources, Inc. 2011). The CALSIM and other models were discussed in the NRC's earlier report (NRC 2010). CALSIM, which has been developed over many years, is a good, system-wide water-routing model. However, it is a water-supply planning model. With climate change, it may need to be linked to watershed hydrology models to investigate the expected changes in hydrology. Besides a planning model, agencies may also need operational models. These models should help improve operations and be able to route high water flows through the system under future conditions.

Multispecies trade-offs have been quantified in other restoration programs to find possible solutions to what appear to be irreconcilable conflicts. Quantifying trade-offs is a way to initiate discussions that cut across traditional barriers. It is essential in finding solutions and identifying next steps in addressing the challenges that face the bay-delta rehabilitation effort. The SERES[24] report concludes with a lesson that is as applicable to the bay-delta as it is to the Everglades: "If the trade-offs inherent within the . . . system are not acknowledged, and management actions switch between the extremes of what is best for one group versus another, the outcome is likely to be more harmful than need be for all groups involved."

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[24] See the food web section of the Everglades Restoration Synthesis of Everglades Research and Ecosystem Services (SERES); http://www.everglades-seres.org/Products_files/SERES_Food_Web_Review%20copy.pdf.

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4

Environmental Change: Challenges and Opportunities

INTRODUCTION

Anthropogenic influences have rapidly and radically altered the bay-delta ecosystem over the past 150 years. Major changes such as land subsidence, climate change, habit alteration, water quality, population growth, water exports, invasion by nonnative species, and in-delta physical changes will continue to change the delta during the current century and beyond. Consequently, delta planning must envision a system that may be very different from what exists today, both physically and functionally. Rehabilitation planning in such a setting is extremely challenging as it is confounded by numerous uncertainties in the drivers of change. However, the projections of anticipated changes will allow many opportunities to tailor the restoration strategies to steer the future delta to a desirable state (Lund et al. 2010) and to include flexibility and wide tolerances in the design of water infrastructure and ecosystem rehabilitation. Some of the primary challenges include, but are not limited to, habitat loss, climate change including sea level rise, and levee stability. In this chapter, we discuss the details and the potential implications of these challenges and opportunities.

HABITAT LOSS

Habitat loss has been implicated as a major factor in species extinctions (e.g., NRC 1995, 1996, Seabloom et al. 2002). This relationship has been established over a very wide range of habitats and species, and there is no reason to conclude that it is any less important in the delta than elsewhere.

Indeed, the extent of changes in the delta (e.g., Lund et al. 2010; see discussion of changing delta environments below) compound the effects of the many dams on major delta tributaries that remove habitat for migratory species whose passage is blocked by the dams (e.g., NMFS 2009).

Habitat is the physical and biological setting in which organisms live and in which other components of the environment are encountered (Krebs 1985, NRC 1995). Thus, all aspects of the delta, past and present, serve as habitat and all the environmental changes described in Chapters 1 and 3 affect habitat and the species that depend on it. Many efforts have been made and are ongoing to measure and assess habitats in terms of their suitability for organisms (e.g., NRC 2008a). The habitats of the delta are diverse in character and include the water column; submerged substrates; adjacent intertidal, wetland, and upland areas; agricultural fields; levees; rivers and streams; the estuary; and so on. All of them have changed markedly in the past 150 years. Based on the complexity of delta habitats and the modifications to them, the interactions between stressors (for example, the interactions among temperature, salinity, and invasive cyanobacteria) must be considered.

In many cases, substantial knowledge exists around habitat needs for individual species. For example, much is known about what salmon need with respect to temperature, water flows and velocities, turbidity, water depths, substrate and gravel types, seasonality of many of the preceding factors, riparian vegetation, and especially access (e.g., see Williams 2006, McLain and Castillo 2010, NMFS 2009). For delta smelt, important habitat factors include open water, semienclosed bays, flow rates and volumes, temperature, turbidity, and salinity. The list of factors increases when habitat for their prey is also considered. Changes in pelagic fish habitat have been described (e.g., Nobriga et al. 2008). One key aspect for pelagic organisms is that, unlike species that require specific substrate conditions, high-quaity habitat (and, similarly, low-quality habitat) for these species shifts location with changes in water conditions, especially in tidal areas. Thus, management of the salinity gradient, for example, in the estuary has important implications for delta smelt and other pelagic species.

The delta ecosystem will never return to its predisturbance state. Changes in the template combined with changes in community composition provide a context for efforts to "restore" the delta. The changes in delta geometry in the past 150 years, in both vertical and horizontal planes, have resulted in a system dominated by subsided islands and deep, levee-bound channels. The continued loss of peat from the islands combined with rising sea level continues to lead the system away from its former topography and bathymetry (Mount and Twiss 2005). Recent studies (Brooks et al. 2012) point to subsidence of 3 to 20 mm per year associated with compaction of underlying Quaternary sediments. Brooks et al. conclude that "[b]y 2100, all scenarios except the lowest rate [of sea-level rise] combined with the lowest reference frame bias project that at least ~38 percent and likely closer to ~97 percent of all levees" will subside by at least 0.5 m below their current elevations. In addition, the changes in water chemistry, nutrient concentrations, altered residence times, and their consequences challenge the re-creation of habitat. As an example, one of the challenges in rehabilitating the Everglades in Florida is that nonnative species, increased phosphorus loads, and changed hydrology mean that simply restoring water flow without other actions will not lead to a recovery of the former community structure and composition (e.g., NRC 2010).

Even if tidal water and dredged material were reintroduced to flooded islands to return them to an intertidal or shallow subtidal elevation, continued maintenance of such elevations in the face of sea level rise will be necessary to maintain native wetland plant communities within their hydrologic tolerance limits and will require the accumulation of organic matter and sediment. Reed (2002) showed that even though delta wetland soils are frequently described as peats, the proportion of minerals in wetland soils even in the sediment-starved central delta was more than 75 percent on a dry-weight basis. Periodic inputs of sediments to the delta and redistribution of erodible material by tidal and flood flows were likely important in maintaining historic marsh elevations given underlying subsidence and sea level. However, Wright and Schoellhamer (2004) show that "the delivery of suspended sediment from the Sacramento River to San Francisco Bay has decreased by about one-half during the period 1957 to 2001." They attribute this decline to many factors, "including the depletion of erodible sediment from factors that affect sediment load, including hydraulic mining in the late 1800s, trapping of sediment in reservoirs, riverbank protection, altered land-uses (such as agriculture, grazing, urbanization, and logging), and levees."

Even if the historic mosaic of wetlands, mudflats, and shallow tidal channels could be re-created, changes in delta biological communities mean these habitats would likely be used by a different suite of species. Grimaldo et al. (2012) compared fishes caught in shallow subtidal areas in a remnant natural wetland with several areas returned to tidal action by inadvertent levee breaches. They conclude that physical habitat modifications and biological introductions have had irreversible effects on native fish assemblages and their habitats. Even in areas that had not undergone any physical modification to its historic marsh area, the subtidal mudflats surrounding the marsh were entirely colonized by invasive submerged aquatic vegetation (SAV) to the extent that it "choked out" any transitional open-water habitat between the shallow shoals and the marsh. The fish assemblage at the unaltered site in Grimaldo et al.'s study was dominated by introduced fishes, such as centrarchids, which are well adapted to SAV.

Recreating wetland-mudflat-channel configurations with land sculpturing may be possible, and reintroducing tidal flows to formerly isolated areas is a well-established restoration technique. However, a restored geomorphic-hydrologic condition would not support the same assemblage of species in the same numbers as were present before the delta was altered, although it might be possible to approach previous community compositions in some places.

CLIMATE CHANGE AND THE DELTA ECOSYSTEM

Climate change is a challenge confronting the management and restoration of the Central Valley and bay-delta ecosystem. Future changes in the mean climate and its variability are expected to profoundly affect the physical and ecological structure of the ecosystem as well as the nature of water issues in California. The cascading effects of climate change begin with increasing temperature, which over the 50-year planning horizon of the delta is predicted to increase between 1°C and 3°C (Cayan et al. 2009). This equates to the mean annual air temperature in Sacramento increasing from the current 16°C (~61°F) to somewhere between 17°C (~63°F) and 19°C (~66°F). At first glance, this does not seem especially significant, since the average low temperature in Sacramento in December is 4°C and the average high in July and August is 34°C. However, accompanying a rising temperature, the pattern of precipitation and runoff is expected to change significantly and the sea level is projected to rise (USBR 2011). These factors will affect the bay-delta ecosystem, its tributary watersheds, and the water supply critical to both urban and agricultural users (Chung et al. 2009; USBR 2011).

Physical impacts of climate change in the bay-delta region have been well studied (e.g., Field et al. 1999, Cayan et al. 2008, Franco et al. 2008, CDWR, 2010, CAT 2010, USBR 2011). The work to date includes a systems approach for understanding the natural variability including the potential global teleconnections to the region's climate (Redmond and Koch 1991, Greshunov et al. 2000), detection and attribution of historical changes in climate (Bonfils et al. 2008), quantification of potential changes in primary stressors of climate through analyses of the General Circulation Model (GCM) predictions (Cayan et al. 2009) and downscaling (Hidalgo et al. 2008. Maurer and Hidalgo 2008), impacts of projected sea level rise (Knowles 2009), and the sensitivity of the water resources system to climate change and sea level rise (USBR 2008, 2011). However, only a few projections have quantified the impacts of warming, consequent changes in hydrology, and the sea level rise on the ecology of the Central Valley–bay-delta region. Some initial work is under way to integrate links between climate, hydrology, and ecology in the bay-delta system and its watersheds

(CASCaDE 2010, Cloern et al. 2011), which should prove to be beneficial information for planners in the future.

In considering climate impacts on the ecosystem, the change and especially the variability in the seasonal patterns of precipitation, flows, and temperature are probably most important in disrupting the life history patterns of delta species. The delta is changing continuously and natural but extreme variations could pose significant threats to the sustainability of its desirable ecological functions.

A conceptual framework for addressing climate change effects in the bay-delta system includes the linkages between global drivers, both natural and anthropogenic, the regional and local stressors, and the corresponding effects. Warming due to anthropogenic greenhouse gases, as highlighted recently by the recent report of the Intergovernmental Panel on Climate Change (IPCC 2007), is the primary change in climate and the cause of sea level rise in the Central Valley. The other primary driver, natural variability, is manifested in multidecadal changes in precipitation and temperature patterns (Pagano and Garen 2005) and intradecadal variations associated with such phenomena as the El Niño/Southern Oscillation (ENSO) (Redmond and Koch 1991), the Pacific Decadal Oscillation (Francis and Hare 1994), and the North Pacific Oscillation (Pierce 2005). For example, Pagano and Garen (2005), who studied streamflows from 1901 to 2002 in California, showed that the period from 1980 to 2002 had the greatest variability and persistence in streamflows. This means that there were periods of wet years along with multiyear extreme droughts. El Niño winters result in wetter winters, particularly in South California, but have had a lesser impact on northern regions of the state (Redmond and Koch 1991, Cayan et al. 2009). Ocean-atmospheric patterns will also elevate the sea levels along the west coast during the El Niño years (Cayan et al. 2008).

In the ensuing sections, we begin with a review of the magnitude of climate change and sea level rise and large-scale hydrologic effects of climate change, scale down to how changes may disrupt the life cycles of listed delta species, assess how these effects might impact restoration planning efforts, and finally provide suggestions for dealing with climate change.

Estimates of Climate Change

Temperature and Precipitation

Results of climate modeling are not necessarily accurate predictions of the magnitude of warming. However, model projections consistently show that the gradual warming in California during the earlier part of the 21st century is very similar for various emission scenarios, but they may differ in the later decades. Projection estimates vary but the midcentury warming is in the range of 1°C to 3°C, which will increase to 2°C to 6°C by the end of the 21st century (Cayan et al. 2009). Climate models also predict substantial variability in warming across the Central Valley (USBR 2011). This asymmetry in temporal (both seasonal and decadal-scale) and spatial warming will substantially affect precipitation patterns (snow versus rain), snowpack, and the snowmelt in the tributary watersheds of the bay delta. Compared to the historical period, spring temperatures are projected to be warmer, particularly during the second half of the century, and reduce April 1 snowpack, a key indicator of water supply for the following summer and fall. The duration of extreme warm temperatures grows from 2 months (July-August) to 4 months (June to September) (Climate Action Team Report 2010). Heat waves are also projected to increase in frequency and magnitude.

Projections indicate that precipitation may decline in some regions of the Central Valley, particularly during the mid- to late 21st century (Cayan 2009, USBR 2011). They also show that precipitation may increase slightly until the middle of the century, which may be followed by a decline during the later part of the century. Although precipitation predictions are highly uncertain (Chung et al. 2009), projections of increases in temperature, predicted by all models, are more certain. The effect on snowpack and snowmelt of these projected temperature increases would be a significant change in the timing and magnitude of flows in the tributary rivers of the bay-delta system (USBR 2011).

Sea Level Rise

Sea level rise driven by global-scale climate change will affect, perhaps irreversibly, the bay-delta hydrodynamics, levee stability, and salinity conditions (Mount 2007, Lund et al. 2010). Higher ocean levels, particularly in the presence of tides, and storms, which may be exacerbated by ENSO conditions, will increase water depths and push salty water further inland, affecting vertical mixing. The exact effect of sea level rise depends on its magnitude. The historical rate of sea level rise at the Golden Gate is estimated to be about 2 mm/yr (equivalent to about 0.2 m over the 20th century).

During the 20th century, the global mean sea level rise has been estimated to be about 1.7 mm/yr (Church and White 2011). IPCC (2007) projected the sea level rise by 2100 to be in the range of 0.18 to 0.59 m but it did not include possible rapid changes in ice sheet dynamics. The current research suggests that, during the 21st century and beyond, sea level rise may accelerate, but the estimates of the rate of acceleration vary as indicated by the wide range of sea level rise suggested for 2100 in the literature. The uncertainties in projections have been attributed to the difficulties in projecting the melt rate of land-based ice, particularly in Greenland and Antarctica. Temperature-based projections (Rahmstorf 2007) suggest that the global mean sea level rise may be as much as 1.4 m or more (Pfeffer et al. 2008, Vermeer and Rahmstorf 2009). Clearly the magnitude of the future global sea level rise is uncertain but the range 0.18-1.4 m or the sea level rise that has been suggested by USACE (2011) should be useful for scenario planning in restoration efforts (e.g., Heberger et al. 2009, 2011).

Effects of Climate Change on Delta Hydrology

Climate change could have a variety of impacts on both natural and human systems in the bay-delta region. In terms of hydrologic changes, one of the key outcomes of warming will be to alter the temporal patterns of precipitation and tributary runoff. Under warmer conditions, precipitation during the winter will occur more as rain instead of snow and, as a consequence, the April 1 snowpack will decline (Mote et al. 2005, Knowles et al. 2006, Chung et al. 2009, USBR 2011), which will reduce the summer low flows (Maurer 2007). The modeling results indicate that the runoff resulting from increased rain during the winter months of December through March will increase during the 21st century (USBR 2011). However, the snowmelt runoff from tributaries during the April-July period will decrease with larger magnitudes expected during the later part of the 21st century. Such significant changes in the magnitude and timing of runoff into major reservoirs in the Central Valley could have important impacts in terms of reduced storage opportunities, less year-to-year carryover storage, and less water for cold-water releases during the hot summer months (USBR 2011).

Unless changes to the operational rules are made, the increased runoff into major reservoirs in the tributary watersheds during winter months may have to be released earlier for flood protection. This would in turn reduce the amount of storage available to meet the demands during the following summer and fall. The recent records already show changes in timing of flows from the headwaters of the Sierra Nevada region (Dettinger et al. 2004, Knowles and Cayan 2004, Stewart et al. 2004, Vicuna and Dracup 2007, Kapnick and Hall 2009). With high confidence, it can be concluded that the future temperature increases will continue to cause changes in streamflow timing and such projected changes will exceed those from natural variability (Knowles and Cayan 2002, Maurer et al. 2007). For example, Chung et al. (2009) have shown that in case of a 4°C warming scenario, the average day by which Lake Oroville receives half its annual inflow shifts from mid-March to mid-February (about 36 days) and that the annual runoff fraction during the snowmelt period of April through July will decrease from about 35 percent to about 15 percent.

Warming has the potential to increase evaporative losses from both soils and water bodies and as a consequence increase water demands of both agriculture and landscape irrigation. Increased CO_2 will have complex interactions among processes affecting evapotranspiration from plants. Baldocchi and Wong (2006) have suggested that warming effects on agriculture may include the lengthening of the growing and transpiration seasons of the crops and a reduction of winter cold affecting fruit species. Groves et al. (2008) determined that climate change could increase the outdoor water demand by up to 10 percent by 2040 and decrease local water supply by up to 40 percent. With a decrease in spring and summer runoff, the difference between supply and demand will grow at a faster pace. Climate change will require a change in future operation and planning of water resources systems and the current regulatory policies (Willis et al. 2011).

In a widely quoted paper, Milly et al. (2008) claimed that the traditional "stationarity" assumption used in planning of water resources projects was no longer viable or prudent. The changes in hydrology described above would pose significant challenges for the management of the water resources systems such as the Central Valley Project (CVP) and the State Water Project (SWP). Willis et al. (2011) suggested that the "static" rules curves that exist today may perform poorly under the climate change scenario and that more flexible dynamic operating rules may be needed in the future (see Trimble et al. [2005] for an example of such rules). The U.S. Bureau of Reclamation in its 2008 Biological Assessment analyzed the sensitivity of future state and federal projects in the bay-delta region to potential climate change and associated sea level rise (USBR 2008), finding that CVP/SWP deliveries and carryover storages were sensitive to precipitation changes and sea level rise would lead to great salinity intrusion into the delta. Increased air temperature would reduce the cold-water storage of the reservoirs and increase temperature regimes of the major tributaries of the delta, which in turn would affect the survival of both delta smelt and salmon. The study also indicated that the negative flows in the Old and Middle rivers will increase under climate change scenarios, primarily during the winter, exacerbating fish entrainment at the CVP/SWP pumps. However, the study also found that uncertainty in precipitation projections makes it difficult to assess the level of impacts, as a potential increase in precipitation may offset the warming impacts.

The Department of Water Resources conducted a separate modeling study to investigate the effects of climate change on both the federal and state water projects (Chung et al. 2009). The results (Table 4-1) suggest that the SWP/CVP water supply reliability would be affected significantly under the projected climate change scenarios. Reduction in delta exports to the Central Valley was predicted to be in the range of 7 to 21 percent and the water supply deficit in the south, resulting from such conditions, would likely be met by increased groundwater mining, exacerbating the current

TABLE 4-1 Summary of Water Resources Impacts Considering 12 Future Climate Scenarios

	Midcentury: Some Uncertainty	End of Century: More Uncertainty
	Lower to Higher GHG Emissions	Lower to Higher GHG Emissions
Delta Exports	– 7 to –10%	–21 to –25%
Reservoir Carryover Storage	–15 to –19%	–33 to –38%
Sacramento Valley Groundwater Pumping	+5 to +9%	+13 to +17%
CVP Generation	–4 to –11%	–12 to –13%
CVP Use	–9 to –14%	–24 to –28%
SWP Generation	–5 to –12%	–15 to -–16%
SWP Use	–5 to –10%	–16%
X_2 Delta Salinity Standard	Expected to be met	Expected to be met
System Vulnerability to Interruption[a]	1 in 6 to 8 years	1 in 3 to 4 years
Additional Water Needed to Meet Regulations and Maintain Operations[b]	750 to 575 TAF/yr	850 to 750 TAF/yr

NOTE: CVP, Central Valley Project; GHG, greenhouse gas; SWP, State Water Project; TAF, thousand acre-feet.
[a] The SWP-CVP system is considered vulnerable to operational interruption during a year if the water level in one or more of the major supply reservoirs (Shasta, Oroville, Folsom, and Trinity) is too low to release water from the reservoir. For current conditions, the SWP-CVP system is not considered vulnerable to operational interruption.
[b] Additional water is needed only in years when reservoir levels fall below the reservoir outlets.
SOURCE: Chung et al. (2009).

problem of declining groundwater levels in the Central Valley (Famiglietti et al. 2011). Reservoir carryover storage, the quantity of water available on September 1 for improving water-supply reliability during the ensuing year, is expected to decline by 15 to 38 percent depending on the climate change scenario. Significantly, the study indicated that in some years the water levels in reservoirs may fall below the lowest release outlets leading to operational interruptions, which may occur as frequently as once every 3 years (Table 4-1). In spite of the water shortages, the CVP/SWP system was expected to meet the delta salinity standard related to the position of X_2 ("delta salinity standard"). Other modeling suggests that there is considerable physical and economic flexibility in the system, although at some cost (Tanaka et al. 2006, Harou et al. 2010, Buck et al. 2011). This flexibility likely will be needed to adapt to future conditions.

Effects of Sea Level Rise

Ecosystems physically connected to the ocean, such as the California bay-delta system, will have compounding effects of climate change due to accompanying sea level rise on both global and regional scales. Increases in ocean levels at the mouth of the San Francisco Bay will have significant impact on the upstream regions of the bay as well as the delta. A larger concern is the changes in the sea level extremes, which are exacerbated not only by the mean sea level, but also by astronomical tides, winter storms, and the presence of large-scale ocean phenomena such as El Niño. Predictions of the changes related to additional factors are uncertain but it is likely that today's extremes experienced by the bay-delta system will become more frequent.

As discussed in the next section, the projected changes in both the average and extreme sea levels in the interior of the delta may significantly affect the structural integrity of levees protecting delta islands. In view of the changes in the tidal fluctuations, particularly during storms, the frequency of levee failures and the flooding of delta islands are likely to increase. Historical efforts to control floods do not appear to have reduced the levee failure frequency (Florsheim and Dettinger 2007). The frequency of levee failure is likely to increase in the future with potential increases of flood flows from the upstream reservoirs as a result of timing change in runoff and increased water levels in the delta conveyance canals due to sea level rise. The dual effect of sea level rise and the increased flood flows will be largest when the astronomical and weather factors (e.g., high tides and sea level increases due to storms and teleconnections such as El Niño) and the peak discharges from the upstream coincide to create a rare combination of factors affecting the water levels in the bay and delta. Levee failures will flood delta islands, either permanently changing the geomorphology and the habitats of the delta system or requiring massive investment to reestablish the status quo. It has been suggested that restructuring of bay-delta habitats as a result of levee failure could increase habitat diversity, expand floodplain area, and increase extent of open-water habitats. Such changes could improve conditions for some desirable delta fish species (Moyle et al. 2010).

Another effect of sea level rise will be increased saltwater intrusion into freshwater parts of the delta system. When saltwater intrusion occurs in the interior parts of the delta, quality of water that is exported will degrade significantly and aquatic habitats will shift or may be eliminated entirely. Frequent interruptions of water supply to the south via the export pumps will clearly pose problems for providing adequate water supply for farmers and the urban users in Southern California (Medellin-Azuara et al. 2008, Chen et al. 2010). The ultimate result will be for the users south of the delta to depend on more and more groundwater supplies in the regions to the south, which have already been mined through excessive pumping (Famiglietti et al. 2011). Permanent changes to the salinity levels in delta channels will also degrade the quality of water that is used for agriculture and other uses within the delta islands.

Climate Change Effects on Water Temperature

The water temperature in the delta and upper San Francisco Bay varies considerably through the year with a range of 7°C to 30°C (see Figure 4-1). While temperatures primarily vary seasonally, as seen in Figure 4-2B below, temperatures on any given day can be several degrees warmer or colder than the seasonal average.

At any point in the system this temperature reflects the combined effects of solar insolation, surface heat exchanges, river flow, and dispersion, as well as the temperatures in the rivers upstream and ocean downstream (Monismith et al. 2009). To examine the potential effects of climate change on delta temperatures, Wagner et al. (2011) created a statistical model based on fitting 10 years of data using an autoregressive model for daily water temperature as a function of air temperature and solar insolation. On the basis of this model, Wagner et al. argue that the effects of flow are generally small and are confined to shorter time scales, and so could be ne-

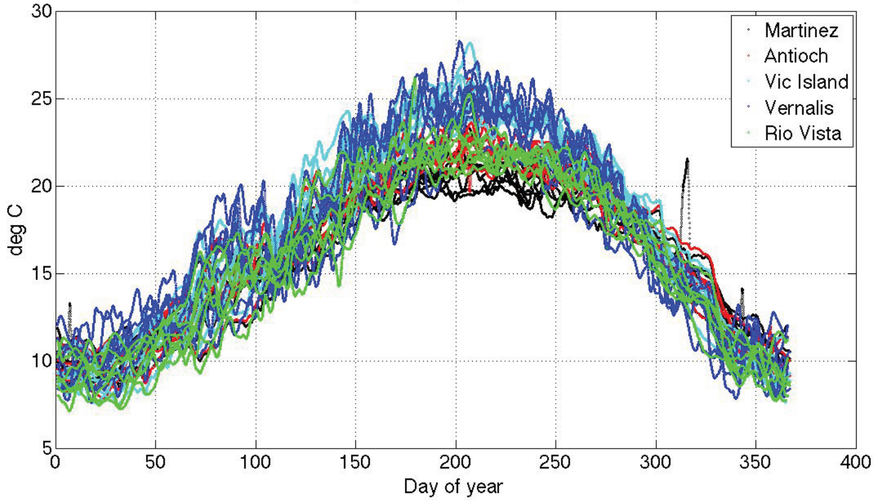

FIGURE 4-1 Suisun Bay delta water temperature for the period 2000-2006.
SOURCE: Data from California Data Exchange Center.

glected, at least when considering climate effects. In particular, the residuals of their model are weakly correlated (San Joaquin River) or uncorrelated (Sacramento River) with flow. This is plausible given that travel distances between sources of cold water (i.e., reservoirs) and the delta may be sufficiently great for river temperatures to approach the equilibrium temperature, that is, the temperature at which the net heat flux is zero (Mohseni et al. 1999). Additionally a statistical regression model, developed under the CASCaDE (2010) project, demonstrated some promise for predicting water temperatures in the delta.

Climate Effects on Species

To understand the effects of climate change on the delta fish species, we need to consider the effect of climate change on the intensity and duration of summer heat, the frequency of floods and multiyear droughts, and the level of snow pack. In short, while climate change is typically described in terms of trends in mean weather patterns, what matters to fish are the frequency and intensity of extreme events that can disrupt their life history strategy and ultimately their survival. Here we illustrate how climate events will challenge fish.

Salmon

Salmon and steelhead are poikilothermic (cold-blooded) animals that thrive over a wide range of temperatures. However, at the upper limit of the range (~22°C), their respiration increases, growth declines rapidly (Figure 4-2A), and they become susceptible to infection: all factors that increase mortality. Central Valley salmon experience nearly 100 percent mortality when temperatures exceed 23°C (Baker et al. 1995). In the Central Valley, summer water temperature regularly exceeds salmons' threshold (Figure 4-2B); consequently, heat-avoiding strategies have been selected for. Fall/late-fall runs of Chinook salmon have the most straightforward strategy, which is simply to avoid the Central Valley in the summer. The adults enter the valley in the autumn and move quickly into tributaries to lay their eggs. The juveniles hatch in the winter and spring and leave the Central Valley before the summer. More complex strategies involve either eggs or adults being in cool-water refuges in the summer. For the winter-run Chinook salmon, the adults enter the valley in the winter and move to the upper Sacramento where they spawn in the summer, in fractured basalt habitats fed by cool-water springs. The juveniles emerge from the gravel in the fall and migrate downstream in the winter. For spring-run Chinook salmon, the adults enter the Central Valley in the spring and migrate to high-elevation tributaries where they "oversummer" in cooler waters. When the temperature drops in the autumn, they move into spawning habitats in the streams.

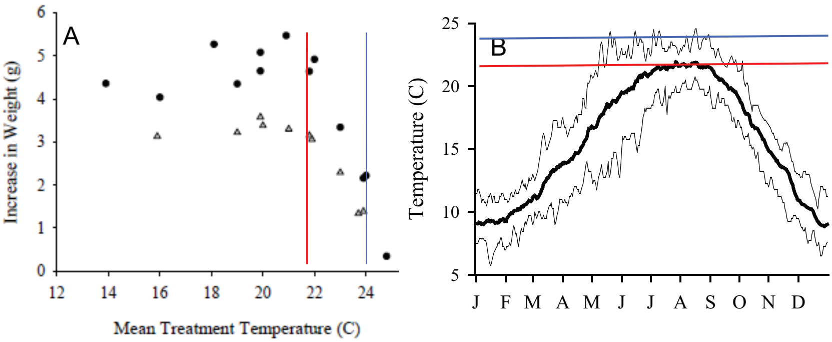

FIGURE 4-2 (A) effect of temperature on growth of Chinook raised at various temperatures for 28 days. From Williams (2006) redrawn from data in Brett et al. (1982). (B) Daily minimum, maximum, and average water temperature in the northern delta (Sacramento River at Freeport, near Sacramento). In panels A and B the red lines demark the temperature (~22° C) above which salmon growth declines and the blue lines depict the lethal temperature threshold (24° C) for salmon.
SOURCE: Williams (2006).

The juveniles emerge in the winter and migrate downstream before the onset of summer. In essence, each run exploits a spatiotemporal window of opportunity within the Central Valley. The strategies allow what are essentially cold-water species to occupy warm-water habitats. However, these habitats are the southern boundary of salmon. Windows of opportunity for avoiding lethal temperatures do not exist south of the Central Valley. Furthermore, human development has significantly reduced the limited windows of opportunity that did historically exist here. Dams block access of spring Chinook to the most high-elevation habitats, as well as access of winter Chinook to cool groundwater habitats and access of fall Chinook to tributaries (Lindley et al. 2006). How climate change will affect these windows is highly relevant in the rehabilitation of Central Valley salmon and steelhead. The effects of climate change on phenotypic plasticity and evolution, and their implications for population persistence (survival), are discussed by Reed et al. (2010).

To explore how the windows will change, consider a scenario in which Central Valley streams warm by 1°C, which is a reasonable midcentury estimate (Wagner et al. 2011). The average daily temperature would become what is now the maximum daily temperature line in Figure 4-2B. This temperature increase would increase mortality for outmigrating spring-run salmon smolts. Supporting evidence includes (1) observations of increased mortality in salmon at high temperatures (Williams 2006), (2) observations (1976-1981) of a strong negative correlation between June smolt survival and average June water temperature at Sacramento (Kjelson et al. 1982), and (3) a statistical study revealing the importance of temperature on smolt survival in the delta (Newman and Rice 1997).

Not only are summer temperatures expected to become more lethal to fish by midcentury, the number of months with high temperatures is expected to double or more (Wagner et al. 2011). Expanding the duration of high temperature would narrow the window in which fall Chinook runs could occupy the Central Valley, which would disrupt both their growth pattern and migration timing. At the very least, the population would undergo a period of rapid selection under a new temperature pattern (Crozier et al. 2008). Hotter summers would increase the temperature of high-elevation streams and reduce, or intermittently remove, the cool-water habitat spring Chinook seek in the summer, a situation already observed in the Central Valley (Williams 2006). Winter Chinook runs would also be affected. Using the statistical life-cycle OBAN[1] model calibrated with recruitment and environmental data between 1967 and 2008, Lessard et al. (2010) found that egg-rearing temperature of winter Chinook above Red Bluff Diversion Dam was a major determinant of year class strength. Furthermore, climate models predict increased variability in climate extremes, so infrequent but intense summer heat waves could have even greater effects on sensitive life history strategies.

Climate change models also predict increased duration and intensity of droughts in the western United States (CCSP 2008). Here the potential effects on salmon would be uniformly negative. Summer flows in high elevations would be reduced, affecting adult spring Chinook; summer groundwater flows would be reduced, affecting winter Chinook eggs; and autumn and spring flows in tributaries would be reduced, affecting growth opportunity and migration timing of fall/late-fall Chinook. Droughts extending over multiple years are of particular concern because several brood years would be affected, thus reducing the natural resiliency salmon obtain by intermixing fish from different brood years on the spawning grounds. Another aspect of the predictions of climate change models is more-intense precipitation events and floods (Min et al. 2011), which can scour the gravels, killing fish eggs while they incubate.

Finally, climate change can affect salmon indirectly through its effect on coastal winds, which drive coastal upwelling that fertilizes the food web on which salmon depend when they enter the ocean (Lindley et al. 2009). Furthermore, because large-scale climate patterns affect both the freshwater and ocean habitats of salmon (Lawson et al. 2004), extreme stream temperatures and reduced coastal winds could act together to amplify the impacts of climate change.

[1] Oncorhynchus Bayesian ANalysis

Thus, even though summer temperatures in most of the Central Valley streams are lethal to salmon, the fish exploit windows of opportunity for when to enter the Central Valley and where to spawn, so that they and their offspring avoid the high temperature. However, over the 21st century, if predictions of warmer and longer summers and shifts in precipitation and coastal winds come true, the windows of opportunity for many runs will narrow and some will eventually close. Furthermore, the process is not expected to be gradual. The frequency and intensity of daily and seasonal weather extremes will exceed the historical levels in which the salmon evolved their current life history strategies. The consequences are potentially great because even now Central Valley salmon live at the threshold of their temperature range. For the most part, studies of the impact of climate change have been cast in the context of mean trends, not in terms of changes in extremes. For example, a conceptual model was developed to explore possible evolutionary responses of Pacific Northwest salmon life history and tolerance to heat with changing environmental conditions (Crozier et al. 2008). Such evolutionary-scale focuses are highly relevant to the long-term effects of climate change on fish, but the more immediate issue, especially for the Central Valley, which is the southern end of the salmonid range, is the impact of extreme events such as heat waves and multiyear droughts. Indeed, demonstrable effects of climate events may already have occurred as evidenced by the 60 percent summer mortality of spring Chinook in Deer Creek in 2002 (Williams 2006) and the failure of the 2004 and 2005 fall Chinook classes because of the collapse of the Gulf of Farallones food web (Lindley et al. 2009).

Delta Smelt

The effects of temperature may be more critical for delta smelt than for other fish in the basin. In his assessment of the state of the delta smelt population, Bennett (2005) notes that few delta smelt were caught in any of the various surveys when the water temperature exceeded 20°C. Moreover, lab studies cited by Bennett find that spawning was confined to temperatures between 15°C and 17°C, whereas an optimal range for spawning determined from field observations of larval delta smelt distributions appears to be 15°C to 20°C. Additionally, Bennett (2005) found that a significant correlation exists between delta smelt abundance and the length of time that the water temperature in the delta was between 15°C and 20°C. Finally, Swanson et al. (2000) found that temperatures over 25°C are lethal for delta smelt. Importantly, using downscaled predictions of atmospheric temperature from several GCMs, Wagner et al. (2011) projected that the delta can be expected to warm by several degrees over the next century. As a result, this will shift the window in time when temperatures are suitable for delta smelt spawning 2 weeks earlier in the year and will mean that large portions of the delta will be lethal for delta smelt for a significant portion of the year (10 to 60 days; see their Figure 12).

Other Species

Besides salmon and smelt, it is likely that temperature will affect several other organisms, including the listed green sturgeon. However, to the best of our knowledge, there are no studies of temperature effects on other organisms, e.g., benthic infauna like the invasive clam *Corbicula fluminae*, or the various zooplankton species resident in the system. Increases in water temperature might produce more subtle food-web changes. For example, since growth rates of cyanobacteria like *Microcystis aeruginosa* increase substantially with temperature, a warmer delta might be more prone to *Microcystis* blooms that could reduce production of phytoplankton that are more easily grazed and made use of by larval fish or by zooplankton that make up the prey of juvenile and adult fish (Lehman et al. 2005). Evidence for temperature related shifts in phytoplankton community structure in the delta is given by Lehman and Smith (1991) and by Lehman et al. (2008).

Managing Temperature

From the perspective of water resources management, it does not appear that the increasing delta water temperatures can be efficiently mitigated by project and reservoir operations. In principle, delta water temperatures can be affected by river flow rate and reservoir release temperature, since flow determines the time required for water to travel between reservoir outlets and the delta and hence the time over which radiative heating and heat exchanges with the atmosphere can raise the water temperature to the equilibrium temperature[2] (Monismith et al. 2009). Thus, the farther the reservoir is from the delta, the less effect a given flow rate has on the temperature since the longer it takes for water to travel to the delta, the more likely it will be close to the equilibrium temperature (Deas and Lowney 2000). The farther the reservoir is from the delta, the more flow it takes for a given release temperature to produce a desired temperature at the delta.

Looking at data relating water temperature at Vernalis for a critical window (April 15 to May 13) of salmon smolt outmigration in the San Joaquin River, Cain et al. (2003) suggested that a flow of 5,000 cubic feet per second (cfs) in the main stem of the San Joaquin was needed to provide water temperatures suitable for salmon migration, although this correlation may mask the effects of other variables like air temperature. In contrast, the statistical model of Wagner et al. (2011), suggests little influence of flows.

[2] The equilibrium temperature is the temperature at which the net heat flux into the water is zero. It is generally above the atmospheric temperature.

Most reservoirs, particularly the largest ones, Shasta and Oroville, are too far upstream or have insufficient water in the cold water to affect delta temperatures significantly.

Thus, while further work to understand the linkage of flow, and hence water operations, and delta water temperatures (e.g., along the lines described by Deas et al. [1997]), may refine the picture presented above, the committee concludes that it is unlikely that reservoir releases can be effectively used to control delta water temperatures.

Integrating the Analyses

The preceding discussion suggests that many variables and factors need to be considered in projecting the effects of climate change on the Central Valley system. In such a situation, an integrated analysis using a series of linked models would be required to understand the cascading effects and the feedbacks on the large water resources system, including the delta. Since comprehensive biological models are not available for analyzing how climate change and sea level rise may affect species in the greater ecosystem, many attempts have been made to project indicators of hydrologic and ecological changes that may result from a range of climate change scenarios. Cloern et al. (2011) present such an analysis using nine indicators of changing climate, hydrology, and habitat quality where projections were made using a series of linked models for simulating meteorology, hydrology, sea level rise, estuarine salinity, sediment transport, and water temperature. This type of analysis, where alternative scenarios are used to link climate change to hydrologic and then biological processes, is extremely useful for understanding the range of changes that may be expected and planning future strategies for dealing with climate change. An example would be a life history model for San Joaquin salmon abundance based on flow and water temperature; the hydrologic parameters would be driven by climate change projections. Depiction of changes in the form of decadal trends, as shown in Figure 4-3, is useful for bracketing the future changes that may be expected in key indicators important for the development of response strategies. The range of climate change impacts discussed in the preceding sections, primarily in the form of increased air and water temperatures, less precipitation, higher sea levels, reduced runoff and late spring snow pack, and increased salinity, is similar to that estimated by Cloern et al. (2011) and shown in Figure 4-3. The committee concludes that the type of analysis conducted by Cloern et al. (2011) is extremely important to understand interacting effects and encourages the agencies to continue to improve their approach by adding other models such as those designed to predict species response.

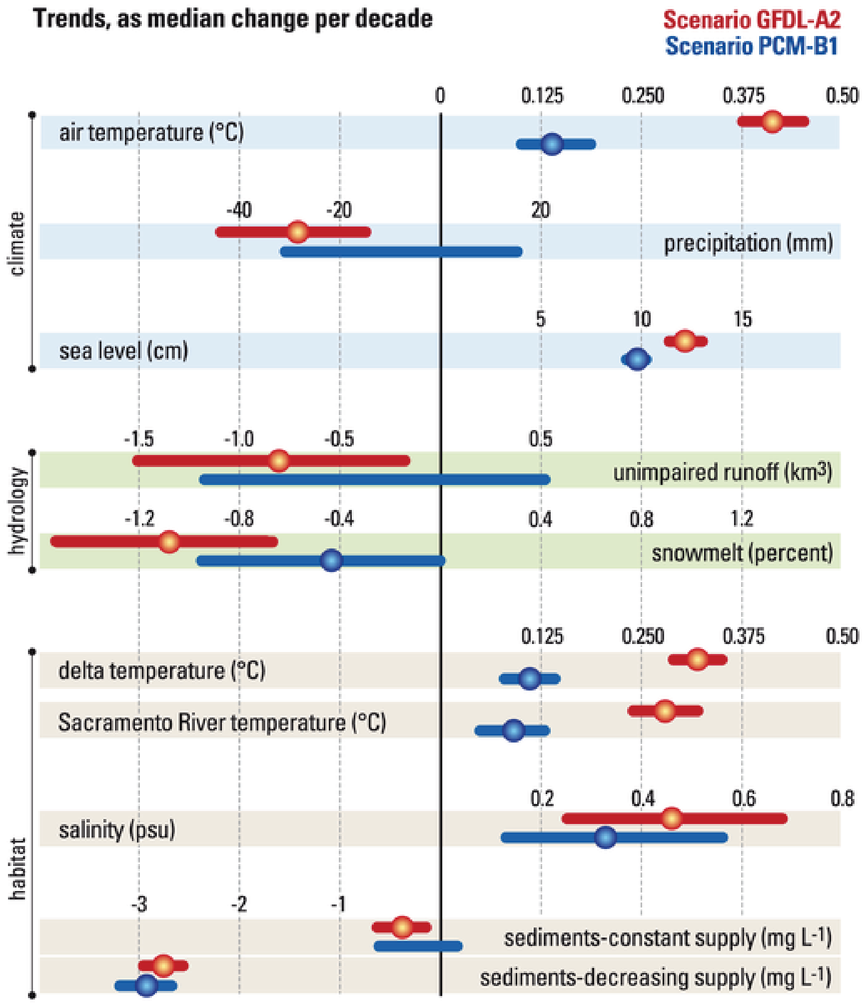

FIGURE 4-3 Projected 2010-2099 changes in selected environmental indicators expressed as median trend per decade for two climate scenarios (red and blue). Statistically significant ($p < 0.05$) trends are indicated with solid circles and the horizontal lines show the 95 percent confidence limits for the trend estimates.
SOURCE: Reproduced from Cloern et al. (2011).

Dealing with Climate Change

Because extreme events, whether they are from floods, droughts, or heat waves, will have large effects on fish and other delta populations, the adequacy of restoration actions and population models need to be considered in the context of increasing frequency and intensity of events. For example, if the frequency of extended hot dry summers increases, the frequency of year class failures would increase and the probability of extirpation of several salmon runs would increase. However, projecting the impacts of a changing frequency of extreme events is difficult. Current life-cycle models (e.g., Holmes 2001, Hinrichsen 2002, 2009, Lessard et al. 2010) assume that the pattern of demographic variability in the population is stable into the future. With climate change this assumption is violated, as described by Thompson et al. (2011). Furthermore, models are sensitive to choices of parameters characterizing future trends and so those not validated with data should be used with caution (Hulme 2005). In spite of these limitations, models linking climate variability and fish ecology are essentially the only way to project future impacts of climate change on fish (Jackson et al. 2009). However, those models need to be tested by careful monitoring; some effects of climate change on fish can be tested experimentally.

Information on climate science shapes public opinion regarding climate change, and the studies have much to contribute to the adaptive management of the Central Valley. While individuals typically form opinions either by learning from experience or from descriptions, experiential learning is the most compelling. However, when climate change is gradual, it has not been very noticeable to the public (Weber 2010). However, extreme events and resulting fishery closures are directly experienced by the public and noticed, although the public will not necessarily notice a connection between extreme events and long-term change. Yet if the climate predictions are correct, frequent extreme events will increase the need for Central Valley water resources by both the ecosystem and the public. In this case, managers may be asked to consider hard choices that are more in the context of triage than rehabilitation (e.g., CASCaDE 2010, Hanak et al. 2011, SPUR 2011). While such a scenario may not come to fruition, the committee encourages continued critical and comprehensive studies of the full range of future possibilities and how to adapt to climate change. Indeed, the committee recommends this kind of approach to delta issues in general.

In the future, effects of climate change will increase the need for Central Valley water resources by both the ecosystem and the public and induce even more competition among them. In developing alternative scenarios for the implementation of water management measures, it will be necessary to consider a larger variability in water supply and potential impacts on the ecosystem.

Incorporating climate change requires adoption of a nonstationary view; in other words, it reuires recognition that environmental correlates of climate continually change (Milly et al. 2008). Public investments and habitat management or water conveyance facilities should be evaluated and ranked for their adaptability to anticipated changes. In view of many uncertainties in the future extent of climate change, integrated analysis should be followed up with adaptation strategies using scenario planning and risk management strategies (e.g., Linkov et al. 2006). An approach that does not consider alternative futures may fail to achieve the anticipated benefits leading to the further degradation of the bay-delta ecosystem. Sustainability planning efforts will be successful only if they address the above challenges and the associated uncertainties. In the light of potential increases in water shortages and the competition for water, the committee judges that there are many opportunities and basic strategies for ensuring the long-term sustainability of the bay-delta ecosystem. Key considerations are discussed below.

Demand Management

Targeted reduction of demands through water conservation, and changes to the system of water rights and marketing, and alternative water supply (e.g., reuse), improvement of water use and conveyance efficiencies should be considered as integral components of future plans.

Increased Storage

Restoration of variability in flows that has been lost due to water management, hydrologic changes due to climate change, and the increased demands may require flexible operating strategies and increased water storage. In particular, anticipated changes in timing and magnitude of inflows may require additional storage in the system in order to meet the deficits in water supply, restore cold-water pools, and carry over storage in the system. Furthermore, additional flows may be required to mitigate impacts of saltwater intrusion and upstream migration of the delta X_2 salinity standard during droughts. Groundwater storage with artificial recharge, particularly in the Central Valley south of the delta, should be considered, along with opportunities to increase reservoir storage in the system or to change the operating rules for existing systems. The expansion of storage should not come at the expense of negative environmental impacts, and comprehensive planning investigations will be needed to explore this option (Medellin-Azuara et al. 2008, Tanaka et al. 2008, Harou et al. 2010). Another example, which is nonstructural, is the reestablishment of Environmental Water Accounts, a measure that had been used in the past.

Operational Flexibility

Water exports through the current CVP and SWP systems during dry periods through delta channels have shown to be harmful for delta smelt and other resident fish species. Conveyance of water through the delta is likely to experience additional constraints due to climate change. Flexibility in operations achieved through the establishment of multiple conveyance routes and operation of the water storage with foresight (e.g., based on climate outlooks) should help reduce the harmful effects of constraints and competition among urban and agricultural users and the ecosystem. However, a strong regulatory framework will be needed to ensure that the increased flexibility is not used to favor one user type over the other.

Establishment of Environmental Flows

Climate change will increase the competition for water among the users. Maintaining the flows necessary to sustain the protected species in the delta likely will require establishment of minimum flows but, more important, will require consideration of the timing, frequency, duration, and magnitude of flows and the rates at which those flow parameters change. Establishment of such flows will require a careful analysis of environmental water needs, water availability during droughts, development of water shortage policies, and the implementation of specified conveyance priorities.

The committee has identified a variety of tools for predicting the effects of climate change on the key variables that will affect the bay delta. Since climate change is expected to alter these variables in new ways, extrapolations of historic data (stationarity) are not a sufficient basis for future public policy. A new combination of predictive models and data that defines actual changes as they occur is needed to assess risk and make investments. State and federal agencies have done much to translate climate change models into predictive regional effects in California and in the bay-delta area. But risk analysis is needed to provide a justification or rationale for public investment. Small investments such as research and data gathering, and some forms of demand management, should not require a high level of confidence that a particular situation will occur. However, if a proposed policy or action is very costly, more confidence that it will actually achieve its purposes will be needed.

This committee's assignment has been focused on the bay-delta environment and water quantity and quality issues. These issues are but part of a larger picture of public investment in anticipation of the continued generation of environmental predictions. The 0.2-m rise of San Francisco Bay during the 20th century did not require large additional flood protection works. However, if the 21st century should see a significant increase in this trend, major investments will be needed in the bay delta to mitigate the broader impacts of climate change. In principle, this will be true with regard to water management practices in the bay delta and throughout the state. A significant effort is needed to develop new tools to assess risk, and to provide the public justification necessary to support the major public and private investments that will be needed.

LEVEES

The hydrology of the delta is profoundly influenced by its 1700 km of levees (CDWR 1995), with its ecology and services described as "levee-dependent" (Lund et al. 2010). Indeed, the levees play a critical role throughout California in reducing flood risk, supporting agricultural production, and providing reliable water supply.

However, despite their importance, the levees of the delta are broadly vulnerable to failure associated with seismicity, flooding, subsidence, seepage, and sea level rise (CDWR 2009). Levee failures have occurred regularly throughout the Sacramento–San Joaquin system since the first breach in 1852, with breaks occurring during 25 percent of years (Florsheim and Dettinger 2007). However, it has been the more recent failures that have acutely revealed the vulnerability of levees in the delta and directed attention toward the likelihood and consequences of their breaching. Beginning with the 1986 flooding in the Central Valley, followed by major levee failure in the 1993 Missouri River floods (Tobin 1995), through levee failures at Mildred Island in 1983, Liberty Island in 1998, and Lower Jones Tract levee in 2004, and with catastrophic breaches in New Orleans during Hurricane Katrina in 2005, the science and engineering around levees is increasingly under scrutiny at the local and national levels.

Locally, a growing body of research and analyses (e.g., Florsheim and Dettinger 2007, Moss and Eller 2007, Mount and Twiss 2005, Burton and Cutter 2008, Lund et al. 2010, CDWR 2009) has been undertaken to understand the likelihood of, the factors driving, and the impacts of future levee failures in the delta. Some ominous projections have been produced. For example, the U.S. Bureau of Reclamation (USBR) reported in 2008 that "[a] breach of one or more of the central delta levees could result in the temporary or long-term disruption of the water supply for about two-thirds of the state's residents and for about half of the state's irrigated agriculture." In the tricounty area encompassing much of the delta, 1.3 million people are projected to live behind levees by 2020, many of whom are considered socially vulnerable (e.g., infirm and institutionalized, elderly, non-English speakers) (Burton and Cutter 2008). Furthermore, efforts at river engineering and flood control management do not appear to have reduced the frequency of breaches in the Sacramento–San Joaquin system (Florsheim and Dettinger 2007).

The hazards contributing to levee failure are likely to increase in the future (CDWR 2009). The relationship between small floods (2-3 return-year interval) and levee breaching (Florsheim and Dettinger 2007) may result in increasingly frequent breaching as small floods are projected to increase in frequency in the system with climate change (Dettinger et al. 2006). Sea level rise and ongoing subsidence will further weaken the stability of the levees (Mount and Twiss 2005).

Expectations surrounding an increasingly unstable levee network are documented and include islands filling with water, potential for secondary failures, salinity intrusion, reduction in water quality, channel incision, and suspended water exports (Mount and Twiss 2005, CDWR 2009). Analyses indicate that widespread failure along the levee network, as would occur with a 6.5-magnitude earthquake, would result in up to $40 billion in damages (CALFED 2007). The 2004 levee failure along the Jones Tract alone is estimated to have cost Californians over $100 million (Burton and Cutter 2008).

As politicians, scientists, and engineers look toward more sustainable water management in the delta, the instability and interdependence of levees is likely to be a chokepoint for achieving any measure of water-supply reliability or ecosystem recovery. Continuing the status quo of improving levees, raising highways, and additional protective infrastructure (CDWR 2009), which characterized the 2006 congressional response to concerns over levee instability, will not always be the most environmentally sustainable or economically defensible response in the years ahead. Indeed, researchers (Suddeth et al. 2010) have found that levee upgrade could not be economically justified for the 34 subsided delta islands they examined.

When considering repair of unstable (and breached) levees in the delta, a transparent and vetted prioritization system is needed. The social and economic benefits and costs of repairs of levees (e.g., Suddeth et al. 2010) (see Ohio Levee Classification system, Ohio Emergency Management Agency 2011) should be balanced against those of repairs for islands where subsidence and other factors have reduced the economic and societal value of the land. Such a balancing should not be based solely on economic values. As highlighted during Hurricane Katrina, and as documented in the delta (Burton and Cutter 2008), socially vulnerable citizens tend to cluster within high-risk flood areas. Thus, decisions regarding levees and flood risk management may need to be localized to address differences in culture and language, age, and mobility of those protected by the levees (Burton and Cutter 2008). An approach to prioritizing repair and abandonment of levees should include a mix of economic and social values.

In some cases, managers will need to look beyond levee repair and follow efforts at the national scale that have emphasized revisiting flood management policies and engineering. For example, the U.S. Army Corps of Engineers has adopted flood and levee management strategies, following levee failures during Hurricane Katrina, that include restricting building and repairing levees in areas of high risk (Sills et al. 2008). From a policy perspective, the current vulnerabilities to flooding largely result from policies that foster perceptions that construction of levees eliminates risk (Tobin 1995). Thus, rather than always moving to repair levees and maintain incorrect notions regarding flood control, experts have recommended at the national level that water resources managers "Give full consideration to all possible alternatives for vulnerability reduction, including permanent evacuation of floodprone areas [and] flood warning" (Interagency Floodplain Management Review Committee 1994).

Finally, given the dependence of the delta hydrology on the network of levees, the benefits provided by restoration activities will also depend on the status of the levees. Restoration projects should be designed with flexibility to accommodate potential changes in hydrology due to levee failure. For example, constructing wetlands in areas where levees and other infrastructure (e.g., roads, docks) severely constrain the hydrology and resulting habitat types are likely not to maintain their benefit over the long-term as levees fail, sea level rises, and upstream hydrology changes.

WHAT ARE REASONABLE EXPECTATIONS FOR DELTA RESTORATION?

The committee's statement of task (Appendix C) includes a request to "[a]dvise, based on scientific information and experience elsewhere, what degree of restoration of the Delta system is likely to be attainable, given adequate resources." There are many uncertainties, including to some degree about the goals of the restoration (NRC 2011), but a few things can be said with confidence.

First, the delta as it was before large-scale alteration by humans (before about 1880) cannot be recovered. We probably cannot even know with precision and detail what the pre-alteration delta looked like. Many of the species in the delta are new (introduced from elsewhere), and even if one could remove all the human-made infrastructure, which is not economically or practically feasible, the biophysical environment would not return to its former state. This is because the changes that already have occurred in response to the human-caused changes in the delta preclude some restoration pathways. Indeed, an earlier NRC committee (NRC 1996) advocated the use of the word *rehabilitation* instead of *restoration* and defined it as meaning "a process of human intervention to modify degraded ecosystems and habitats to make it possible for natural processes of reproduction and production to take place. Rehabilitation would protect what remains in an ecosystem context and regenerate natural processes where cost-effective opportunities exist."

Second, as long as the delta is not radically transformed or contaminated or otherwise destroyed, a functioning ecosystem probably will remain there. It will differ from the original ~~and~~ probably from the current ~~eco~~-system in its species, habitats, productivity, and other aspects, but it will continue to have algae, invertebrates, fish, birds, and other creatures. It will provide for some recreation and it will continue to provide some ecosystem services. And it, like all ecosystems, will continue to respond to environmental changes. We live in a human-modified world that has created many "novel" ecosystems (Figure 4-4; Hobbs et al. 2009), including the one now found in the delta. Hobbs and colleagues identify two categories of human-induced change: biotic (primarily species introductions and extinctions) and abiotic change (e.g., land use, climate change). Both sources of ecosystem modification are prominent in the delta. The degree of change in both biotic and abiotic categories affects the likelihood of restoration (Figure 4-4). Many species currently in the delta are invasive, and, as in other systems, their elimination is highly unlikely (Vander Zanden and Olden 2008). Moreover, undoing all of the abiotic changes is neither economically desirable nor practically feasible. These two dimensions of

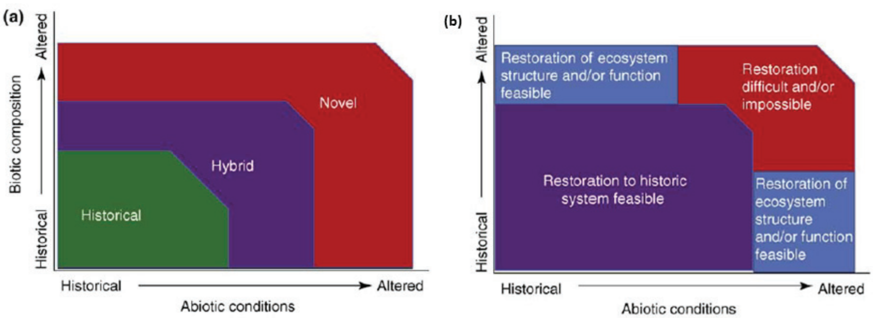

FIGURE 4-4 Types of ecosystem that develop under varying levels of biotic and abiotic alteration. (a) Three main types of system state: (i) historical, within which ecosystems remain within their historical range of variability; (ii) hybrid, within which ecosystems are modified from their historical state by changing biotic and/or biotic characteristics; and (iii) novel, within which systems have been potentially irreversibly changed by large modifications to abiotic conditions or biotic composition. (b) The state space can be divided into an area within which restoration to a system within the historic range of variability remains feasible (which includes some or most hybrid systems), areas within which restoration of ecosystem structure and/or function can be achieved without a return to historic system characteristics, and an area within which restoration is likely to be difficult or impossible and hence alternative management objectives are required.
SOURCE: Hobbs et al. (2009).

change preclude recovery of the delta as it was before large-scale alteration by humans (before about 1880). Scott et al. (2005) pointed out that for many species, their survival will depend on continued human inputs. They suggested that "[p]reventing delisted species from again being at risk of extinction may require continuing, species-specific management actions." They called such species "conservation-reliant." The committee agrees with their conclusions.

It is common for ecosystems to exhibit nonlinear changes in aspects of their structure and functioning (Scheffer et al. 2001). Abiotic factors (such as climate, e.g., Scheffer and Carpenter 2003), biotic factors (changes in species distributions, e.g., Frisk et al. 2008), or an interaction of both (van Nes et al. 2007) often underlie these abrupt changes. However, while external factors can influence ecosystem conditions in slow and imperceptible ways, they can also trigger a regime change as critical thresholds, or tipping points, are crossed. Importantly for restoration and rehabilitation, the critical thresholds that bring about regime change in one direction may be different from those bringing about change in the reverse direction. As a result, ecosystem change can show hysteresis (Scheffer et al. 2001, Tett et al. 2007); sometimes, reversal is not feasible. The presence of these nonlinear processes suggests that the path by which the delta arrived at its current state, even if well understood, is likely not the same path by which the system will move toward any desired state. Even if it were possible to restore the environmental conditions to a historical baseline, the ecosystem may not return to its former state and additional actions or ecological transitions might be required to achieve some more desirable ecosystem condition (Duarte et al. 2009). Moreover, since the pioneering early work of Watt (1947), many ecosystems also show alternative stable states (e.g., Gargett 1997, Fogarty and Murawski 1998, Chavez et al. 2003, Watson and Estes 2011). The implication of this is that the return of an ecosystem to a former state is unlikely, especially with large, complex systems like the delta. With respect to the delta ecosystem, building habitat or restoring flows does not mean "they will come." Together the experiences from studies of change in ecosystems around the world suggest the importance of considering both alternate states and hysteresis in visions for a future delta.

However, the presence of substantial biotic and abiotic changes, together with the potential for alternative stable states, does not mean that we cannot effect changes to yield a more desired delta ecosystem. Recently, Choi (2007) has drawn the analogy that, just as a prosthesis rehabilitates a patient by restoring the function of a lost limb and not the structure, we should focus more on restoring ecosystem functioning than individual constituents. Additionally, just as the biophysical environment today is different from that present previously, it is likely that the biophysical environment will continue to experience change, and thus rehabilitation should focus on promoting changes that lead to resilient ecosystems that promote desirable ecosystem services (Harris et al. 2006). A focus on rehabilitation would act to protect the delta ecosystem that remains while promoting the regeneration of natural processes and functions that would lead to a resilient ecosystem that produces services valued by society (e.g., water supply, recreational opportunities, and a sense of place).

A new focus on ecosystem functioning and resilience as rehabilitation targets does not mean that we abandon efforts on restoring individual species, nor does it mean a laissez-faire acceptance of the current degraded ecosystem. Indeed, ensuring ecosystems that are resilient in part relies on maintaining resilience at the individual species level. Maintaining genetic diversity within individual populations increases the likelihood that the population will be sustained in the face of environmental change—a point recognized in recent hatchery and recovery plans for salmon by the National Marine Fisheries Service (NMFS). Managers must promote diversity at the species level and in the configuration of the ecosystem so that it too is resilient to change. However, we should recognize also that we cannot "will" a sustainable ecosystem that contains a list of desired species. We should instead focus on management that promotes diverse, resilient ecosystems that sustain most desired species and that provide the greatest suite of ecosystem services.

Third, and perhaps most important, there appears to be considerable capacity to guide the response of ecosystems to environmental change. The larger and more complicated the ecosystem and the greater the changes caused by humans, the harder it is to produce desired changes, but even severely altered ecosystems can be rehabilitated to varying degrees. No ecosystem as large, as complicated, and as significantly altered as the bay delta has been fully rehabilitated, and indeed "full rehabilitation" seems to be an undefined and possibly unachievable goal. Managers must maintain flexibility in their definition of an achievable target, because no matter what humans do, the system will continue to evolve, both ecologically and genetically. Nonetheless, ongoing efforts in comparable ecosystems such as the Everglades (NRC 2007, 2008b, 2010), the Klamath Basin (NRC 2004, 2008a), the Columbia River, and others have shown limited recovery in some areas. While some of these activities are still in their early stages and all are beset by many challenges, they do provide some cause for optimism for the delta's future if a *sustained, thoughtful, long-term, and well-funded* effort is mounted.

Finally, experience in the delta and in other ecosystems highlights the importance of clear, well-articulated goals and of a workable governance system (Chapter 5). While no plan, however well thought out and developed, will be fully realized, without an effective plan, rehabilitation efforts are doomed. The development and implementation of such a plan depend heavily on a workable governance system (see, e.g., recent NRC reviews of the Everglades restoration efforts cited above, and especially Chapter 5 of this report).

CONCLUSIONS

Habitat loss and alterations, climate change, and unpredictable levee failure pose significant challenges in the formulation of sustainable plans for the bay-delta ecosystem. There are many opportunities to steer the future evolution of the ecosystem by addressing future challenges.

Extensive physical changes in the delta ecosystem and the tributary watersheds, and continuously evolving changes such as land subsidence in the delta islands, will not allow the recreation of habitat as it once existed in the predisturbance state. Delta restoration programs will need to balance consideration of an ecosystem approach with the Endangered Species Acts's (ESA's) and other factors' emphasis on individual species (e.g., NRC 1995). Programs will need to focus on the interaction of biological, structural, and physical aspects of habitats and how they may change in the future. Even without ESA-listed species, there still would be a need to guide the ecosystem toward desirable states.

Climate change assessment provides a reasonable picture of what the delta may experience in the future and that picture needs to be incorporated into restoration planning. Such an outlook includes a larger fraction of winter precipitation occurring as rain in tributary watersheds in the Sierra Nevada, reduction in snowpack and correspondingly of water supply during late spring and summer, reduction in water-storage opportunities with a corresponding reduction in the ability to mitigate floods and meet minimum flow targets, challenges in managing the cold-water pools of the upstream reservoirs, and increased probability of water temperatures exceeding lethal limits for delta smelt, salmon, and other species. Many of these changes are already being observed. Projected increases in the mean sea level and the extremes have the potential to increase the frequency of levee failures and inundation of islands, particularly if upstream floods, astronomical tides, and winter storms coincide in the future when the mean sea level has increased due to warming. Sea level rise also has the potential to increase saltwater intrusion and degrade water quality with a significant impact on water exports.

Dealing with climate change implications will require a nonstationary viewpoint that recognizes changes in hydrology, rising sea level, and increased temperature. Planning and evaluation of future scenarios will need to address the uncertainties in projections, integrated analysis, and the development of risk management strategies (e.g., adaptive management). Climate change implications and the continued increase in water demands in the bay-delta system and beyond will exacerbate the competition for water and limit the ability to meet the co-equal goals.

Future planning should include the development of a climate change–based risk model and analysis that incorporates data on the actual changes in delta conditions as well as alternative future scenarios and their probability. The objective should be to develop the basis for priorities for future investments in water-management programs. The real challenge is deciding how to adapt to a new environment. The uncertainties are higher about the environmental aspects of operations than about the reliability aspects of water deliveries. For example, expected environmental and other changes will force policy choices related to replacing water storage currently provided by snow on the ground. Strategies to deal with the expected and unprecedented changes will need to consider many factors, including targeted demand management, increased surface-water and groundwater storage consistent with minimizing environmental impacts, enhanced flexibility in the water-management system through operational optimization and maximum flexibility for moving water, and developing an understanding of and establishing environmental flows for the ecosystem. As described in more detail in Chapter 5, comprehensive strategies would include development of a planning and regulatory framework that incorporates concepts of shared adversity during times of water shortage. They also would include adoption of measures designed to mitigate water temperature increases that are harmful to fish species.

The instability and interdependence of levees are likely to be major issues for achieving any measure of water-supply reliability or ecosystem rehabilitation. Continuing the status quo of improving levees will not always be the most environmentally sustainable or economically defensible response in the years ahead. Indeed, changes in the levee system, and even removal or modification of some levees, could be good for at least parts of the ecosystem. Levee failures are inevitable over the long term and it is essential to plan for either the major investment needed to repair and maintain the levees or the prospect of fundamental change. When considering repair of unstable (and breached) levees in the delta, a transparent and vetted prioritization system is needed. Future delta planning efforts should give full consideration to a wide range of alternatives for vulnerability reduction, including permanent evacuation of flood-prone areas and flood warning. Restoration projects should be designed with flexibility to accommodate potential changes in hydrology due to levee failure.

Resource managers dealing with the delta will need to determine the degree of "restoration" achievable through intervention and adaptation. There is agreement that the delta as it existed before large-scale alteration by humans cannot be re-created. With respect to species, habitats, productivity, and other aspects, the future delta will still be a functioning ecosystem but different from the one that exists today. Furthermore, ecosystems—even those with minimal human impacts—are not constant in space and time. They evolve. But they can retain salient features for long periods, and despite significant changes in both biotic and abiotic conditions that have occurred during the last 150 years, there is a considerable capacity to guide the direction of the delta toward a more desirable future by focusing on a functioning resilient ecosystem without abandoning individual efforts to protect native species. Our experience with other ecosystems suggests that to achieve success, clear goals and a workable governance system will be needed.

Achieving the above will require extensive, thoughtful, and transparent planning. That planning will need to include finding ways to reconcile diverse interests without pretending that everybody can have what they want. The next chapter considers approaches for such planning, as well as constraints on it.

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5

Constraints and Opportunities for Multifaceted Water Planning

INSTITUTIONAL MATTERS

Various studies and the development of plans related to water and environmental management in California's bay delta have been conducted by multiple federal, state, local, and private entities. Their actions are motivated and directed by a variety of federal, state, and local legislation; rules and regulations; and private charters and agreements. The management activities are sometimes independent, other times overlapping, but often inadequately coordinated as part of integrated environmental management programs with clearly defined and agreed-on goals and objectives. This lack of integration and coordination applies also to the conduct and use of science. This assessment is not unique to the delta. Lack of such integration is a common feature of watershed management in the United States (NRC 1999, Imperial and Kauneckis 2005, Ruhl et al. 2007, Pfeffer and Wagenet 2011).

Although delta planning to date, as well as the committee's task, has been focused on the delta, the committee concludes that delta planning cannot be successful if it is not integrated into statewide planning. The delta is fed by large upstream watersheds and water from the delta is used outside the region. Planning for alternative courses of action to meet delta needs will affect water needs upstream of the delta, in areas served by the state and federal projects, as well as water needs in the delta itself. Planning is required to meet public policy goals regarding the delta ecosystem as well as providing a reliable water supply. Planning will likely need to provide flexibility to reallocate water and accommodate wide-ranging watershed practices, conservation, and demand management with regard to all uses, in stream and out of stream. Delta plans will affect and be affected by an important Colorado River basin linkage and other interbasin and interstate transfer agreements. In this chapter the committee attempts to identify some of the planning and water management characteristics that are needed as well of some of institutional opportunities that exist to address these needs.

Management of the water and environment of the delta is fragmented, as noted previously. One outcome of this is that decisions are often problem- or site-specific and not coordinated with related decisions made by other management agencies. For example, groundwater planning and assessment take place locally, but there is no coordination between local plans or statewide regulation of groundwater and it is not clear how the potential of groundwater storage has been incorporated into statewide plans. Rehabilitating an ecosystem requires a systems-oriented management approach, but decision making is almost always in response to the demands of particular and competing interests (Pfeffer and Wagenet 2011). Such reactive decision-making results in decisions that are narrowly cast at meeting specific demands or reconciling differences between the incompatible demands of competing interests. An obvious example of such interest-driven decision making is water allocation during drought when supplies are insufficient to meet all the agricultural, urban, industrial, and environmental demands. In such a situation it is important that a systematic, transparent process be in place to reconcile the demands of specific interests and to represent more general ecosystem needs. The absence of such a process has led to intense political competition for water resources while the adverse effects of scarcity are being felt.

A recent review of the structure and approach to California water planning by the Little Hoover Commission concluded that the fragmentation of management and resulting lack of system-level decision making could be addressed if there were a single entity accountable and in charge of California's water planning (Little Hoover Commission 2010). That report laid out a possible organizational model, which is shown in Figure 5-1. This schematic identifies one possible configuration of responsibilities among the relevant state agencies in California, but such a framework also needs to address how federal responsibilities and interstate factors would be incorporated. There are other options. For example, Hanak et al. (2011), addressing the same issue, made a different but related proposal. A comprehensive vision for governance of California's water policy has yet to be laid out, but it is critically needed if progress is to be made.

This committee did not conduct a management analysis such as that of the Little Hoover Commission Report, which is presented only as an example, but it is clear that the current organizational structure (or absence of structure) makes it difficult to develop a thoughtful, balanced, sustainable

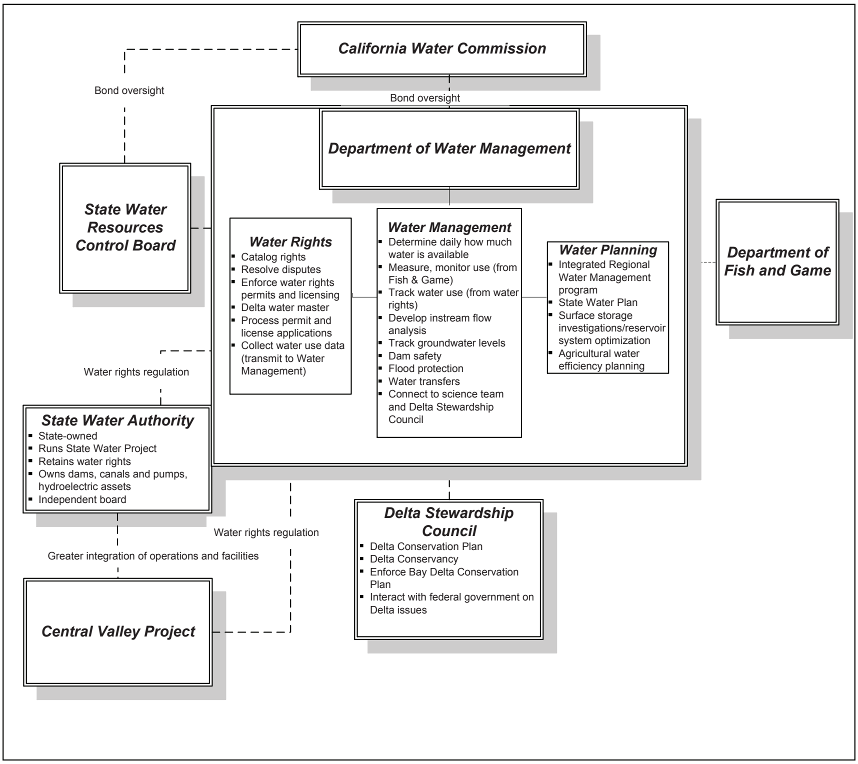

FIGURE 5-1 One possible governance structure for comprehensive water governance in the state of California, proposed by the Little Hoover Commission.
SOURCE: Reproduced from LHC (2010).

plan that could ensure rate and tax payers are making wise investments. The institutional arrangements that have characterized current, and to the best of our knowledge past, planning have not been suited to today's task. These arrangements are the result of an attempt to balance the many vested interests whose work has created the sequential delta plans. In the committee's judgment, California water and environmental planning should include integrated strategies based on current scientific knowledge, and regional and watershed plans. It should take advantage of the best practices and facilities available. It needs to be credible and independent and include relevant statewide if not interstate (Colorado River basin) considerations. It should be designed to achieve constitutional requirements for all reasonable uses, to meet and anticipate environmental requirements, and to provide a guideline for local and regional options, where such options are not inconsistent with the long-term goals of statewide water management.

Some Considerations for Water Management

Several fundamental issues have yet to be addressed in current state and federal planning efforts for the delta. These include, but are not limited to

- providing a workable, operational definition of "co-equal" goals of restoration and water supply reliability (see Chapter 2) in the context of other needs such as flood risk management and navigation;
- reconciling individual endangered species requirements with other priorities;
- understanding the effects of levee failure on habitat conservation measures and water supplies;
- assessing the effectiveness of adaptive management when the reliability of water diversions is a goal (if reliability of diversions is a goal, the flexibility to manage adaptively might not be present);
- understanding the effects of climate change–altered precipitation and runoff on reliability of water supply and related short- and long-term conservation measures;
- evaluating long-term cost of habitat-conservation measures and water-supply reliability measures in light of the principle that beneficiaries pay and with the value of the long-term investments of taxpayers and water users in mind; and
- developing methods for assessing the costs and benefits of public investments in levee security resulting from protecting delta agriculture, and methods for assessing whether and when to stop maintaining the levees.

If these and other issues are not addressed in statewide planning, they should be addressed in the Bay Delta Conservation Plan (BDCP) (see NRC 2011), the Delta Plan, and other delta planning efforts. Some of the more-focused issues that have not been addressed in current planning include

- dealing with current legal constraints and protections with regard to groundwater storage and optimal water transfers, particularly considering long-term reliability of supply and sustainability of storage;
- achieving statewide optimization of water use and equity with regard to water-conservation practices and reuse, urban and agriculture, and environmental allocations during drought periods; and
- a full consideration of alternatives for managing the stressors on the ecosystem, the costs of reducing or remediating them, and their implications for other beneficial uses.

Recent substantial rainfall (especially in 2010), success in water-conservation measures (particularly in the urban sector), and some interim measures such as the facilitation of transfers between users and groundwater storage could provide some breathing room. This is particularly true since some utilities believe that water demands are not expected to return to levels of the early 2000s until about 2020. This period should be seen as an opportunity to build an improved water management system (and plan) cognizant of the realities of long-term water scarcity and sufficiently integrated to deal with that scarcity. If the period of reduced stress is wasted, it could be too late to build a more enlightened approach when the severity and impacts of shortage increase.

A key element in discussions of future water-management options in the delta is the isolated conveyance facility (peripheral canal or tunnel, the principal element of the dual conveyance strategy). Some experts have advocated such a facility since the 1960s. To the northern California public it has become an icon of objection to the impacts of growth in California. Its final form has not been agreed on, but a prominent version as described in the BDCP has been a tunnel(s) under the delta with five screened intakes located downstream of the discharge of the Sacramento regional sewage treatment plant. An isolated conveyance facility is a central element of the BDCP, where it has been described as a conservation measure, and it or something like it has been a focus of discussion in the delta for five decades. The committee has not analyzed the benefits and disadvantages of an isolated conveyance facility, because not enough specific information was available about it (see NRC 2011), and we make no recommendation with respect to its adoption as a major part of water management in the delta.

However, the committee does recommend that before a decision is made whether to construct such a facility and in what form, the sizing of the facility, its location, and the diversion design and operation, including the role of current diversions, should be analyzed as part of any integrated delta plan, and compared to alternative water management options, including current operations. All the alternatives should be evaluated to ensure that the investment currently estimated at between $8 and $12 billion (with considerable uncertainty) will meet both environmental and water-supply objectives. Sustainability, reliability, and environmental objectives require that the design of any new system be as flexible as possible to manage varying and unpredictable flows. Operations should be able to meet adaptive management goals and to routinely and frequently rebalance ecological protection with water supply reliability. The above considerations would apply to any new construction to manage water flows in and around the delta.

Current Management Limitations

Stakeholder advocacy preferences are currently driving delta and related water programs in California. These are reflected in the sequence of delta plans beginning in the 1960s, the current status of environmental review of actions and projects, and most importantly the increasing tendency to design activities as to minimize objections of any politically consequential view. One way of looking at the current situation is that existing laws and regulations are implemented only to the extent that they satisfy significant interests. Nor does such a process inspire public trust. Recognition of this difficulty has led to "collaborative" planning approaches, such as the BDCP, where stakeholders are invited to participate (see NRC [2011] for a review of a draft of the BDCP). However, without any formal structured decision-support process to organize the wealth of information available or to allow preferences to be expressed in quantitative terms, broadly acceptable and effective solutions for resolving delta issues have been hard to come by. Perhaps more important, it has not been clear who has provided the charge to the collaborative decision-making process or body, and to whom the resulting decisions are addressed. In other words, who asked for the process, and who will decide how and whether to execute its recommendations?

The current management approach appears to try to design the restoration and reliability program by committee, directly or indirectly, since authors of various parts of the plan realistically anticipate the reception that various measures might receive. As a result, alternatives, mitigations, or numerical assessments that might cast doubt on a particular course of action can be given limited attention or even be ignored. Trade-offs are rarely analyzed or presented transparently. Such a process reflects inadequacies in leadership that if continued will fail to inspire the kind of public support essential to moving forward constructively.

For many reasons, not the least of which are specific court rulings, water management in the delta in recent years has been reactive and singular rather than proactive and comprehensive. Planning for the future should reflect a clear vision of future water use and availability that recognizes the likelihood of future variability, and that the water management desires of all sectors or interests cannot be fully met. Such planning should create a basis for public comparison of alternative scenarios and strategies, including costs and benefits. It should incorporate a variety of well explained and documented models that include life cycles of individual species, as well as multielement strategies. The committee recognizes that there are many uses of the delta and its waters and the requirements of diverse statutes, regulations, and policies might not always be consistent with each other.

This does not negate the need for comprehensive planning; rather, it makes it more urgent. But it does make it more difficult.

Ideally public policy such as the established "co-equal goals" would precede the development of a plan: objective and complete analysis of needs and solutions for achieving environmental restoration, reliable water supply, and anticipated future requirements. Then goals would be reconsidered in whole or in part, in light of the activities necessary to achieve them. In that way the BDCP and the delta plans could inform California policy for the future. Recent individual Endangered Species Act (ESA) court rulings that have led to changes in water exports from the delta, together with the planning thus far, represent a collection of discrete pieces of important information, and not a balanced and prioritized set of recommendations constituting a strategic plan for the state. Achievement of a scientifically, technically, and societally supportable plan requires the individual and collective consideration of "significant environmental factors," a quantified effects analysis, and goal-based adaptive management programs that provide a platform for future investments in water-supply and restoration activities. These all require clear-headed decision making and leadership that are difficult to come by if governance of the plan or water management as a whole remains fragmented.

In considering ways to improve water planning and management for the delta, it is logical to search for examples here or abroad that have achieved success, or approaches that have allowed disparate opinions to converge toward a common goal. The committee could not identify any examples that would achieve every aspect of the process described here. However, several examples provide aspects of good governance that could be informative for the delta. The examples include the Ruhrverband in the Ruhr River watershed in Germany,[1] the Murray Darling Basin Authority in Australia,[2] a study of long-term augmentation of the water supply of the Colorado River system (Colorado River Water Consultants 2008), and the South Florida Water Management District and restoration of the Greater Everglades Ecosystem in Florida (USACE and SFWMD 1999, NRC 2006, 2008, 2010).

Managing Science

In the examples above, the independent water agency's functions included monitoring, data management, and research: coordinating and using science. The need for a strong science component to water management is increasingly well accepted (Jacobs et al. 2003). But the degree to

[1] See http://www.ruhrverband.de/en. Accessed July 17, 2012.
[2] See http://www.mdba.gov.au/. Accessed July 17, 2012.

which science is integrated into water management will depend on how it is managed. The South Florida Water Management District, which has large responsibility for the restoration of Florida's Everglades, is, like the Ruhrverband, an example of a water agency with a strong technical staff that is well integrated into the water management system. At its inception science management was also an important aspect of CALFED, in the form of a formal Science Program. The Science Program is one of the few aspects of the CALFED that was retained by the Delta Stewardship Council although with considerably less funding. An informal poll of stakeholders held in 2005 as CALFED was evolving into the Delta Stewardship Council (Chapter 2) found stronger support for sustaining the Science Program than for almost any other element of the program (Sam Luoma, University of California, Davis, personal communication, February 2012). Important elements of the science program include an independent lead scientist, with authority to report directly to the governing council; using consultation with experts and stakeholders to define strategic science directions; funding research proposals only if they pass robust peer review; and fostering communication about the technical aspects of controversial policy issues via dialogue and reviews using independent experts (the program has involved many independent experts from outside the bay delta). These "meetings" are focused on reaching consensus on uncertainties and identifying next steps to resolving those uncertainties. Advocacy debates are explicitly avoided. All meetings are open to the public.

Water planning and management for the delta occur in the context of statewide California water planning. The committee has considered a variety of institutional models and factors that illustrate some of the important attributes of an effective water-management approach, including a watershed-based scope, consideration of water resource sources and uses of both surface and groundwater, incorporation of water-quality considerations for all environmental and consumptive uses, coordination with existing agencies, the ability to conduct independent research and scientific analyses, a commitment to community engagement, and oversight of monitoring. All the factors are linked in some way to water management in the delta. Given the history and disagreements regarding science and water planning, an independent structure of some sort (without the committed missions of any state or federal agency) could provide for the appearance and reality of objective guidance. This would enhance credibility and the likelihood that the delta and statewide water interests are broadly considered and balanced.

The committee has mentioned organizations and activites in the United States and elsewhere that contain elements of good governance that could be informative for the delta (above). There is no best model for California. The existing web of water institutions would be best aided by a new professional planning function that could provide decision makers and managers with science-based guidance, particularly regarding the tradeoffs, costs, benefits, and likely environmental consequences of alternative courses of action, and better integration of local and regional water management activities within a statewide environmental and water planning framework.

THE ROLE OF SCIENCE

California has been making major investments in its water and environmental infrastructure for decades, including varying amounts of support for science specifically to inform management actions. Many of the findings from monitoring and scientific studies, especially since the late 1990s, have affected the strategic view of California's water issues. For example, recognition of the threatened status of a number of species native to the delta stems from the approximately 60 years of aquatic monitoring in the system, led since 1970 by the Interagency Ecological Program. This is no small accomplishment. Places with analogous issues (e.g., the Murray-Darling system in Australia) have no such systematic biological monitoring. One of the early syntheses of scientific knowledge about San Francisco Bay (Jassby et al. 1995) formed the basis and justification for a regulatory approach that remains a core ingredient in managing water for the delta (managing the position of X_2; see Chapters 1 and 3). As a result of numerous studies through the past 15 years, we now have a robust understanding of the likely implications of climate change for water management in the delta (and California in general).

Recent multidisciplinary studies that tie together complex models to evaluate different climate change scenarios provide a model for future efforts on how to address the challenges these changes will present (Cloern et al. 2007). Our basic understanding of hydrodynamics in the delta has changed from an assumption that net inflows from rivers drove the major processes to an appreciation of the strong role of tides during much of the year. The ecology of the delta itself was essentially unknown as late as the mid-1990s; much has been learned that has implicitly, if not explicitly, changed the way that scientific and policy problems are addressed. These are but a few of many possible examples of the importance of a strong science underpinning to support policy needs in this system. The committee recommends that whatever management structure is carried forward, that the strong combination of monitoring and assessment, agency driven science, and academic peer-reviewed proposal-driven science be perpetuated.

On the other hand, it is clear that managers, policy makers, scientists, judges, and the public have struggled to interpret information about the delta and its inhabitants, and they have struggled to find consensus on critical aspects of policy based on that and other information. This committee has struggled, too, as have others, with both the scientific information available and how to move forward. Indeed, there are genuine scientific uncertainties. While it is clear how the delta has changed in many ways, and that many aspects of its environment are less hospitable to many of the organisms that live there than they used to be, it often is difficult to unequivocally identify any one factor responsible for any specific ecological change. It remains difficult to forecast the outcome of specific rehabilitation actions with much confidence. It also is very difficult to identify cause and effect by correlating the timing of human-caused environmental changes and the timing of resultant ecological changes. However, the committee remains confident that science can be useful to policy makers in and around the delta.

Many authors have discussed the challenges in establishing an effective relationship between science and policy in an uncertain environment (e.g., Lubchenco 1998, Policansky 1998, Lawton 2007). Sarewitz (2004) even suggested that science makes environmental controversies worse! The difficulties often revolve around a lack of clear articulation of values and goals. Indeed, uncertainty can be used to make decisions to undertake expensive actions difficult to justify and easy to oppose. This problem has been all too evident in the delta in recent years as evidenced by the return to litigation around 2004. However, uncertainty does not have to lead to conflict. If at least a portion of the scientific dialogue is directed toward identifying areas of disagreement, rather than who is right and who is wrong, consensus is at least possible on next steps (Jacobs et al. 2003), and management of conflict can be improved. CALFED experimented with this type of dialogue (Jacobs et al. 2003), but that approach appears to have eroded over time.

Managing conflict is only one ingredient in making progress on policy via constructive use of science, however. Much good science has been conducted in and around the delta. However, there has been inadequate construction of the resulting knowledge into consensus for action. That has not been for want of trying. One part of the problem is that conflict and litigation among different interest groups have soured what collaborations and trust once existed. But it appears to this committee that a second, more important problem is present; it is that a successful method of governance—in the broad sense—of the state, the delta, and of science has not taken root. This lack of a leadership model is a major contributor to the controversies, litigation, disagreements, and continuing lack of consensus.

While it is beyond the charge of the committee to specify a reorganization of science or the science-policy relationships that would lead to rehabilitating the delta, it has identified some problem areas whose resolution would be helpful and some of the ingredients for such a resolution. An independent leadership position is needed that is charged with accruing scientific knowledge into a coherent conceptual model. Another way to say this is that nobody is yet charged with, or even tries, to construct coherent stories of how a large, interacting, complex system (or significantly complex pieces of it) work. Excellent work is done by universities, by state and federal agencies, by consultants, and by commissions and committees, but there are few if any successful examples of synthesizing the information or for gaining *scientific* consensus. The white papers that were commissioned by CALFED were an attempt at drawing together such consensus, but they have had only a minor impact. It has been evident during the tenure of this committee that dueling scientific presentations are more common than collaborations between scientists from different backgrounds and with differing sources of financial support. In other arenas, where the goals are more clearly defined and more widely shared (e.g., medicine, space exploration, defense), collaboration and consensus on next steps among university, industry, and agency scientists seem to be more common and effective. But in all these cases a leader is essential who can focus on identifying the path forward based on what was learned to date. In the delta, one possible solution is that the Delta Stewardship Council's independent lead scientist job might be reframed to focus on leading and reporting out on the synthesis efforts, leaving management responsibilities to a separate leadership position.

In general, nonscientist governance professionals have difficulty defining for scientists what they want or need to know. Similarly, scientists have difficulty defining what kind of knowledge or evidence nonscientist governance professionals would accept as a basis for actions and for defining alternatives. These gaps need bridging for science to be most responsive to decision makers' needs, but there does not appear to be a strong incentive for scientists and nonscientist professionals to bridge these gaps. It probably is not possible for governance professionals to set forth in a specified way what science they need to know, and what kind of science they would accept as a basis for actions, but this committee judges that a collaborative effort is needed, where scientists and governance professionals work together as a single team, rather than as two separate entities. Critical questions to be addressed by such a team include how one characterizes risk and how one assesses the degree to which risks are acceptable, what tools are available for dealing with uncertainty, and what methods are available for assessing trade-offs among options. Such conversations should lead to better ways that scientists can contribute to addressing such questions. Below and in Appendix F the committee discusses collaborative modeling as an example of this kind of approach.

Finally, there needs to be an honest assessment of how reliable all the scientific information is. For example, censusing widely but patchily distributed small fishes like adult delta smelt and juvenile striped bass, just to name two, is an extremely challenging endeavor. It is difficult to distinguish population fluctuations from changes in distribution. If one samples in the same places each year, and one records a change in the number of fish sampled, it will not be clear whether the change is due to a change in population size or a change in distribution. If, on the other hand, sampling sites often change, then it becomes easier to miss a genuine change in population size. This is a difficult problem. It can be solved, but solving it is very expensive and takes time. Of course almost any sampling scheme will distinguish between a population that is widespread and abundant and one that is small and patchy, but that is too coarse a filter for the problem at hand.

FUTURE UNCERTAINTIES AND UNKNOWNS

Scientific understanding of the ecological functioning of the delta is not complete, and never will be. Many unknowns contribute to the difficulties in formulating plans for ensuring sustainability. For example, the factors affecting the pelagic organism decline (POD) are not completely understood. The relative importance of water exports and other stressors are difficult to quantify. As a result of the lack of knowledge regarding the ecological functions in the delta, quantification of how various water-management options affect the ecosystem is not straightforward. Although the quantification of the water-supply needs for agricultural and urban users of the system with reasonable accuracy is possible, without clearly being able to include the regime of freshwater availability necessary to sustain desired components of the ecosystem, it is not possible to identify trade-offs and conduct multifaceted planning in balancing the goals of the water resources management in the delta system.

The future of the greater delta system is determined by major drivers of change, some of which are irreversible (Chapters 3 and 4). Future states of these drivers cannot be predicted in detail because of many uncertainties. Such drivers include, but are not limited to (a) land subsidence, (b) invasive species, (c) human population growth and urbanization, (d) seismicity, and (e) climate change and sea level rise (Mount et al. 2006, Dettinger and Culberson 2008, Lund et al. 2010). Most of these drivers are already altering the delta irreversibly.

California's population is likely to continue to grow in this century, and the projected water shortage in the coming decades is significant. In particular, the largest increase is expected to be in the south, which depends on the tributaries of the delta for its water supply. Although groundwater mining in the San Joaquin Valley has supplemented water needs during dry years, it is uncertain to what extent such a source will continue to meet the shortfalls.

The frequency and occurrence of earthquakes in the delta region cannot be predicted with certainty. The stability of levees during earthquakes also is difficult to predict. Risk-assessment techniques are available to evaluate probabilities and related costs to aid decision making. Because these risks affect statewide water use, they should be assessed as part of a comprehensive program.

Perhaps the most significant uncertainty lies in the impacts of climate change and sea level rise (Chapter 4). Although there is increasing evidence as to how warming may affect hydrology, there are significant uncertainties in the future scenarios that should be used in planning (NRC 2011). Moreover, sea level rise predictions have very wide ranges. Depending on the magnitude of sea level rise, the resulting impact on the delta and its functioning can be significantly different. The exact impact of the multiple factors such as potential increase in flood and drought magnitude and frequency, increased sea level and its extremes, changing runoff patterns and habitat quality on the integrity of the levees, water supply to users, and the ecological functioning of the delta is not known precisely.

The above uncertainties should not be allowed to lead to paralysis. Much is known. But the above uncertainties suggest that agencies should consider an array of possible future states, and such an approach should assume "universal nonstationarity," or the idea that all aspects of the environment will constantly be changing. This implies that agencies should develop adaptive strategies for a multitude of possibilities within a broad range including extirpation of listed species and collapse of vital ecological services. Each "future" should be characterized by particular configuration of climatic regime, plausible physical system changes, water demands, and the ecological habitats. In such a setting, it is clear that water resources planning would demand flexibility not only in infrastructure but also water supply options, and dynamic operations.

Several approaches exist to consider these "wicked" problems (Rittel and Webber 1973, Conklin 2005), where uncertainty cannot be fully eliminated by study and not all aspects of the problem can be adequately quantified. The committee recommends that future water resource planning in the delta include one or more of these approaches (e.g., robust decision making and shared vision planning) to explore the multiple consequences of decisions. They are described in some detail in Appendix F.

Perhaps most critical is the need to rationalize the responsibilities for decision making. Who gives the charge to the collaborative decision-making body is an essential element because whoever gives the charge controls the process. Similarly, who does the collaborative decision-making body report to? Who decides whether and how its recommendations are met? Unless these questions can be satisfactorily answered by the people of California and their representatives, the problem of managing and allocating delta water is unlikely to be satisfactorily resolved.

A PATH FORWARD: CONCLUSIONS

The committee concludes that the lack of explicitly integrated comprehensive environmental and water planning and management results in decision making that is inadequate to meet the delta's and the state's diverse needs, including environmental and ecological conditions in the delta. In addition, the lack of integrated, comprehensive planning has hindered the conduct of science and its usefulness in decision making.

Many efforts have been made to improve state and federal water planning, management, and regulation. Examples include the Porter Cologne Act in 1969 (particularly the Basin Plans), the Clean Water Act of 1972 (particularly § 208), and the Urban Water Management Planning Act of 1985, together with recent amendments, state funding for watershed planning activities, local groundwater planning, recent legislation on improving groundwater use databases, and a variety of other regulations and laws designed to improve water management. Each of these efforts recognizes that water science and technology should support planning that is comprehensive and that considers quality and quantity, considers the environment and economics, and does so transparently to gain public confidence.

The committee recommends that California undertake a comprehensive review of its water planning and management functioning and design modifications to existing responsibilities and organizations that will anticipate future needs, including those identified in this report. These needs include dealing with scarcity, balanced consideration of all statewide water-use practices and hardware alternatives, and adaptive management that can adjust to changing conditions. The result should be that regions such as the delta can be effective partners in a coordinated statewide effort.

With respect to water transfers discussed in Chapter 2, the state should facilitate voluntary transfers and identify buyers and sellers for both short-term and long-term needs. An essential element might be options to purchase dry-year entitlements. Thus, reliability-dependent users—urban, industrial, and agricultural—would have some long-term confidence that shortages would be minimized by a predictable amount. As part of its oversight of such transfers, the state must ensure that necessary instream flow levels are maintained.

Delta conditions identified in previous chapters indicate that scarcity of water for all needs will become severe. While more effective planning is being developed, the state will need to get the most overall value from its water resources. A variety of tools are available, including demand-side management (conservation, including more-efficient and more-productive water use) and supply-side management (water transfers, new sources of supply, more-integrated management of groundwater and surface water, enforcement of the constitutional reasonable and beneficial use limitations, and invocation of the state public trust doctrine to reconsider past allocation decisions). The flexible integration of these tools across a large, complex network provides the adaptive capabilities needed to respond to uncertainty.

Although the committee does not have a recommendation for a specific organizational strategy, because that needs to be decided by the people of California, it does have recommendations for the characteristics such an organization should have. They include independence and authority; that is, decisions should be not only enforceable but also accepted as legitimate by most of the stakeholders affected. These are difficult to achieve. Independence and authority require a funding source to provide the administrative capacity to administer a full range of watershed-management tools to enforce and incentivize compliance with rules and procedures; this might be the exclusive province of the legislature, or some entity created and given authority by the legislature. In any case, a method needs to be found to incorporate the public's desires and to achieve the public's trust while allowing for decisions that are made with the broader public interest in mind.

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Appendix A

Summary of A Scientific Assessment of Alternatives for Reducing Water Management Effect on Threatened and Endangered Fishes in California's Bay-Delta

California's Bay-Delta estuary is a biologically diverse estuarine ecosystem that plays a central role in the distribution of California's water from the state's wetter northern regions to its southern, arid, and populous cities and agricultural areas. In addition to its ecological functioning and the ecosystem services it provides, there are numerous withdrawals of freshwater from the delta, the largest being pumping stations that divert water into the federal Central Valley Project (CVP) and the State Water Project (SWP), primarily for agriculture and metropolitan areas. Most former wetland and marsh areas of the delta have been drained for agriculture, and are protected by an aging collection of levees. Some of those areas also contain small urban settlements.

This hydrologic and engineered system has met the diverse water-related needs of Californians for decades. But operation of the engineered system, along with the effects of an increasing population of humans and their activities, has substantially altered the ecosystem. These ecosystem changes have contributed to changes in the abundance, distribution, and composition of species in the delta, including the decline of many native species and the successful establishment of many species not native to the region.

Recently, the Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) issued biological opinions under the federal Endangered Species Act (ESA) that required changes ("reasonable and prudent alternatives," or RPAs) in water operations and related actions to avoid jeopardizing the continued existence and potential for recovery of delta smelt, winter-run and fall-run Chinook salmon, Central Valley steelhead, and green sturgeon. Those changes have reduced the amount of water available for other uses, and the tensions that resulted have been exacerbated by recent dry years.

The RPAs are divided into many separate actions. The RPA in the FWS opinion, divided into 6 actions, applies to delta smelt and thus focuses primarily on managing flow regimes to reduce entrainment of smelt and on extent of suitable water conditions in the delta, as well as on construction or restoration of habitat. The NMFS RPA, divided into five actions with a total of 72 subsidiary actions, applies to the requirements of Chinook salmon, steelhead, and green sturgeon in the delta and farther upstream. In addition to its focus on flow regimes and passage, it includes purchasing water to enhance in-stream flow, habitat restoration, a new study of acoustic-tagged steelhead, and development of hatchery genetics management plans. This committee did not evaluate all 78 actions and subsidiary actions in the two RPAs in detail. It spent most of its time on the elements of the RPAs that have the greatest potential to affect water diversions. It also spent time on elements whose scientific justifications appear to raise some questions.

Protecting all the listed species, as required by the ESA, while simultaneously trying to minimize impacts on existing and projected uses of the region's water, is a serious challenge. In addition, many anthropogenic and other factors, including pollutants; introduced species; and engineered structures such as dams, canals, levees, gates, and pumps adversely affect the fishes in the region, but they are not under the direct control of the CVP or the SWP, and thus are not subjects of the biological opinions.

The complexity of the problem of the decline of the listed species and the difficulty of identifying viable solutions have led to disagreements, including concerns that some of the actions in the RPAs might be ineffective and might cause harm and economic disruptions to water users, and that some of the actions specified in the RPAs to help one or more of the listed species might harm others. In addition, some have suggested that the agencies might be able to meet their legal obligation to protect species with less economic disruptions to other water users. Those concerns led the Department of the Interior and Congress to ask for advice from the National Research Council (NRC), which appointed a special committee of experts to carry out this study.

THE COMMITTEE'S CHARGE

The committee's charge includes the following tasks:

The committee was asked to undertake two main projects over a term of two years resulting in two reports. The first report, prepared on a very short timeline, was to address scientific questions, assumptions, and conclusions underlying water-management alternatives (i.e., the RPAs) in the two biological opinions mentioned above, and this is where the committee focused most of its attention. In addition, three specific issues were to be addressed. First, are there any "reasonable and prudent alternatives" (RPAs) that, based on the best available scientific data and analysis, would provide equal or greater protection for the listed species and their habitat while having lesser impacts to other water uses than those adopted in the biological opinions? Second, are there provisions in the biological opinions to resolve the potential for actions that would benefit one listed species while causing negative impacts on another? And finally, to the extent that time permits, the committee was asked to consider the effects of other stressors (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Bay-Delta. The committee's second report, due in late 2011, will address how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the Bay-Delta.

The committee's charge was to provide a scientific evaluation, not a legal one, and that is what the committee did. **Nothing in this report should be interpreted as a legal judgment as to whether the agencies have met their legal requirements under the ESA.** The committee's report is intended to provide a scientific evaluation of agency actions, to help refine them, and to help the general attempt to better understand the dynamics of the delta ecosystem, including the listed fishes.

THE COMMITTEE'S PRINCIPAL CONCLUSIONS

Context

The California Bay-Delta is a system that has undergone significant anthropogenic changes for more than a century. Those changes include water withdrawals; draining of wetlands; introduction of many nonnative species of plants and animals, some deliberate; construction of canals, gates, marinas, roads, levees, pumps, dams, and other structures that affect the hydrology of the system; the damming of almost all the major rivers and tributaries to the system, which also has altered the seasonal flow regime and other hydrologic aspects of the system; and the release of contaminants, pollutants, and nutrients into the system as a result of the above changes and the increase of agriculture, industrial and residential development, and other human activities. All these changes have affected the distribution, abundance, and composition of species in the delta, some of which have increased dramatically and some, including the species listed under the Endangered Species Act (Chinook salmon, delta smelt, steelhead, and green sturgeon), which have declined precipitously. The biological opinions with their associated RPAs that the committee has reviewed relate only to proposed changes in operations of the CVP and the SWP in the delta and methods to reduce the adverse effects on the listed species of those changes. Some restrictions on CVP and SWP water diversions have been initiated to protect the listed fish species, but so far have not produced measurable effects in slowing their declines.

The committee concludes that reversing or even slowing the declines of the listed species cannot be accomplished immediately. Even the best-targeted methods of reversing the fish declines will need time to take effect amid changing environmental conditions such as multi-year droughts and continued pressures on the system from other human-caused stresses. Especially for fishes whose populations are very low already, the effects of any actions will be difficult to detect at first, and detecting them will be made more difficult by the effects of other environmental changes and uncertainties inherent in sampling small populations.

The FWS Biological Opinion and RPA

The committee considered the six actions contained within the RPA, most of which were judged to have a sound conceptual basis. The committee then focused on the RPA actions that involved Old and Middle River (OMR) flows, the management of the mean position of the contour where salinity is 2[1] (X2), and the creation or restoration of tidal habitat for smelt. The first two actions involve significant requirements for water; the third does not.

The management of OMR flows is predicated on the concept that pumping of water for export from the south delta creates net negative (upstream) flows, averaged over the tidal cycle, that cause delta smelt (and some juvenile salmon) to experience increased mortality in the south delta, especially in winter. The RPA action limits the net OMR flows to levels that depend on conditions during this period, with a variety of environmental triggers and adaptive-management procedures. **Although there are scientifically based arguments that raise legitimate questions about this action, the committee concludes that until better monitoring data and comprehensive life-cycle models are available, it is scientifically reasonable to conclude that high negative OMR flows in winter probably adversely affect smelt populations. Thus, the concept of reducing OMR negative flows to reduce mortality of smelt at the SWP and CVP facilities is scientifically justified.**

However, there is substantial uncertainty regarding the amount of

[1] This is often expressed as a concentration, e.g., "2 parts per thousand," but more recently it has been expressed as a ratio of electrical conductivities, hence it has no units.

flow that should trigger a reduction in exports. In other words, the specific choice of the negative flow threshold for initiating the RPA is less clearly supported by scientific analyses. The biological benefits and the water requirements of this action are likely to be sensitive to the precise values of trigger and threshold values. There clearly is a relationship between negative OMR flows and mortality of smelt at the pumps, but the data do not permit a confident identification of the threshold values to use in the action, and they do not permit a confident assessment of the benefits to the population of the action. As a result, the implementation of this action needs to be accompanied by careful monitoring, adaptive management, and additional analyses that permit regular review and adjustment of strategies as knowledge improves.

The management of the mean position of X2 during the fall (Action 4 of the FWS RPA) is based on observations that relate smelt use of spawning habitat with various salinity regimes. X2 is interpreted by the agencies not as a single line, but rather as an indicator of the spatial pattern of salinity in the delta and thus as indicative of the extent of habitat favorable for delta smelt.

The relationships among smelt abundance, habitat extent, and the mean position of X2 as an indicator of available habitat are complex. The controversy about the action arises from the poor and sometimes confounding relationship between indirect measures of delta smelt populations (indices) and X2. Although there is evidence that the position of X2 affects the distribution of smelt, the weak statistical relationship between the location of X2 and the size of smelt populations makes the justification for this action difficult to understand. In addition, although the position of X2 is correlated with the distribution of salinity and turbidity regimes, the relationship of that distribution and smelt abundance indices is unclear. The X2 action is conceptually sound in that to the degree that the amount of habitat available for smelt limits their abundance, the provision of more or better habitat would be helpful. However, the derivation of the details of this action lacks rigor. The action is based on a series of linked statistical analyses (e.g., the relationship of presence/absence data to environmental variables, the relationship of environmental variables to habitat, the relationship of habitat to X2, the relationship of X2 to smelt abundance). Each step of this logical train of relationships is uncertain. The relationships are correlative with substantial variance left unexplained at each step, yet the analyses do not carry the uncertainty at each step to the next step. The action also may have high water requirements and may adversely affect salmon and steelhead under some conditions. **As a result, the committee concludes that how specific X2 targets were chosen and their likely beneficial effects need further clarification. It also is critical that the adaptive-management requirements included in the RPA be implemented in**

light of the uncertainty about the biological effectiveness of the action and its possibly high water requirements.

The tidal habitat management action in the RPA requires creation or restoration of 8,000 acres of intertidal and subtidal habitat in the delta and in Suisun Marsh. This action has not been controversial because it does not affect other water users. **The committee finds that the conceptual foundation for this action (Action 6) is weak because the relationship between tidal habitats and food availability for smelt is poorly understood. The details of its implementation are not fully justified in the biological opinion. The committee recommends that this action be implemented in phases, with the first phase to include the development of an implementation and adaptive management plan (similar to the approach used for the floodplain habitat action in the NOAA biological opinion), but also to explicitly consider the sustainability of the resulting habitats, especially those dependent on emergent vegetation, in the face of expected sea-level rise.** In addition, there should be consideration of the types and amounts of tidal habitats necessary to produce the expected outcomes and how they can be achieved and sustained in the long term. The committee supports the monitoring program referred to in Action 6, and appropriate adaptive management triggers and actions.

The NMFS Biological Opinion and RPA

The NMFS RPA for salmon, steelhead, and green sturgeon is a broad complex of diverse actions spanning three habitat realms: tributary watersheds, the mainstem Sacramento and San Joaquin Rivers, and the delta. **On balance, the committee concludes that the actions, which are primarily crafted to improve life-stage-specific survival rates for salmon and steelhead, with the recognition that the benefits also will accrue to sturgeon, are scientifically justified.** The strategies underpinning many of the individual actions are generally well supported by more than a decade of conceptual model building about the requirements of salmonids in the region, although the extent to which the intended responses are likely to be realized is not always clearly addressed in the RPA. Given the absence of a transparent, quantitative framework for analyzing the effects of individual and collective actions, it is difficult to make definitive statements regarding the merits of such a complex RPA. Indeed, absent such an analysis, the controversial aspects of some of the RPA actions could detract from the merits of the rest of the RPA.

In general, as described in detail in Chapter 6, the committee concludes that although most, if not all, of the actions in this RPA had a sound conceptual basis, the biological benefits and water requirements of several of the actions are, as with the delta smelt actions, likely quite sensitive to the

specific triggers, thresholds, and flows specified. As a result, the committee recommends that the specific triggers, thresholds, and flows receive additional evaluation that is integrated with the analyses of similar actions for delta smelt.

In particular, the committee concludes that it is difficult to ascertain to what extent the collective watershed and tributary actions will appreciably improve survival within the watershed or throughout the entire river system. The committee concludes that the actions to improve mainstem passage for salmonids and sturgeon, in particular those concerning the Red Bluff Diversion Dam, are well justified scientifically. The committee recommends some kind of quantitative assessment framework for assessing survival be developed and implemented.

The management of OMR flows to reduce entrainment mortality of salmon smolts is similar in concept to the smelt OMR action, and like that action, **the committee concludes that its conceptual basis is scientifically justified, but the scientific support for specific flow targets is less certain. Uncertainty in the effect of the triggers should be reduced, and more-flexible triggers that might require less water should be evaluated.**

Another set of actions in this RPA focuses on managing exports and flows in the San Joaquin River to benefit outmigrating steelhead smolts. The actions are intended to reduce the smolts' vulnerability to entrainment into the channels of the south delta and the pumps by increasing the inflow-to-export ratio of water in the San Joaquin River. It thus has two components: reducing exports and increasing San Joaquin River inflows into the delta. **The committee concludes that the rationale for increasing San Joaquin River flows has a stronger foundation than does the prescribed export action. We further conclude that the action involving a 6-year study of smolt survival would provide useful insight into the effectiveness of the actions as a long-term solution.**

The final two actions considered here were improving the migratory passage of salmon and sturgeon through the Yolo Bypass and the creation of additional floodplain lands to provide additional rearing habitat for juvenile salmon. **The committee concludes that both actions are scientifically justified, but the implications for the system as a whole of routing additional flows through the Yolo Bypass for the system were not clearly analyzed.** In particular, the consequences of the action for Sacramento River flows and for the potential mobilization of mercury were not clearly described.

Other Possible RPAs

The committee's charge requires the identification, if possible, of additional potential RPAs that might have the potential to provide equal or greater protection to the fishes than the current RPAs while costing less in terms of water availability for other uses. **The committee considered a variety of possible actions not in the RPAs (see Chapter 6), and concluded that none of them had received sufficient documentation or evaluation to be confident at present that any of them would have the potential to provide equal or greater protections for the species while requiring less disruption of delta water diversions.**

Other Stressors

Based on the evidence the committee has reviewed, the committee agreed that the adverse effects of all the other stressors on the listed fishes are potentially large. Time did not permit full exploration of the issue in this first report, but examples of how such stressors may affect the fishes are described. The committee will explore this issue more thoroughly in its second report.

Modeling

The committee reviewed the models the agencies used to understand the basis for the resource agencies' jeopardy opinion and to determine to what degree they used the models in developing the RPAs. **The committee concluded that as far as they went, despite flaws, the individual models were scientifically justified, but that they needed improvements and that they did not go far enough toward an integrated analysis of the RPAs. Thus the committee concluded that improving the models by making them more realistic and by better matching the scale of their outputs to the scale of the actions, and by extending the modeling framework to be more comprehensive and to include features such as fish life cycles would improve the agencies' abilities to assess risks to the fishes, to fine-tune various actions, and to predict the effects of the actions.**

Potential Conflicts Between RPAs and Integration of RPAs

The committee concludes that the RPAs lack an integrated quantitative analytical framework that ties the various actions together within species, between smelt and salmonid species, and across the watershed. This type of systematic, formalized analysis, although likely beyond the two agencies' legal obligations when rendering two separate biological opinions, is necessary to provide an objective determination of the net effect of all their actions on the listed species and on water users.

An additional overall, systematic, coordinated analysis of the effect of all actions taken together and a process for implementing the optimized, combined set of actions is required to establish the credibility of the effort overall. The committee is aware that instances of coordination among the agencies certainly exist, including modification of actions to reduce or eliminate conflicting effects on the species. Indeed, the committee did not find any clear example of an action in one of the RPAs causing significant harm to the species covered in the other RPA. But coordination is not integration. The lack of a systematic, well-framed overall analysis is a serious scientific deficiency, and it likely is related to the ESA's practical limitations as to the scope of actions that can or must be considered in a single biological opinion. The interagency effort to clearly reach consensus on implications of the combined RPAs for their effects on all the species and on water quality and quantity within the delta and on water operations and deliveries should use scientific principles and methods in a collaborative and integrative manner. Similarly, this committee's efforts to evaluate potential harmful effects of each RPA on the species covered in the other RPA were hampered by the lack of a systematic, integrated analysis covering all the species together. Full documentation of decisions should be part of such an effort, as should inclusion of the environmental water needs of specific actions and for the entire RPA.

It is clear that integrative tools that, for example, combine the effect over life stages into a population-level response would greatly help the development and evaluation of the combined actions. There has been significant investment in hydrologic and hydrodynamic models for the system, which have been invaluable for understanding and managing the system. An investment in ecological models that complement and are integrated with the hydrologic and hydrodynamics models is sorely needed. Clear and well-documented consideration of water requirements also would seem well advised because some of the actions have significant water requirements. Credible documentation of the water needed to implement each action and the combined actions, would enable an even clearer and more logical formulation of how the suite of actions might be coordinated to simultaneously benefit the species and ensure water efficiency. **This recommendation for integration of models and across species responds to the committee's broad charge of advising on how to most effectively incorporate scientific and adaptive-management concepts into holistic programs for managing the delta, and likely goes beyond the agencies' bare legal obligations under the ESA, and will be addressed more thoroughly in the committee's second report.**

Appendix B

Summary of A Review of the Use of Science and Adaptive Management in California's Draft Bay Delta Conservation Plan

The San Francisco Bay Delta Estuary (Delta, for short) is a large, complex estuarine ecosystem in California (Figure 1). It has been substantially altered by dikes, levees, channelization, pumps, human development, introduced species, dams on its tributary streams, and contaminants. The Delta supplies water from the state's wetter northern regions to the drier southern regions and also serves as habitat for many species, some of which are threatened and endangered. The restriction of water exports in an attempt to protect those species together with the effects of several dry years have exacerbated tensions over water allocation in recent years, and have led to various attempts to develop comprehensive plans to provide reliable water supplies and to protect the ecosystem.

One of those plans is the Bay Delta Conservation Plan (BDCP), the focus of this report. The BDCP is technically a habitat conservation plan (HCP), an activity provided for in the federal Endangered Species Act that protects the habitat of listed species in order to mitigate the adverse effects of a federal project or activity that incidentally "takes"[1] (includes actions that "harm" wildlife by impairing breeding, feeding, or sheltering behaviors) the listed species. It similarly is a natural community conservation

[1] *Take* means "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct." ESA, Section 3, 16 U.S.C. 1532. *Harm,* within the statutory definition of "take" has been further defined by regulation: "Harm in the definition of take in the Act means an act which actually kills or injures wildlife. Such act may include significant habitat modification or degradation where it actually kills or injures wildlife by significantly impairing essential behavioral patterns, including breeding, feeding, or sheltering." 50 C.F.R. 17.3.

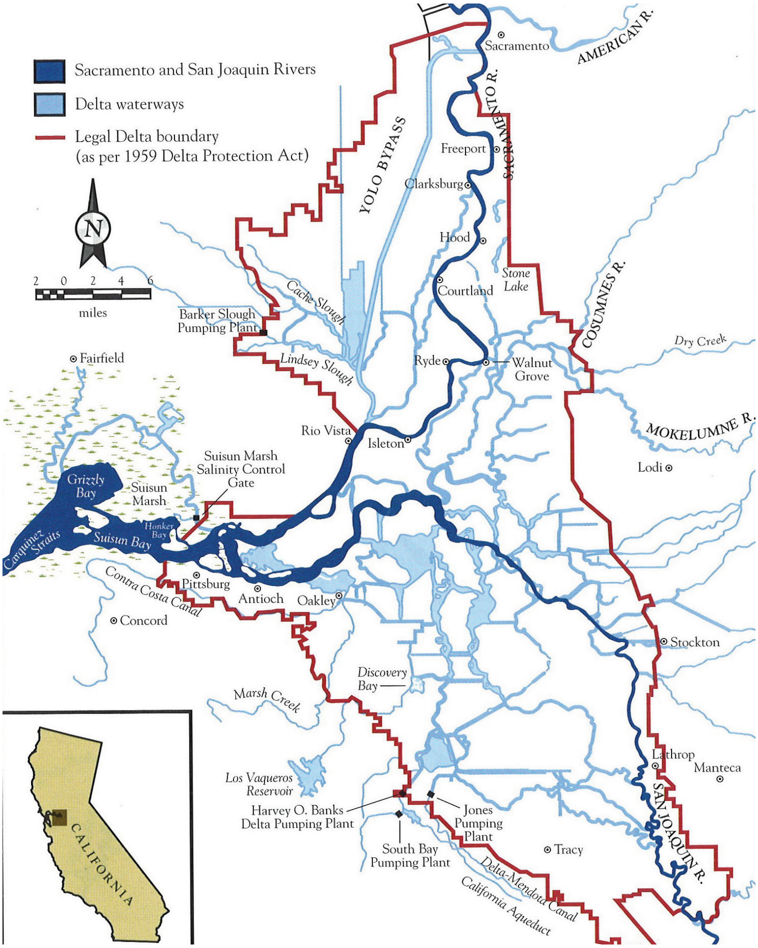

FIGURE 1 The Sacramento-San Joaquin Delta in California. San Francisco Bay, an integral part of the system, is just to the west. SOURCE: Lund et al. (2010). [Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. 2010. Comparing Futures for the Sacramento-San Joaquin Delta. Berkeley, CA: University of California Press. Pp. 1-229.]

plan (NCCP) under California's Natural Community Conservation Planning Act (NCCPA). It is intended to obtain long-term authorizations under both the state and federal endangered species statutes for proposed new water operations—primarily an "isolated conveyance structure," probably a tunnel, to take water from the northern part of the Delta for export to the south, thus reducing the need to convey water through the Delta and out of its southern end.

The U.S. Secretaries of the Interior and Commerce requested that the National Research Council (NRC) review the draft BDCP in terms of its use of science and adaptive-management. In response, the NRC established the Panel to Review California's Draft Bay Delta Conservation Plan, which prepared this report. The panel reviewed the draft BDCP, which was posted on the BDCP website: (*http://www.re-sources.ca.gov/bdcp/*) on November 18, 2010.[2] The panel determined that the draft BDCP is incomplete in a number of important areas and takes this opportunity to identify key scientific and structural gaps that, if addressed, could lead to a more successful and comprehensive final BDCP. Yet science alone cannot solve the Delta's problems. Water scarcity in California is very real, the situation is legally and politically complex, and many stakeholders have differing interests. The effective management of scarcity requires not only the best science and technology, but also consideration of public and private values, usually through political processes, to arrive at plans of action that are scientifically based but also incorporate and reflect the mix of differing personal and group values.

CRITICAL GAPS IN THE SCOPE OF THE DRAFT BDCP

At the outset of its review, the panel identified a problem with the geographical and hydrologic scope of the draft BDCP. The BDCP aims to address management and restoration of the San Francisco Bay Delta Estuary, an estuary that extends from the Central Valley to the mouth of San Francisco Bay. Thus, given that the BDCP describes a *bay* delta conservation plan, the omission of analyses of the effects of the BDCP efforts on San Francisco Bay (aside from Suisun Bay) is notable.

The Lack of an Effects Analysis

The draft BDCP describes an effects analysis as:

> . . . the principal component of a habitat conservation plan. . . . The analysis includes the effects of the proposed project on covered species, including federally and state listed species, and other sensitive species potentially affected by the proposed project. The effects analysis is a systematic, scientific look at the potential impacts of a proposed project

[2] BDCP (Bay Delta Conservation Plan Steering Committee). 2010. Bay Delta Conservation Plan Working Draft. November 18. Available online at: *http://www.resources.ca.gov/bdcp/*. Last accessed April 26, 2011.

on those species and how those species would benefit from conservation actions. (draft BDCP, p. 5-2)

Clearly, such an effects analysis, which is in preparation, is intended to be the basis for the choice and details of those conservation actions. Its absence in the draft BDCP, therefore, is a critical gap in the science in the BDCP and the corresponding conservation actions. Nevertheless, the panel takes this opportunity to present its vision of a successful effects analysis, which includes an integrated description of the components of the system and how they relate to each other; a synthesis of the best available science; and a representation of the dynamic response of the system.

The term "effects analysis" also applies to an analysis of what is causing the listed (and other ecologically important) species to decline. In such a case, the logical sequence would be to perform the effects analysis on the causes of the species' declines, then design a proposed alternative to current operations to help reverse those declines, and then perform a second effects analysis on the probable effects of the proposed alternative. This aspect of an effects analysis is not mentioned in the current draft of the BDCP, and its absence brings the panel to a second critical gap in the scope of the draft BDCP, namely, a lack of clarity of the BDCP's purpose.

The Lack of Clarity as to the BDCP's Purpose

The legal framework underlying the BDCP is complex, as are the challenges of assembling such a large habitat conservation plan. Nonetheless, the BDCP's purpose or purposes need to be clearly stated, because their nature and interpretation are closely tied to the BDCP's scientific elements. The lack of clarity makes it difficult for this panel and the public to properly understand, interpret, and review the science that underlies the BDCP.

The central issue is to what extent the BDCP is only an application for a permit to incidentally take listed species, and to what extent it also is designed to achieve the two co-equal goals of providing for a more reliable water supply for the state of California and protecting, restoring, and enhancing the Delta ecosystem specified in recent California water legislation. To obtain an incidental take permit, it is logical to identify a proposed project or operation and design conservation methods to minimize and mitigate its adverse effects. But if the BDCP were largely a broader conservation program, designed to protect the ecosystem and provide a reliable water supply, then a more logical sequence would be to choose alternative projects or operating regimes only after the effects analysis was complete. Under that scenario, choosing the alternative first would be like putting the cart before the horse, or *post hoc* rationalization; in other words, choosing a solution before evaluating alternatives to reach a preferred outcome.

A related issue is the lack of consideration of alternatives to the preferred proposal (i.e., the isolated conveyance system). To the degree that the reasons for not considering alternatives have a scientific (as opposed to, for example, a financial) basis, their absence makes the BDCP's purpose less clear, and the panel's task more difficult.

THE USE OF SCIENCE AND SYNTHESIS IN THE BDCP

Many scientific efforts are and have been under way to understand and monitor hydrologic, geologic, and ecological interactions in the Delta, efforts that constitute the BDCP's scientific foundation. But overall it is not clear how the BDCP's authors synthesized the foundation material and systematically incorporated it into the decision-making process that led to the plan's conservation actions. For example, it is not clear how the Delta Regional Ecosystem Restoration Implementation Plan has been incorporated into the draft BDCP (see Appendix F of the draft BDCP). It also is not clear whether and how the draft BDCP incorporated the analyses for the Delta Risk Management Strategy and the framework developed by the Interagency Ecological Program related to factors affecting pelagic organism decline.

Furthermore, some of the scientific efforts related to the BDCP were incomplete at the time of this review. For example, warming, sea level rise, and changes in precipitation patterns and amounts will play a central role in Delta water allocation and its effects. Although the draft BDCP does mention incorporation of climate variability and change and model uncertainty, such information was not included in the draft BDCP that was provided.

Several other conservation efforts have been undertaken in the Delta in response to consultations with the National Marine Fisheries Service and the U.S. Fish and Wildlife Service concerning the potential for project operations (e.g., pumping) to jeopardize the listed species. The link between the BDCP and these other efforts is unclear. For example, the Delta Plan is a comprehensive conservation, restoration, and water-supply plan mandated in recent California legislation. That legislation also provided for potential linkage between the BDCP and the Delta Plan, but the draft BDCP does not make clear how this new relationship will be operationalized.

Much of the analysis of the factors affecting the decline of smelt and salmonids in the Delta has focused on water operations there, in particular, the pumping of water at the south end of the Delta for export to other regions. However, a variety of other significant environmental factors ("other stressors") have potentially large effects on the listed fishes. In addition, there remain considerable uncertainties surrounding the degree to which different aspects of flow management in the Delta, especially management of the salinity gradient, affect the survival of the listed fishes. Indeed, the significance and appropriate criteria for future environmental flow optimization have yet to be established, and are uncertain at best. The panel supports the concept of a quantitative evaluation of stressors, ideally using life-cycle models, as part of the BDCP.

The lack of clarity concerning the volume of water to be diverted is a major shortcoming of the BDCP. In addition, the BDCP provides little or no information about the reliability of supply for such a diversion or the different reliabilities associated with diversions of different volumes. It is nearly impossible to evaluate the BDCP without a clear specification of the volume(s) of water to be diverted, whose negative impacts the BDCP is intended to mitigate.

The draft BDCP is little more than a list of ecosystem restoration tactics and scientific efforts, with no clear over-arching strategy to tie them together or to implement them coherently to address mitigation of incidental take and achievement of the co-equal goals and ecosystem restoration. The relationships between scientific programs and efforts external to the BDCP and the BDCP itself are not clear. Furthermore scientific elements within the BDCP itself are not clearly related to each other. A systematic and comprehensive restoration plan needs a clearly stated strategic view of what each major scientific component of the plan is intended to accomplish and how this will be done. The separate scientific components should be linked, when relevant, and systematically incorporated into the BDCP. Also, a systematic and comprehensive plan should show how its (in this case, co-equal) goals are coordinated and integrated into a single resource plan and how this fits into and is coordinated with other conservation efforts in the Delta, for example, the broader Delta Plan.

ADAPTIVE MANAGEMENT

Numerous attempts have been made to develop and implement adaptive management strategies in environmental management, but many of them have not been successful, for a variety of reasons, including lack of resources; unwillingness of decision makers to admit to and embrace uncertainty; institutional, legal, and political preferences for known and predictable outcomes; the inherent uncertainty and variability of natural systems; the high cost of implementation; and the lack of clear mechanisms for incorporating scientific findings into decision making. Despite all of the above challenges, often there is no better option for implementing management regimes, and thus the panel concludes that the use of adaptive management is appropriate in the BDCP. However, the application of adaptive management to a large-scale problem like the one that exists in California's Bay-Delta will not be easy, quick, or inexpensive. The panel concludes that the BDCP needs to address these difficult problems and integrate conservation measures into the adaptive management strategy before there can be confidence in the adaptive management program. In addition, the above considerations emphasize the need for clear goals and integrated goals, which have not been provided by the draft BDCP. Although no adaptive management program can be fully described before it has begun, because such programs evolve as they are implemented, some aspects of the program could have been laid out more clearly than they have been.

Adaptive management requires a monitoring program to be in place. The draft BDCP does describe its plan for a monitoring program in considerable detail. However, given the lack of clarity of the BDCP's purpose and of any effects analysis, it is difficult to evaluate the motivation and purpose of the monitoring program. An effective monitoring program should be tied to the effects analysis, its purpose should be clear (e.g., to establish reference or baseline conditions, to detect trends, to serve as an early-warning system, to monitor management regimes for effectiveness), and it should include a mechanism for linking the information gained to operational decision making and to the monitoring itself. Those elements are not clearly described in the draft BDCP.

In 2009, the BDCP engaged a group of Independent Science Advisors to provide expertise on approaches to adaptive management. The panel concludes that the Independent Science Advisors provided a logical framework and guidance for the development and implementation of an appropriate adaptive management program for the BDCP. However, the draft BDCP lacks details to demonstrate that the adaptive management program is properly designed and follows the guidelines provided by the Independent Science Advisors. The panel further concludes that the BDCP developers could benefit significantly from adaptive management experiences in other large-scale ecosystem restoration efforts, such as the Comprehensive Everglades Restoration Program. The panel recognizes that no models exactly fit the Delta situation, but this should not prevent planners from using the best of watershed-restoration plans to develop an understandable, coherent, and data-based program to meet California's restoration and reliability goals. Even a soundly implemented adaptive management program is not a guarantee of achieving the BDCP's goals, however, because many factors outside the purview of the adaptive-management program may hinder restoration. However, a well-designed and implemented adaptive management program should make the BDCP's success more likely.

MANAGEMENT FRAGMENTATION AND A LACK OF COHERENCE

The absence of scientific synthesis in the draft BDCP draws attention to the fragmented system of management under which the plan was prepared—a management system that lacks coordination among entities and clear accountability. No one public agency, stakeholder group or individual has been made accountable for the coherence, thoroughness, and effectiveness of the final product. Rather, the plan appears to reflect the differing perspectives of federal, state, and local agencies, and the many stakeholder groups involved. Although this is not strictly a scientific issue, fragmented management is a significant impediment to the use and inclusion of coherent science in future iterations of the BDCP. Different science bears on the missions of the various public agencies, and different stakeholders put differing degrees of emphasis on specific pieces of science. Unless the management structure is made more coherent and unified, the final product may continue to suffer from a lack of integration in an attempt to satisfy all discrete interests and not, as a result, the larger public interests.

IN CONCLUSION

The panel finds the draft BDCP to be incomplete or unclear in a variety of ways and places. The plan is missing the type of structure usually associated with current planning methods in which the goals and objectives are specified, alternative measures for achieving the objectives are introduced and analyzed, and a course of action is identified based on analytical optimization of economic, social, and environmental factors. Yet the panel underscores the importance of a credible and a robust BDCP in addressing the various water management problems that beset the Delta. A stronger, more complete, and more scientifically credible BDCP that effectively integrates and utilizes science could indeed pave the way toward the next generation of solutions to California's chronic water problems.

Appendix C

Committee on Sustainable Water and Environmental Management in the California Bay-Delta

STATEMENT OF TASK

At the request of Congress and the Departments of the Interior and Commerce, a committee of independent experts will be formed to review the scientific basis of actions that have been and could be taken to simultaneously achieve both an environmentally sustainable Bay-Delta and a reliable water supply. In order to balance the need to inform near-term decisions with the need for an integrated view of water and environmental management challenges over the longer-term, the committee will undertake two main projects over a term of two years resulting in two reports.

First, on March 18, 2010, the committee issued a report focusing on scientific questions, assumptions, and conclusions underlying water-management alternatives in the U.S. Fish and Wildlife Service's (FWS) Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project (Dec. 15, 2008) and the National Marine Fisheries Service's (NMFS) Biological Opinion on the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan (June 4, 2009). This review will consider the following questions.

Are there any "reasonable and prudent alternatives" (RPAs), including but not limited to alternatives considered but not adopted by FWS (e.g., potential entrainment index and the delta smelt behavioral model) and NMFS (e.g., bubble-curtain technology and engineering solutions to reduce diversion of emigrating juvenile salmonids to the interior and southern Delta instead of towards the sea), that, based on the best available scientific data and analysis, (1) would have lesser impacts to other water uses as compared to those adopted in the biological opinions, and (2) would provide equal or greater protection for the relevant fish species and their designated critical habitat given the uncertainties involved?

Are there provisions in the FWS and NMFS biological opinions to resolve potential incompatibilities between the opinions with regard to actions that would benefit one listed species while causing negative impacts on another, including, but not limited to, prescriptions that: (1) provide spring flows in the Delta in dry years primarily to meet water quality and outflow objectives pursuant to Water Board Decision-1641 and conserve upstream storage for summertime cold water pool management for anadromous fish

Second, in approximately November 2011, the committee will issue a second report on how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the Bay-Delta. This advice, to the extent possible, should be coordinated in a way that best informs the Bay Delta Conservation Plan development process. The review will include tasks such as the following:

- Identify the factors that may be contributing to the decline of federally listed species, and as appropriate, other significant at-risk species in the Delta. To the extent practicable, rank the factors contributing to the decline of salmon, steelhead, delta smelt, and green sturgeon in order of their likely impact on the survival and recovery of the species, for the purpose of informing future conservation actions. This task would specifically seek to identify the effects of stressors other than those considered in the biological opinions and their RPAs (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Delta, and their effects on baseline conditions. The committee would consider the extent to which addressing stressors other than water exports might result in lesser restrictions on water supply. The committee's review should include existing scientific information, such as that in the NMFS Southwest Fisheries Science Center's paper on decline of Central Valley fall-run Chinook salmon, and products developed through the pelagic organism decline studies (including the National Center for Ecosystem Analysis and Synthesis reviews and analyses that are presently under way).
- Identify future water-supply and delivery options that reflect proper consideration of climate change and compatibility with objectives of maintaining a

species; and (2) provide fall flows during wet years in the Delta to benefit Delta smelt, while also conserving carryover storage to benefit next year's winter-run cohort of salmon in the event that the next year is dry?

To the extent that time permits, the committee would consider the effects of other stressors (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Bay-Delta. Details of this task are the first item discussed as part of the committee's second report, below, and to the degree that they cannot be addressed in the first report they will be addressed in the second.

sustainable Bay-Delta ecosystem. To the extent that water flows through the Delta system contribute to ecosystem structure and functioning, explore flow options that would contribute to sustaining and restoring desired, attainable ecosystem attributes, while providing for urban, industrial, and agricultural uses of tributary, mainstem, and Delta waters, including for drinking water.

- Identify gaps in available scientific information and uncertainties that constrain an ability to identify the factors described above. This part of the activity should take into account the Draft Central Valley Salmon and Steelhead recovery plans,[1] particularly the scientific basis for identification of threats to the species, proposed recovery standards, and the actions identified to achieve recovery.
- Advise, based on scientific information and experience elsewhere, what degree of restoration of the Delta system is likely to be attainable, given adequate resources. Identify metrics that can be used by resource managers to measure progress toward restoration goals.

The specific details of the tasks to be addressed in this second report will likely be refined after consultation among the departments of the Interior and Commerce, Congress, and the National Research Council, considering stakeholder input, and with the goal of building on, rather than duplicating, efforts already being adequately undertaken by others.

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[1]National Oceanic and Atmospheric Administration (NOAA). 2009b. Draft Central Valley Salmon and Steelhead Recovery Plan Available on line at http://swr.nmfs.noaa.gov/recovery/centralvalleyplan.htm

Appendix D

Public Session Speakers

Federico Barajas, U.S. Bureau of Reclamation
Letty Belin, U.S. Department of the Interior
David H. Blau, Senior Water Resource Planner, AECOM
Dan Castleberry, U.S. Fish and Wildlife Service
Mike Chotkowski, U.S. Bureau of Reclamation
Francis Chung, California Department of Water Resources
James Cloern, U.S. Geological Survey
The Honorable Representative Jim Costa
DeeDee D'Adamo, Senior Policy Advisor for Representative Dennis Cardoza
Cliff Dahm, Delta Stewardship Counsil
Rick Deriso, Inter-American Tropical Tuna Commission
William Fleenor, Department of Civil and Environment Engineering, University of California, Davis
David Fullerton, Metropolitan Water District of Southern California
Greg Gartrell, Contra Costa Water District
Patricia Glibert, Horn Point Laboratory, University of Maryland
Cay Goude, U.S. Fish and Wildlife Service
Scott Hamilton, Coalition for a Sustainable Delta
Campbell Ingram, The Nature Conservancy
Jerry Johns, California Department of Water Resources
Michael Johnson, Aquatic Ecosystems Analysis Laboratory, University of California, Davis
Linda Katehi, University of California, Davis
Wim Kimmerer, San Francisco State University

Steve Lindley, Southwest Fisheries Science Center, National Marine Fisheries Service
Gerald Meral, Deputy Secretary, California Resources Agency
BJ Miller, Consultant
Ron Milligan, U.S. Bureau of Reclamation
Jeffrey Mount, Center for Wetland Sciences, University of California, Davis
Peter B. Moyle, Department of Wildlife, Fish, and Conservation Biology, University of California, Davis
Dave Mraz, California Department of Water Resources
Anke Müeller-Solger, Interagency Ecology Program, Delta Stewardship Council
Armin Munevar, CH2M HILL
Karla Nemeth, California Natural Resources Agency
Matt Nobriga, California Department of Fish and Game
Bruce Oppenheim, National Marine Fisheries Service
Roger Patterson, Metropolitan Water District
Jason Peltier, Westlands Water District
Maria Rea, National Marine Fisheries Service
Rhonda Reed, National Marine Fisheries Service
Richard Roos-Collins, American Rivers or National Heritage Institute
Melanie Rowland, National Oceanic and Atmospheric Adiministration General Counsel's Office
Karen Schwinn, Associate Director, Water Division, EPA Region 9, U.S. EPA
Lester Snow, California Department of Natural Resources
Jeff Stuart, National Marine Fisheries Service
Christina Swanson, Executive Director, The Bay Institute
Michael Tucker, National Marine Fisheries Service
Dr. Donald Weston, Adjunct Professor, Department of Integrative Biology, University of California, Berkeley
Carl Wilcox, California Department of Fish and Game
Garwin Yip, National Marine Fisheries Service

Appendix E

Changes in the Zooplankton of the San Francisco Estuary[1]

By Wim Kimmerer, San Francisco State University, 22 November 2011

This section discusses changes in the zooplankton that have occurred over the past four decades and how these changes may influence the population status of delta smelt, listed anadromous fishes, and other species of concern. Of these species only delta smelt feeds mainly on zooplankton and remains within the upper estuary throughout its life cycle. Therefore this section addresses zooplankton as a key element of the food web throughout the estuary, while focusing on details in delta smelt habitat, particularly brackish water (the "low-salinity zone"), during summer and fall.

Considerable data are available to support this summary. The long-term monitoring program run by the Interagency Ecological Program (IEP) has sampled and identified zooplankton regularly since 1972 in the delta and Suisun Bay ("upper estuary") and in most of those years in San Pablo Bay (Winder and Jassby 2011). Additional sampling has occurred since 1995 as part of a spring survey of young delta smelt, and recently zooplankton sampling has been added to other fish surveys. Numerous research projects have examined zooplankton, including several investigations of zooplankton abundance and species composition in San Pablo to South Bay (Ambler et al. 1985, Bollens et al. 2011, Kimmerer et al. in preparation) and studies of processes such as tidally oriented vertical migration, feeding, predation by fish and clams, and population dynamics (e.g., Kimmerer et al. 1994, 1998, 2005, Hooff and Bollens 2004, Kimmerer 2006, Bouley and Kimmerer 2006, Gould and Kimmerer 2010, Bollens et al. 2011).

Zooplankton live in a moving frame of reference. Their swimming

[1] The committee thanks Professor Wim Kimmerer for providing this material.

ability is limited by their small size; while they can migrate vertically on a diurnal or tidal cycle, they cannot swim against tidal currents, but rather they move passively with horizontal movements of water. Therefore it is often better to sample zooplankton and characterize their habitat according to salinity rather than location (Laprise and Dodson 1993). This way of looking at zooplankton is helpful when analyzing the food supply of delta smelt, which also move with the water.

The long-term data show several periods of substantial change in the last 38 years. Many species or groups of species are now at much lower population levels than they were when monitoring started. Declines have occurred throughout the estuary, except possibly Central Bay, but have been most severe in the freshwater delta and the low-salinity zone.

From 1972 through 1986 the zooplankton species composition of the upper estuary was stable except for the introductions of three species of copepod from Asia (Orsi and Mecum 1986). The introduction and subsequent spread of the overbite clam in 1987 caused an immense disruption of the food web in brackish to saline waters between San Pablo Bay and the west-central delta, and several zooplankton species declined sharply (Kimmerer et al. 1994, Kimmerer and Orsi 1996, Orsi and Mecum 1996). Between 1988 and 1994 a series of additional introductions essentially filled in the gap in the summer food web left by the earlier declines (Kimmerer and Orsi 1996, Orsi and Ohtsuka 1999). Since 1994 the food web has seen no further major introductions, yet some declines continue, and most of the species in the low-salinity zone are introduced (Orsi and Ohtsuka 1999, Winder and Jassby 2011).

Most of the introduced species probably arrived in ballast water, although Winder et al. (2011) reported that droughts may have facilitated the spread of some introduced species. Regulations requiring exchange of ballast water at sea since 2000 seem to have reduced the frequency of invasions. A study conducted in 2002-2003 found some potential invaders in ballast water of ships entering the estuary, but their numbers were low and in some cases their condition was poor, suggesting that they were unlikely to overcome the rigors of their new habitat to establish new populations (Choi et al. 2005). The lack of invasions could also be a matter of chance, since a successful invasion requires several coincident conditions that may be met only infrequently (Choi and Kimmerer 2009).

Many of the changes discussed above occurred within the low-salinity habitat of juvenile delta smelt (Bennett 2005). The overbite clam clearly had a substantial effect through grazing on phytoplankton, resulting in poor feeding conditions for some zooplankton. The clam also consumes larval stages of some zooplankton (Kimmerer et al. 1994). The zooplankton species introduced after the clam became abundant have had several advantages over the previously abundant species. First, anchovies abandoned this region of the estuary, probably because of poor food conditions compared to higher salinity, which removed a significant consumer of plankton from this region (Kimmerer 2006). Second, each of these species has mechanisms for counteracting the effects of clam grazing; for example, one species (*Limnoithona tetraspina*) is very small, making it less vulnerable than other species to predation by fish, and it eats ciliates and other microzooplankton rather than phytoplankton (Bouley and Kimmerer 2006). Notably, *Pseudodiaptomus forbesi* is most abundant in freshwater, where the overbite clam is absent, and its population in brackish water is subsidized by movement from the freshwater population center, offsetting losses to clams and other consumers (Durand, 2010).

Causes of the declines in abundance likely differ by region within the estuary, and some may never be identified. However, the abrupt changes in the zooplankton in brackish water in the mid- to late 1980s was very likely due to the establishment of the overbite clam (Kimmerer et al. 1994). A more recent decline in *Pseudodiaptomus forbesi* may be due to competition with the highly abundant but small *Limnoithona tetraspina*. This is worrisome because the latter does not provide as valuable a food resource to small fish as does *Pseudodiaptomus forbesi* (L. Sullivan, SFSU, personal communication). The long-term decline in phytoplankton biomass and changes in size and species composition (Lehman 2000, Kimmerer 2005, Kimmerer et al. (2012) have also limited the food supply for zooplankton.

Today, growth of delta smelt in their summer-fall low-salinity habitat is probably limited by the low abundance of suitable zooplankton species there (Bennett 2005, Kimmerer 2008). Zooplankton growth and reproductive rates are also low, indicating that their food supply is limited (Kimmerer et al. 2005, unpublished). At such a low level of growth and reproduction, these populations can support only a very low level of consumption by fish such as delta smelt.

The situation in the freshwater delta is somewhat similar to that in the low-salinity zone. Although the food available to zooplankton is more abundant in freshwater, some species have declined over the years and are now much less abundant than formerly. Some species may be harmed by blooms of freshwater cyanobacteria ("blue-green algae"), which have become prominent in the past decade (Lehman et al. 2005), or by various toxic substances. In areas of higher salinity including San Pablo and San Francisco bays, zooplankton appear to be more abundant than in low salinity, but still less so than in many other estuaries.

One component of the zooplankton that has only recently been examined is microzooplankton such as ciliate protozoa. These organisms are the second most important consumers of phytoplankton after clams, and the most important food for many larger zooplankton (Murrell and Hollibaugh 1998, Bouley and Kimmerer 2006, Gifford et al. 2007, York et al. 2010, Rollwagen-Bollens et al. 2011). All of the copepods consumed by delta smelt rely on microzooplankton for most of their food. The abundance and species composition of microzooplankton is highly variable, so monitoring of their abundance is essential for interpreting changes in the larger zooplankton fed on by fish.

Opportunities to reverse the declines in zooplankton are severely limited, at least with our current knowledge of their ecology. Producing more food for them is impracticable because adding more phytoplankton to the system would probably just produce more clams. There may be opportunities to enhance populations of some zooplankton through manipulations of freshwater flow, and control of nutrient inputs to the delta may improve growth conditions for phytoplankton and reduce the frequency of harmful algal blooms. These are active areas of research which will help to clarify the potential responses to these changes.

Significant gaps in the available information limit our understanding of zooplankton. First, most of the sampling by the zooplankton monitoring program has focused on the delta and Suisun Bay, with limited sampling in San Pablo Bay and none in San Francisco Bay. Because zooplankton move with the water, during high freshwater flows their populations move seaward, and the monitoring misses the bulk of these populations. Thus, the potentially important influence of freshwater flow on the zooplankton is known only from low to moderate flows.

Another gap is the lack of information on important changes in the more seaward reaches of the estuary, such as the potential response of zooplankton in South San Francisco Bay to a recent upsurge in production of algal food. We also lack a system for detecting new and potentially harmful introductions, and neither the rate of arrival of organisms in ballast nor the efficacy of ballast exchange in removing organisms is being monitored.

The third gap is a complete lack of routine monitoring for microzooplankton and bacteria. The current monitoring program was begun in the late 1960s under a conceptual model for planktonic food webs that is now outdated. The key role of microzooplankton in the planktonic food web, well known from other marine and estuarine locations, has been established for the San Francisco Estuary by several researchers. Bacteria are sometimes as important in the food web as phytoplankton, but only a few short-term studies have examined the roles of bacteria in the estuary. An expansion of the monitoring program to include these key components is long overdue.

The existing zooplankton monitoring program is very well run and, after a great deal of work, the database is in excellent condition. However, the other programs that monitor zooplankton are not well coordinated with the core program, and none of the data from any of these programs is readily available online. Thus, there are several opportunities to update and improve the existing programs to make them more useful and relevant to our current understanding.

Despite the gaps discussed above, the knowledge of zooplankton in this estuary is considerable. This body of knowledge has benefited from the valuable data from the consistent, long-term monitoring program, put in place 40 years ago by agency scientists who clearly had an ecosystem-level perspective.

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Appendix F

Methods to Support Decision Making

We highlight here four approaches to formalizing decision making and the rationalization of decisions that have been useful in complex water resources planning. These are robust decision making, collaborative modeling for decision support, decision scaling, and joint fact finding. We present these as examples of formal frameworks for tracking and understanding decisions in complex situations. We recommend that these, and others, be evaluated and some version (or perhaps a hybrid) be adopted for the delta. These approaches are frameworks that include a transparent procedure with a series of structured linkages and steps. Some of these steps include the use of statistical and numerical models, some of which already exist for the delta and others that would need to be developed should one of these approaches be adopted.

ROBUST DECISION MAKING

Robust decision making (RDM) (Lempert et al. 2003, 2006, Groves and Lempert 2007) is a quantitative, scenario-based method for identifying policies (or strategies) that are relatively insensitive to poorly understood uncertainty. Instead of developing a single and potentially contested probabilistic forecast and associated optimal solution, RDM evaluates candidate solutions against large ensembles of possible outcomes to illuminate critical vulnerabilities and suggest approaches for increasing the strategies' robustness. RDM has been applied to problems related to climate change mitigation or adaptation in a variety of different contexts, including global sustainability (Lempert et al. 2004, 2006) and long-term water planning

(Groves and Lempert 2007, Groves et al. 2008a, 2008b, 2008c, 2008d). It has been a useful framework for developing robust climate adaptation strategies for water agencies. Key challenges to deploying RDM include retooling existing models to be evaluated many more times than is typical, deploying new and often unfamiliar statistical approaches for identifying vulnerabilities, and ensuring that decision makers and stakeholders understand the new approach.

RDM proceeds through a series of steps that can be customized depending on the application. In the first step, analysts, often in conjunction with stakeholders and decision makers, specify the key uncertain exogenous factors (X) that are likely to be disputed by different parties to the decision, draw up a list of policy levers (L) that comprise strategies, identify measures (M) to consider when evaluating policy outcomes, and identify models and/or relationships (R) that relate the uncertainties and strategies to outcomes. The resulting information, termed an "XLRM" chart, is used to assemble the quantitative models to be used to evaluate the performance of strategies under many alternative scenarios.

The resulting analysis is not used to identify a single "optimal" strategy. Instead, one or a few strategies are identified for a structured evaluation of their performance against a wide array of plausible scenarios (steps 2 and 3). In the fourth step, statistical tools are used to identify the key vulnerabilities, or sets of assumptions that lead the proposed strategy to fail. These vulnerabilities thus represent future conditions (or scenarios) that are critically important to the choice of strategies—they are the conditions that might lead the promising strategy to perform poorly. Under these conditions, alternative strategies would be preferred. The trade-offs among alternatives under these vulnerable conditions can be helpful in identifying new hedging options that can then be used to develop more robust strategies. These more robust strategies are then evaluated as before. Through iteration, RDM helps the analyst explore across a broad range of possible strategies without requiring the contentious specification of uncertain future parameters. The strategies identified become more robust, thus reducing the sensitivity of the strategy's performance to the key uncertainties.

In contrast to probabilistic assessments, which typically provide rankings of strategies based on a set of underlying assumptions about climate change, RDM identifies the key uncertainties relevant to the choice of strategy and then provides trade-off curves that enable decision makers to assess the implications of different expectations of the key uncertainties to their choices. This information has been compelling to stakeholders and decision makers when evaluating climate change impacts on water-management systems (Groves et al. 2008c).

COLLABORATIVE MODELING FOR DECISION SUPPORT

To evaluate alternative delta scenarios it would be helpful to have a multifaceted analysis that could address scarcity economics, water market prices, energy utilization, and alternatives for adaptive management. Collaborative modeling for decision support (abbreviated CMDS or COMODES) is the "generic" (Cardwell 2011) name given to a suite of techniques that can be used to achieve consensus on complex, contentious issues. Indeed, Lorie (2010) defined CMDS as "integrating collaborative modeling with participatory processes to inform natural resource management decisions." CMDS is an approach to reach consensus and make decisions about complex systems that combines technical skills required to understand the systems scientifically and stakeholder involvement (Cockerill et al. 2006, Langsdale et al. 2011). With respect to stakeholder involvement, process skills such as an appreciation of institutional setting and ability to engage stakeholders and build their trust are essential (Langsdale et al. 2011).

Various "brand names" of CDMS are Shared Vision Planning (SVP), the brand of CMDS used by the Institute for Water Resources (IWR) of the U.S. Army Corps of Engineers (Cardwell et al. 2008); Computer-Assisted Dispute Resolution or CADRe (Stephenson et al. 2007); or mediated modeling (van den Belt 2004). Although CMDS has been practiced in one form or anther since the late 1980s (Langsdale et al. 2011), only recently has there been specification of guiding principles and best practices.

Langsdale et al. (2011) listed eight guiding principles:

1. Collaborative modeling is appropriate for complex, conflict-laden decision making processes where stakeholders are willing to work together.
2. All stakeholder representatives participate early and often to ensure that all their relevant interests are included.
3. Both the analysis and the process remain accessible and transparent to all participants.
4. Collaborative modeling builds trust and respect among parties.
5. The analysis supports the decision process by easily accommodating new information and quickly simulating alternatives.
6. The analysis addresses questions that are important to decision makers and stakeholders.
7. Parties share interests and clarify the facts before negotiating alternatives.
8. Collaborative modeling requires both modeling and facilitation skills.

One aspect of CMDS that can perplex sophisticated modelers is the premise that stakeholders, many of whom have little or no experience with either the development or application of simulation models, will be active participants in the modeling process. For a system as complex as the delta, this may seem to be an impossible situation. Langsdale et al. (2011) offer some guidance on this.

Often, system dynamics (SD) modeling techniques are applied to conduct collaborative modeling studies because they allow participants to examine complex physical systems that involve social and economic factors involved (Cockerill et al. 2006).

This section would be incomplete without addressing the prospects for consensus that collaborative modeling seeks to achieve. Madani and Lund (2012) have traced changes in the delta conflict in the context of game theory and suggest that the conflict has evolved with time from cooperation to "chicken." In the early 20th century, stakeholders agreed to cooperative solutions; later on, fights over water allocations led to stakeholders competing as opposed to cooperating (Madani and Lund 2012). They do state that a win-win resolution may be possible but that a cooperative solution is unlikely without external influence.

Indeed, they conclude their paper with the following:

> Including the state of California (or federal government) did not fundamentally alter the game. For the cases examined, the Chicken characteristics remained and cooperation was unlikely. Adding the state to the game suggested that California can be the victim and loser in the conflict, bearing much of the cost of a Delta failure, due to its past failure so far to develop reliable mechanisms to enforce cooperation.
>
> Whatever plan is adopted to fix the Delta in the coming decades, the Delta's sustainability is not guaranteed without powerful mechanisms which provide incentives for cooperation or penalties for deviation from cooperation. While recent efforts address symptoms of the problem, they have not yet solved a main cause - lack of effective and responsive governing mechanisms. California must "govern" the Delta or pay for absence of effective governance.

The prospect for achieving consensus, whether by collaborative modeling or some other means, is a daunting task.

Collaborative Modeling in the Delta

Two episodes in the recent history of delta management illustrate the value of collaborative modeling. The first of these was the development of flow standards by the U.S. Environmental Protection Agency (EPA) in the period 1992-1994, which began with the 1992 EPA workshops (Schubel et al. 1993, Kimmerer and Schubel 1994). The key step in translating the conclusions of this workshop into a workable standard for flow, in this case based on the position of X_2, was modeling used to understand the water-supply recommendations of the standard. This was done through a collaboration between a regulatory agency (the EPA) and by engineers from the Contra Costa Water District acting on behalf of the California Urban Water Agencies (CUWA), an organization of stakeholders who would have been affected by the regulation (R. Denton, personal communication, 2012). In the end, the EPA X_2 regulations as modified by CUWA were adopted as the 1994 Bay-Delta Accord, an agreement that helped lead to the establishment of CALFED (Rieke 1996, Hanemann and Dyckman 2009).

The second episode was the gaming carried out to design the Environmental Water Account (EWA). In this case, a group of regulators, consultants, and representatives of water agencies and environmental groups explored the water-supply implications of different-size EWAs using the water resources system model CALSIM (Brown et al. 2004, Booher and Innes 2010). Using historical salvage data, this gaming was used to developing strategies for deploying EWA assets in order to have maximal effect (Brown et al. 2009). Importantly, as Connick and Innes (2003) write,

> it [the EWA] would not have been even imaginable without the trust and co-operation of the stakeholders. Moreover the details could not have been worked out without this social capital. Agency personnel and stakeholders from agricultural and urban water interests and environmental groups spent hundreds of hours working through various scenarios to test how the approach could be used before recommending that it be part of the CALFED programme.

Thus, the aims of these collaborative efforts were in some ways modest; that is, the outcomes of the modeling they used were relatively straightforward, being focused on water operations and their effect on the physical environment. Nonetheless, the committee views them as examples worth emulating in future efforts to manage the delta ecosystem.

Collaborative Modeling in Everglades Restoration

In 1993, the U.S. Army Corps of Engineers (USACE), in partnership with the South Florida Water Management District (SFWMD) and other stakeholders, initiated the Comprehensive Review Study of the Central and Southern Florida (C&SF) Project. This study, commonly called "the Restudy," was intended to integrate solutions which when implemented will enhance the ecological values of the Florida Everglades by increasing the total spatial extent of natural areas, improving the habitat and functional quality, plant and animal species abundance, and diversity. Another objective was the enhancement of economic values and social well-being through increase of the availability of freshwater for agricultural, municipal, and industrial users, reduction of flood damages, provision of recreational and navigational opportunities, and protection of cultural and archeological resources and values.

The Restudy followed a transparent, multiagency, participatory, and highly iterative process with a strong collaborative modeling component for the development of the Comprehensive Everglades Restoration Plan (CERP). The core Restudy team of analysts consisted of multidisciplinary professionals from numerous federal, state, local, and tribal organizations, and subteams for modeling, alternatives design, alternative analysis, and public involvement. The Restudy's success in meeting deadlines and consensus building required the use of a large team consisting of over 150 individuals from 30 different public entities representing over 20 different professional disciplines. The modeling team relied heavily on the use of several hydrologic, ecological, and water-quality simulation models and expert judgment.

Plan formulation began by developing a list of many different ideas to achieve goals and objectives. The ideas, called "components," were the individual building blocks that were combined in various ways to form alternative plans that included both structural and nonstructural features. In each iteration, alternative plans were formulated by the Alternative Design Team (ADT) and modeled by the Modeling Team. The designs of the alternative plans were built into the South Florida Water Management Model (SFWMM), a regional-scale hydrologic model, for performance evaluation and to provide input to other models in the toolbox. The modeling output was used to produce a large suite of performance measures that had been developed from conceptual models of the major landscapes and water-supply planning efforts. Each alternative plan was evaluated by another multiagency team called the Alternative Evaluation Team (AET), which incorporated comments from different agencies and the public, together with their own evaluation to make recommendations to the ADT for the next iteration. The AET was responsible for evaluating each plan's strengths and weaknesses, and describing plan shortfalls to the ADT. This repetitive formulation and evaluation process progressively refined and improved the performance of subsequent alternative plans. Because of the large and geographically dispersed number of people involved and interested in the Restudy, the Internet was used to communicate formulation and evaluation results. This allowed the Restudy team to solicit comments from a broad base of the public and permitted people to participate as team decisions were being made.

The collaborative modeling effort continues today through a newly created Interagency Modeling Center (IMC) with key leadership of sponsoring agencies and participation by others. It is a single point of service for the modeling needs of CERP projects and programs and provides coordination, review of other modeling efforts. Through interagency collaboration IMC acts as a clearinghouse for all project-specific modeling and conducts its own regional-scale analysis.[1]

DECISION SCALING

Brown et al. (2011) have recently described an alternative approach to decision making under climate change that may be applicable to the delta. Rather than begin with climate change predictions and their associated uncertainty downscaled to the problem at hand, the concept is to turn traditional decision analysis around and start by identifying which uncertainties are important from the viewpoint of the decision maker. In the case of climate change, the framework facilitates the identification of climate information that is critical to the planning decision. As a result, decision analysis provides an analytic framework that can be exploited to link bottom-up climate vulnerability analysis with the generation of climate change projections. The process is entitled "decision scaling."

The key tenet of the approach is that the appropriate orientation for adaptation planning is one of acceptance of large uncertainties and planning for a wide variety of possible futures. This runs contrary to the general scientific orientation of focusing on the reduction of uncertainty and then planning for the accepted expert characterization of the future. Instead, the approach emphasizes robustness over a wide range of climate futures. It has been applied to the development of a regulation plan for the Upper Great Lakes (Brown et al. 2011). The regulation plan utilizes dynamic responses to evolving conditions and adaptive management of uncertainties and surprise. However, Brown et al. present a general process for water resources planning under climate change (or any other uncertainty for which a variety of predictions are possible) based on a decision-analytic approach to identifying and tailoring the necessary information. The framework links insight from bottom-up analysis, including performance metrics defined by stakeholders with the processing of, in the Great Lakes example, climate change projections to produce decision-critical information.

A key aspect of decision scaling is that the specification of the climate states, that is, the specific climate information that causes a particular decision to be favored over another (or an impact to be large enough to warrant preventative actions, i.e., the identification of thresholds), may allow the credibility of climate information derived from GCM projections (or other sources) to be improved. That is, with the information from the

[1] See www.evergladesplan.org. Accessed July 17, 2012.

bottom-up, decision-analytic framework in hand, the generation of climate information may be tailored to best provide credible information through the selection of process models, temporal and spatial scales, and scaling techniques given the time.

The approach begins with stakeholders rather than predictive system models. Planners ask stakeholders and resource experts what conditions they could cope with and which would require substantial policy or investment shifts. This is then formalized within a framework that links the multiple models needed to relate changes in the physical climate conditions to performance metrics of interest to stakeholders. After these are established, hydrologists and climate scientists estimate the plausibility of the water conditions that exceed the coping thresholds, taking into account not only climate change but also natural climate variability and stochastic variability observed with a stationary climate assumption. While the existing applications of decision scaling focus on uncertainties associated with climate change, the approach could be adjusted to consider other uncertainties that are key in the bay delta including consumption patterns and environmental factors.

Joint Fact-Finding in Bay-Delta Science

The products of the delta science process involve at least three science efforts: one carried out by wildlife agencies, one by water users, and a third effort by professional environmental organizations. They each involve many scientists, including agency staff, academics, consulting firms, and individual experts with national reputations, and are carried out largely separately. There are fundamental disagreements. Each attempts to present the objective truth on a variety of issues. While there are several forms for collaboration, there does not seem to be a format for resolving professional scientific differences of opinion.

A process called "joint fact-finding" may be of value. Ehrmann and Stinson's seminal chapter in the *Consensus Building Handbook: A Comprehensive Guide to Reaching Agreement*, describes the process as follows:

> "Joint fact-finding" offers an alternative to the process of "adversary science" [what has been, perhaps inappropriately, termed, "combat science" in this estuary] when important technical or science-intensive issues are at stake. Joint fact-finding is a central component of many consensus building processes; it extends the interest-based, cooperative efforts of parties engaged in consensus building into the realm of information gathering and scientific analysis. In joint fact-finding, stakeholders with differing viewpoints and interests work together to develop data and information, analyze facts and forecasts, develop common assumptions and informed

opinion and, finally, use the information they have developed to reach decisions together.

Several references describe the important features of joint fact-finding (see Ehrmann and Stinson 1999, Karl et al. 2007[2]), which can be summarized as

- participation by all parties with interest and scientific contributions to make;
- use of a neutral, expert facilitator to manage the process;
- identification of key scientific questions to be addressed by the process;
- development of an agreed-on process for answering the questions; and
- carrying out that process and jointly evaluating the results.

Although this process might rely in part on outside, independent experts, it primarily involves the disputing experts, those with the most at stake, those whose ultimate buy-in is necessary to resolve or narrow scientific disputes. It certainly is true that without joint fact-finding, long-held positions can change. As Kuhn (1970/1996) observed, “Sometimes the convincing force is just time itself and the human toll it takes,” or as Kuhn quoted Max Planck, “a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.” One purpose of joint fact-finding is to speed this process and make its outcomes relevant to decisions that will be made soon.

Where “joint fact-finding” can run awry is the premise sometimes put forward by the advocates of that concept that once the facts are on the table then the scientists can “resolve the issue.” It is very important that the goal of the “jointly evaluating results” segment is clear. Clear “resolution” of a complex problem is rarely how science works (see Chapter 5). For example, ranking stressors certainly has many policy benefits, but it is a simplification that, if resolved by a joint fact-finding panel, would be turned over by the next panel, ad infinitum. The benefit of properly focused joint fact-finding is broad involvement of many parties in the scientific dialogue. Adversary science can be minimized for the purposes of dialogue, if the immediate discussion of a workshop, for example, is constrained to defining the state of the science, defining where disagreements exist and what they are, and

[2] For additional information on joint fact-finding, see http://ocw.mit.edu/courses/urban-studies-and-planning/11-941-use-of-joint-fact-finding-in-science-intensive-policy-disputes-part-i-fall-2003/readings/.

deciding on the path forward and/or what the policy choices are. If the dialogue is allowed to turn into an argument about who is right and who is wrong, constructive progress is lost; this is where the court cases have taken California to today. A dialogue in which public events are focused on constructive progress, if given time and supported by the policy community, (a) helps develop at least some commonalities in views of the state of the science among adversaries; (b) points out where new work is needed as agreed on by all parties; (c) can smooth the waters of conflict by providing a nonadversarial forum in which people from different sides can find at least some subjects on which they can agree; and (d) improves public trust if the dialogue takes place in public forums. The Science Program of the Delta Stewardship Council has a history of attempting to build such a dialogue. In a speech in 2002 Secretary of Resources Mary Nichols suggested this approach was gaining traction with policy makers. It appears that Madani and Lund's game of "chicken" reasserted itself after CALFED was declared a failure in 2004. But there is still an undercurrent of constructive scientific dialogue taking place, sponsored by the Science Program of the Delta Stewardship Council, from which there are opportunities to build if given support.

A return to an enthusiastic joint, constructive scientific dialogue, perhaps mediated by independent experts, might possibly be an ingredient that could help bridge what is now an ever-widening gap between key interest groups. Seeking points of agreement among adversaries, even if only over the science, would be a step toward consensus about at least some aspects of important science-driven policy issues and their uncertainties. This small, easily implemented change could begin to improve public trust, placing decision making on firmer ground. It is a process that can provide a more timely result than that which might occur by waiting for the professional demise of leading proponents of the opposing viewpoints. It is a process whose application to the delta science process is long overdue.

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Appendix G

Water Science and Technology Board

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Appendix H

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Appendix I

Biographical Sketches for Members of the Committee on Sustainable Water and Environmental Management in the California Bay-Delta

ROBERT J. HUGGETT, ***Chair***, is an independent consultant and professor emeritus and former chair of the Department of Environmental Sciences, Virginia Institute of Marine Sciences at the College of William and Mary, where he was on the faculty for over 20 years. He also served as Professor of Zoology and Vice President for Research and Graduate Studies at Michigan State University from 1997 to 2004. Dr. Huggett is an expert in aquatic biogeochemistry and ecosystem management whose research involved the fate and effects of hazardous substances in aquatic systems. From 1994 to 1997, he was the Assistant Administrator for Research and Development for the U.S. Environmental Protection Agency (EPA), where his responsibilities included planning and directing the agency's research program. During his time at the EPA, he served as Vice Chair of the Committee on Environment and Natural Resources and Chair of the Subcommittee on Toxic Substances and Solid Wastes, both of the White House Office of Science and Technology Policy. Dr. Huggett founded the EPA Star Competitive Research Grants program and the EPA Star Graduate Fellowship program. He has served on the National Research Council's (NRC) Board on Environmental Studies and Toxicology, the Water Science and Technology Board (WSTB), and numerous study committees on wide-ranging topics. Dr. Huggett earned an M.S. in marine chemistry from the Scripps Institution of Oceanography at the University of California at San Diego and completed his Ph.D. in marine science at the College of William and Mary.

JAMES J. ANDERSON is a research professor in the School of Aquatic and Fisheries Sciences at the University of Washington, where he has been teaching since 1983, and Co-Director of Columbia Basin Research. Prior to joining the faculty at the University of Washington, he did research work at the University of Kyoto in Japan, the National Institute of Oceanography in Indonesia, and the Institute of Oceanographic Sciences in Wormley, U.K. Dr. Anderson's research focuses on models of ecological and biological processes from a mechanistic perspective, specifically (1) migration of organisms, (2) decision processes, and (3) mortality processes. For three decades he has studied the effects of hydrosystems and water resource allocations on salmon and other fish species. He has developed computer models of the migration of juvenile and adult salmon through hydrosystems and heads the DART website, an Internet database serving real-time environmental and fisheries data on the Columbia River. His other research interests include mathematical studies in ecosystems, biodemography, toxicology, and animal behavior. He has served on a number of regional and national panels and has testified numerous times before Congress on the impacts of hydrosystems on fisheries resources. He received his B.S. and Ph.D. in oceanography from the University of Washington.

MICHAEL E. CAMPANA is professor of hydrogeology and water resources in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University (OSU), former Director of OSU's Institute for Water and Watersheds, and Emeritus Professor of Earth and Planetary Sciences at the University of New Mexico. Prior to joining OSU in 2006 he held the Albert J. and Mary Jane Black Chair of Hydrogeology and directed the Water Resources Program at the University of New Mexico and was a research hydrologist at the Desert Research Institute and taught in the University of Nevada-Reno's Hydrologic Sciences Program. He has supervised 70 graduate students. His research and interests include hydrophilanthropy, water resources management and policy, communications, transboundary water resources, hydrogeology, and environmental fluid mechanics, and he has published on a variety of topics. Dr. Campana was a Fulbright Scholar to Belize and a Visiting Scientist at Research Institute for Groundwater (Egypt) and the IAEA in Vienna. Central America and the South Caucasus are the current foci of his international work. He has served on seven committees. Dr. Campana is founder, president, and treasurer of the Ann Campana Judge Foundation (www.acjfoundation.org), a 501(c)(3) charitable foundation that funds and undertakes projects related to water, sanitation, and hygiene (WASH) in Central America. He operates the WaterWired blog and Twitter. He is a former president of the American Water Resources Association. He earned a B.S. in geology from the College of William and Mary and M.S. and Ph.D. degrees in hydrology from the University of Arizona.

THOMAS DUNNE is a professor in the Donald Bren School of Environmental Science and Management at the University of California at Santa Barbara. He is a hydrologist and a geomorphologist, with research interests that include alluvial processes; field and theoretical studies of drainage basin and hill-slope evolution; sediment transport and floodplain sedimentation; debris flows and sediment budgets of drainage basins. He served as a member of the WSTB Committee on Water Resources Research and Committee on Opportunities in the Hydrologic Sciences and was elected to the National Academy of Sciences in 1988. He has acted as a scientific advisor to the United Nations, the governments of Brazil, Taiwan, Kenya, Spain, the Philippines, Washington, Oregon, several U.S. federal agencies, and The Environmental Defense Fund. He is a recipient of the American Geophysical Union Horton Award. Dr. Dunne holds a B.A. from Cambridge University and a Ph.D. in geography from the Johns Hopkins University.

JEROME B. GILBERT is a consulting engineer based in Orinda, California. His interests and expertise include integrated water supply, water-quality planning, and management. Mr. Gilbert has managed local and regional utilities, and developed basin/watershed water-quality and protection plans. He has supervised California's water rights and water quality planning and regulatory activities, chaired the San Francisco Bay Regional Water Quality Control Board, and led national and international water and water research associations. Areas of experience include authorship of state and national water legislation on water rights, pollution control, water conservation, and urban water management; optimization of regional water project development; groundwater remediation and conjunctive use; economic analysis of alternative water improvement projects; and planning of multipurpose water-management efforts including remediation. He has served on national panels related to control and remediation of ground- and surface-water contamination, and the National Drinking Water Advisory Council. Mr. Gilbert is a member of the National Academy of Engineering. He received his B.S. from the University of Cincinnati and an M.S. from Stanford University.

ALBERT E. GIORGI has been a senior fisheries scientist at BioAnalysts, Inc., in Redmond, Washington, sincce 1990. He has been conducting research on Pacific Northwest salmonid resources since 1982. Prior to 1990, he was a research scientist with the National Oceanic and Atmospheric Administration (NOAA) in Seattle, Washington. He specializes in fish passage migratory behavior, juvenile salmon survival studies, and biological effects of hydroelectric facilities and operation. His research includes the use of radiotelemetry, acoustic tags, and PIT-tag technologies. In addition to his research, he acts as a technical analyst and advisor to public agencies and private parties. He regularly teams with structural and hydraulic engineers in the design and evaluation of fishways and fish bypass systems. He served on the NRC Committee on Water Resources Management, Instream Flows, and Salmon Survival in the Columbia River. He received his B.A. and M.A. in biology from Humboldt State University and his Ph.D. in fisheries from the University of Washington.

CHRISTINE A. KLEIN is the Chesterfield Smith Professor of Law at the University of Florida Levin College of Law, where she has been teaching since 2003. She offers courses on natural resources law, environmental law, water law, and property. Previously, she was a member of the faculty of Michigan State University College of Law, where she served as Environmental Law Program Director. From 1989 to 1993, she was an assistant attorney general in the Office of the Colorado Attorney General, Natural Resources Section, where she specialized in water rights litigation. She has published widely on a variety of water law and natural resources law topics. She holds a B.A. from Middlebury College, Vermont; a J.D. from the University of Colorado School of Law; and an LL.M. from Columbia University School of Law, New York.

SAMUEL N. LUOMA is a research professor at the John Muir Institute of the Environment, University of California, Davis, and an emeritus Senior Research Hydrologist in the Water Resources Division of the U.S. Geological Survey, where he worked for 34 years. He also holds an appointment as a Scientific Associate at The Natural History Museum, London. Dr. Luoma's research centers on processes that control the fate, bioavailability, and effects of contaminants, particularly in the San Francisco Bay Delta. He served as the first lead on the CALFED Bay-Delta Program and is the Editor-in-Chief of *San Francisco Estuary and Watershed Science*. He has helped refine approaches to determine the toxicity of marine and estuarine sediments and developed models that are used in development of water-quality standards. His most recent research interests are in environmental implications of nanotechnology and better connecting water science to water policy. He has served multiple times on the EPA's Science Advisory Board Subcommittee on Sediment Quality Criteria and on other NRC committees. Dr. Luoma received his B.S. and M.S. in zoology from Montana State University, Bozeman, and his Ph.D. in marine biology from the University of Hawaii, Honolulu.

THOMAS MILLER is professor of fisheries at the Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, where he has been teaching since 1994. Prior to UMCES-CBL, he was a postdoctoral fellow at McGill University, Montreal, Canada, and research specialist with the Center for Great Lakes Studies, University of Wisconsin, Milwaukee. His research focuses on population dynamics of aquatic animals, particularly in understanding recruitment, feeding and biophysical interactions, and early life history of fish and crustaceans. He has been involved in the development of a Chesapeake Bay fishery ecosystem plan, which includes detailed background information on fisheries, food webs, habitats, and monitoring required to develop multispecies stock assessments. Most recently, he has developed an interest in the sublethal effects of contamination on Chesapeake Bay living resources using population dynamic approaches. He received his B.Sc. (hons) in human and environmental biology from the University of York, U.K., his M.S. in ecology, and Ph.D. in zoology and oceanography from North Carolina State University.

STEPHEN G. MONISMITH is a professor of environmental fluid mechanics and directs the Environmental Fluid Mechanics Laboratory at Stanford University. Prior to coming to Stanford, he spent 3 years in Perth as a research fellow at the University of Western Australia. Dr. Monismith's research in environmental and geophysical fluid dynamics involves the application of fluid mechanics principles to the analysis of flow processes operating in rivers, lakes, estuaries, and the oceans. Making use of laboratory experimentation, numerical modeling, and field measurements, his current research includes studies of estuarine hydrodynamics and mixing processes, flows over coral reefs, wind-wave turbulent flow interactions in the upper ocean, turbulence in density stratified fluids, and physical-biological interactions in phytoplankton and benthic systems. He received his B.S., M.S., and Ph.D. from the University of California, Berkeley.

JAYANTHA OBEYSEKERA is the Chief Modeler at the South Florida Water Management District (SFWMD) and an affiliate research professor at Florida Atlantic University. At SFWMD, he managed a modeling team for the development and applications of computer simulation models for Kissimmee River restoration and the restoration of the Everglades ecosystem. He has taught courses in hydrology and water resources at Colorado State University, Fort Collins; George Washington University, Washington, DC; and Florida Atlantic University, Boca Raton, Florida. He has published numerous research articles in refereed journals in the field of water resources and has over 20 years of experience practicing water resources engineering. He has taught short courses on modeling in the Dominican Republic, Colombia, Spain, Sri Lanka, and the United States. He was a member of the Surface Runoff Committee of the American Geophysical Union and served as a member of the Federal Task Group on Hydrologic Modeling. He served as a member of NRC's Committee on Further Studies of Endangered and

Threatened Fishes in the Klamath River. He was recently appointed as a member of the National Climate Assessment Development & Advisory Committee (NCADAC). Dr. Obeysekera has a B.S. degree in civil engineering from University of Sri Lanka; an M.E. in hydrology from University of Roorkee, India; and a Ph.D. in civil engineering with specialization in water resources from Colorado State University.

HANS W. PAERL is Kenan Professor of Marine and Environmental Sciences at the UNC-Chapel Hill Institute of Marine Sciences, Morehead City. His research includes microbially mediated nutrient cycling and primary production dynamics of aquatic ecosystems, environmental controls of harmful algal blooms, and assessing the causes and consequences of man-made and climatic (storms, floods) nutrient enrichment and hydrologic alterations of inland, estuarine, and coastal waters. His studies have identified the importance and ecological impacts of atmospheric nitrogen deposition as a new nitrogen source supporting estuarine and coastal eutrophication. He is involved in the development and application of microbial and biogeochemical indicators of aquatic ecosystem condition and change in response to human and climatic perturbations. He heads up the Neuse River Estuary Modeling and Monitoring Program, and the ferry-based water quality monitoring program, FerryMon, which employs environmental sensors and a various microbial indicators to assess the near-real-time ecological condition of the Pamlico Sound System, the nation's second largest estuarine complex. In 2003 he was awarded the G. Evelyn Hutchinson Award by the American Society of Limnology and Oceanography for his work in these fields and their application to interdisciplinary research, teaching, and management of aquatic ecosystems. He received his Ph.D. from the University of California, Davis.

MAX J. PFEFFER is International Professor of Development Sociology and Senior Associate Dean of the College of Agriculture and Life Sciences at Cornell University. His teaching concentrates on environmental sociology and sociological theory. His research spans several areas including farm labor, rural labor markets, international migration, land use, and environmental planning. The empirical work covers a variety of rural and urban communities, including rural/urban fringe areas. Research sites include rural New York and Central America. He has been awarded competitive grants from the National Institutes of Health, the National Science Foundation, the EPA, the U.S. Department of Agriculture's National Research Initiative and its Fund for Rural America, and the Social Science Research Council. Dr. Pfeffer has published a wide range of scholarly articles and has written or co-edited four books. He recently published (with John Schelhas) *Saving Forests, Protecting People? Environmental Conservation in Central*

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