PPIC | PUBLIC POLICY INSTITUTE OF CALIFORNIA

Aquatic Ecosystem Stressors in the Sacramento–San Joaquin Delta

Jeffrey Mount, William Bennett, John Durand, William Fleenor, Ellen Hanak, Jay Lund, Peter Moyle

Supported with funding from the S. D. Bechtel, Jr. Foundation

Summary

The native fishes of the Sacramento–San Joaquin Delta have been declining at an increasingly rapid rate for more than two decades. This decline has significant consequences for water resource management in the Delta, particularly for operations of the State Water Project (SWP) and the federal Central Valley Project (CVP). There is no single cause for the decline of these fishes. All facets of the Delta ecosystem have changed dramatically in the past century, and most changes have been detrimental to native fishes. The factors that cause harm to native species are broadly referred to as stressors. For any native species, many stressors affect both individuals and populations.

Stressors can be grouped in different ways, depending on the scientific, policy, or regulatory point of view. Here, we have grouped them into five broad categories. Each category contains stressors with similar processes, causes, or consequences. While overly simplistic for scientific purposes, this approach is straightforward enough to facilitate policy discussions regarding causes of stress, allocations of responsibility, and options for management. In alphabetical order, our five general categories of multiple stressors are:

- Discharges that alter water quality (through land and water use activities),
- Fisheries management actions (such as regulation of harvest and operation of hatcheries),
- Flow alteration (through a variety of water management activities),
- Invasive species that alter food webs or change physical habitat, and
- Physical habitat loss and alteration (through actions such as the draining and diking of tidal marshes and seasonal floodplains).

Climate change will likely exacerbate conditions associated with all five groups. Ocean conditions also affect anadromous fishes, such as salmon and steelhead, amplifying the effect of stressors. For each group of stressor, we identify the affected native species, assign historical and on-going responsibility, and consider a range of actions that may reduce effects of the stressors on the viability of native species populations.

Companion reports

This report presents results from an analysis of the institutional and legal options for more effective ecosystem management in the Sacramento-San Joaquin Delta. It is part of a wide-ranging study on the management of multiple ecosystem stressors in the Delta. For a summary of overall study findings, see *Stress Relief: Prescriptions for a Healthier Delta Ecosystem* (Hanak et al. 2013). Several companion papers address related topics in greater depth: (1) *Costs of Ecosystem Management Actions for the Sacramento-San Joaquin Delta* (Medellín-Azuara et. al. 2013) provides cost estimates for a suite of management actions addressing various sources of ecosystem stress; (2) *Integrated Management of Delta Stressors: Institutional and Legal Options* (Gray et al. 2013) presents our proposals for institutional reform of science, management, and regulation; (3) *Scientist and Stakeholder Views on the Delta Ecosystem* (Hanak et al. 2013) presents the results of surveys of scientific experts and engaged stakeholders and policymakers on Delta stressors and management actions; and (4) *Where the Wild Things Aren't: Making the Delta a Better Place for Native Species* (Moyle et al. 2012) describes a realistic long-term vision for achieving a healthier ecosystem. All of these reports are available on PPIC's website at www.ppic.org.

Contents

Introduction

The Delta Reform Act of 2009 stipulates that the Sacramento–San Joaquin Delta will be managed to meet the co-equal goals of water supply reliability and ecosystem health and function, with consideration to the Delta as an evolving place. Implicit in this co-equal policy is the assumption that water supply activities are directly linked to the decline of the Delta ecosystem, and that a new balance should resolve the ecological problems. Yet water supply—including the retention, diversion, transport, and use of water—is not the sole balancing function in the Delta. If it were, it might be easier to address the Delta's problems.

The decline of the Delta ecosystem, as reflected in the decline of native fish species, is well-documented and is not in dispute (Healey, Dettinger, and Norgaard 2008; Lund et al. 2010). However, the causes of this decline, along with the remedies needed to reverse it, are vigorously debated. Water flows are indeed the "master" ecological variable in the Delta—an essential component of the aquatic ecosystem—and flows have been dramatically altered by water use and operations. But flows move through and across a landscape that has been fundamentally and irreversibly changed from its original condition. Additionally, contaminants and non-native species are now an integral part of these managed flows and landscape. This new Delta significantly differs from the historical Delta, and the effects of this change on native species are widespread and profound (Moyle and Bennett 2008; National Research Council 2012).

The most difficult scientific problem facing Delta environmental managers involves disentangling the many causes of native species' decline and crafting an effective response. The difficulty lies in identifying not only the processes that cause harm, but also the interactions and feedbacks among them. And because the Delta is undergoing rapid change toward an uncertain future state, remedies effective under current conditions may be ineffective in the future (Lund et al. 2010, Cloern et al. 2011, Moyle et al. 2012).

The numerous processes that cause harm to native species, along with their complex interactions, fall under the term "multiple stressors," based on the perception that they cause stress to individuals, populations, and communities of organisms. These stressors are unfavorable attributes of the ecosystem, leading ultimately to diminished populations and, in the worst case, extinction.

This report focuses on how to organize multiple stressors in a useful way for setting Delta environmental policy. The diverse range of species affected and the large number of stressors that affect them is too complex for most policy and management discussions. The goal here is to provide a straightforward synthesis of stressors and potential remedies that may be useful in guiding discussions on how to prioritize ecosystem investments and to allocate responsibility for supporting these investments. Our analysis, tailored to address on-going discussions over the Bay-Delta Conservation Plan (http://baydeltaconservationplan.com/Home.aspx) and the Delta Stewardship Council's *Delta Plan* (http://deltacouncil.ca.gov/delta-plan/current-draft-of-delta-plan), focuses on the Delta ecosystem; it does not address the multiple beneficial uses of water in the Delta or trade-offs among various environmental, water supply, and recreation objectives.

We focus here on the factors that adversely affect native fishes in the Delta. The much-publicized instability of the populations of delta smelt, longfin smelt, salmon, steelhead, and sturgeon over recent decades reflects a decline in ecosystem function (Sommer et al. 2007). For this reason, native fish populations are often used as an indicator of ecosystem conditions. The decline of native fishes imposes a management imperative; many of these species are already listed under the federal and state Endangered Species Acts, and many others are on the road to listing unless efforts are made to reverse their decline (Moyle, Katz, and Quiñones 2011).

This report is part of a larger study on the management of multiple stressors in the Delta, which is looking at a range of technical, legal, institutional, and economic issues related to the improving environmental outcomes in this complex and troubled region. A companion report, *Where the Wild Things Aren't: Making the Delta a Better Place for Native Species* (Moyle et al. 2012) provides one vision of how the Delta might be managed to better accommodate native fish species, while continuing to serve human demands for water and land resources within the Delta and the wider watershed. Future publications will seek to prioritize stressors and mitigation actions and provide options for funding these actions and managing stressors in a more integrated and effective manner.

Analyzing the Effects of Stressors

Although a variety of scientific approaches to understanding stressors are possible, two basic approaches have commonly been used in studying the Delta: experimental and regression-based analyses. Experimental approaches assume that all potential stressors are known and that a set of hypotheses can be developed and tested to systematically identify key stressors. Experimental designs also often assume that stressors are mutually exclusive. For example, this single-factor approach is typically used to evaluate how contaminants affect specific species. Multifactor experiments require much larger sample sizes and more careful designs. While experimental approaches can be useful for setting basic standards such as concentrations of certain toxins or water quality conditions such as temperature, a large body of literature has demonstrated that experimentation alone cannot always capture interactions of multiple factors that affect organisms and their populations (Adams 2002; Ives et al. 2003; Hampton and Schindler 2006).

Where multiple stressors are identified as likely causes of species decline, numerous efforts have identified or tested different stressors or environmental factors through regression-based approaches, which analyze the individual or joint effects of multiple variables on a dependent variable (e.g. Jassby et al. 1995; Mac Nally et al. 2010). This approach has yielded important insight into some potential causes of fish decline. However, regression-based approaches to assessing multiple stressor effects are criticized for many reasons. In particular, they generally assume that all stressors are identified and measured appropriately (unlikely for the full suite of multiple stressors) and that nonlinearities, interactions, and serial correlations have been accounted for adequately. Despite the various techniques available for reducing such bias, regression is often still applied without clear understanding or documentation of the underlying ecological relevance of the statistical relationship or multiple alternative explanations (Scheinter and Gurevitch 1993). This rote application of regression has tended to foster beliefs that reducing a single stressor (such as limiting ammonium discharge from water treatment plants, eliminating entrainment at export pumps, reducing contaminants, or returning to more natural flows) will, on its own, lead to recovery of listed species.

Three additional approaches to the assessment of stressors and their consequences for populations of fish species show promise for eventual use in managing the Delta: conceptual models, life-cycle models, and process-oriented studies. Conceptual models are verbal or visual attempts to describe the processes underlying ecosystem function and stressors.[1] Life-cycle models attempt to quantitatively assess the effects of stressors on the populations of specific species, either by using average values of vital rates (e.g., birth and survival) or by tracking the fate of numerous individuals. These models have the potential to show how populations respond to multiple stressors throughout the life cycle. They are generally of two types: mechanistic models that track fish and their populations through time and life stage based on relationships to environmental conditions (Rose et al. 1999; Lindley and Mohr 2003) and statistical models that are based on correlations between historic environmental conditions and population numbers (Mac Nally et al. 2010; Maunder and Deriso, 2011). Finally, process-oriented studies use information from field studies that measure processes or stressors directly and analyze relationships using various quantitative approaches (Bennett et al. 2002; Lucas et al. 2002). These studies are often used to inform the life-cycle and conceptual models.

[1] The most comprehensive approach to conceptual models comes from the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP: http://www.dfg.ca.gov/ERP/conceptual_models.asp) and the Interagency Ecological Program Pelagic Organism Decline (POD) program (Baxter et al. 2010).

Although these three approaches—conceptual models, life-cycle models, and process-oriented studies—are promising ways to assess multiple stressors, each has drawbacks for use in setting policy.[2] All five methods, including experimental and regression-based approaches, suffer from a common problem. They focus on current or historical conditions in the Delta and have not been used or cannot be used to examine a future, reconciled Delta that meets both human needs and those of the ecosystem as well.[3]

---

[2] Conceptual models lack a numerical basis for comparisons among different stressors and allocation of responsibility, and they do not capture stochastic or non-linear relationships well (Bennett and Moyle 1996). And in addition to being incomplete, the DRERIP models and their innumerable submodels are too complex to be useful for setting policy at this time. Life-cycle models, informed by process-oriented studies, are still focused on single species with a limited range of potential stressors (e.g. delta smelt, Maunder and Deriso 2011) and as such cannot yet be used for ecosystem-based management.

[3] See recent efforts by Feyrer et al. (2010) and Cloern et al. (2011) to address this issue.

Classifying Stressors

In the Delta, and much of California water resource management in general, there is a long history of policy needs outpacing the development of the scientific tools or technical capacity that could adequately address such needs (Hanak et al. 2011). This gap is particularly acute in the case of managing multiple stressors, and it will remain so for the foreseeable future. Yet policymaking on multiple stressors in the Delta must proceed, despite the uncertainties. To facilitate policy discussions regarding causes of stress, allocations of responsibility, and options for management, we organize stressors into five general categories of like process or consequence. From a scientific perspective, this approach oversimplifies a system of complex processes, responses, and feedbacks. However, this complexity, its many uncertainties, and the difficulty of communicating it to a broad audience has been an impediment to discussing, setting, and implementing policy. The classification used here aims to strike a balance between capturing the complexity of Delta stressors and organizing them in a policy-relevant way.

In alphabetical order, the five general categories of stressors harming native fish populations are as follows:

1. **Discharges**: Land and water use activities that directly alter water quality in the greater Delta watershed by discharging various contaminants that degrade habitat, disrupt food webs, or cause direct harm to populations of native species.
2. **Fisheries management**: Policies and activities that adversely affect populations of native species through harvest (commercial and sport) or hatcheries.
3. **Flow regime change**: Alterations in flow characteristics due to water management facilities and operations, including volume, timing, hydraulics, sediment load, and temperatures.
4. **Invasive species:** Alien (non-native) species that negatively affect native species by disrupting food webs, altering ecosystem function, introducing disease, or displacing native species.
5. **Physical habitat alteration**: Land use activities that alter or eliminate physical habitat necessary to support native species, including upland, floodplain, riparian, open water/channel, and tidal marsh.

None of these categories is entirely independent of the others, and significant interactions can amplify or suppress the negative effects each has on native populations. For example, water operations that reduce flow may intensify the effects of agricultural and urban discharges that, in turn, promote conditions favorable to invasive species that alter food webs and ecosystem functions. Yet for each class, there is a specified human activity that either initiates a stressor or magnifies its effects. Viewing stressors in this way allows for a broad analysis of the causes of ecosystem stress and a prioritization of actions to mitigate their effects.

This list excludes two factors commonly included in discussions of Delta stressors: climate change and ocean conditions. Climate change is not treated as a separate stressor class because its various manifestations—warmer temperatures, accelerated sea level rise, and changing patterns of runoff—will influence the Delta ecosystem through their effects on the five stressor categories listed above. Obviously, management actions to mitigate the effects of these stressors will need to be sensitive to the likely changes resulting from a changing climate. Ocean conditions directly affect populations of anadromous native fishes that migrate through the Delta (salmon and steelhead), as well as the weather in California through such processes as El Niño-Southern Oscillation, the Pacific Decadal Oscillation, and other patterns of climate variability. Ocean conditions are excluded because they are not locally manageable or amenable to policy actions.

Stressor Characteristics and Potential Mitigation Responses

This section provides brief summaries of each class of stressors, including a general description, the parties responsible for introducing the stressor into the ecosystem, major interactions with other stressors, types of habitat and species directly affected, and potential mitigation responses.

1. Discharges

Description: Water management and use within the Delta's watershed (the combined Sacramento, San Joaquin, and Delta tributary watersheds) results in the discharge of a broad range of contaminants, including salts, pesticides, metals, toxins, and excessive levels of nutrients that can harm native species directly or indirectly by disrupting or altering ecosystem conditions (U.S. Environmental Protection Agency 2011). The agricultural and urban sectors are the two primary sources of discharge. A third source is historic mining activity, which results in ongoing discharges of heavy metals, particularly mercury.

Agricultural discharges include farming and animal husbandry practices from both "point" and "non-point" sources. (Point sources are easily identifiable locations such as large animal feeding operations and dairies; non-point sources include cropped areas and rangeland). These discharges impair water within the Delta watershed (Central Valley Regional Water Quality Board, 1998). Irrigation and tilling activities leach dissolved solids, discharging them into adjacent rivers. These activities are the major cause of high salinities (including high levels of highly toxic selenium) in the San Joaquin River and south Delta channels, creating a "reverse" salinity gradient (in contrast to historical conditions, water becomes fresher as it moves into the central Delta before becoming saline again in the San Francisco Bay). The application of saline groundwater, fertilizers, herbicides, and pesticides adds other dissolved solids to the excess irrigation water that returns to rivers. Organic and inorganic compounds can also adhere to soil particles and be discharged into rivers. Confined animal practices (stockyards, dairies, poultry ranches) are significant point sources of salt, nitrates, ammonia, and coliform bacteria.

Urban discharges that affect the Delta include both point sources (principally municipal wastewater treatment facilities) and non-point runoff from residential and industrial areas (particularly after storms). Municipal wastewater can include salts from saline groundwater and from water softeners. Wastewater discharges include salts and excessive levels of nutrients (with particular recent concern over ammonia/ammonium concentrations), as well as metals, pharmaceuticals, pesticides, and personal care products. Stormwater can contain varying levels of urban fertilizers, herbicides, pesticides, petroleum products, and heavy metals.

Mining in the Delta's watershed is much less important today than it was historically. However, drainage and runoff from abandoned mines, particularly on the east slope of the Coast Ranges, along with the reworking of historical hydraulic mining sediments, causes high background levels of mercury in the Delta (Conaway et al. 2008).

As summarized in the recent Advanced Notice of Proposed Rulemaking by the U.S. Environmental Protection Agency (2011), there is much debate about whether agricultural and urban discharges are leading stressors in the Delta (see also, National Research Council 2012). The principal concerns pertain to direct sublethal effects on fish and indirect changes to aquatic food webs associated with pesticides from urban discharges (principally pyrethroids) and agricultural discharges (principally organophosphates), as well as concerns about ammonia/ammonium from wastewater treatment plants, toxic selenium and other salts from irrigated lands in the San Joaquin Valley, and contaminants of emerging concern (e.g., pharmaceuticals and other chemicals that are not yet regulated) from both urban and agricultural dischargers. Metals from historic mining activity remain a concern but do not appear to have reached a sufficient level of bioaccumulation to harm fish populations. However, they are of concern for individuals engaging in subsistence fishing, a practice that appears to be growing in the Delta among some low-income immigrant groups (Shilling et al. 2010).

Who's responsible: Under federal and state water quality laws, the Central Valley Regional Water Quality Control Board, San Francisco Bay Regional Water Quality Control Board, and the State Water Resources Control Board are responsible for setting water quality standards for the Delta and the Sacramento and San Joaquin Rivers and their tributaries and for developing Basin Plans that meet these standards.

Major interactions: Agricultural and urban discharges interact with other stressors through multiple pathways. The most substantive interaction is associated with changes in water flows. Reductions in flow, whether due to upstream diversions, in-Delta use, or exports, increase the concentrations of contaminants, lowering overall water quality (U.S. Environmental Protection Agency 2011). By reducing habitat quality and availability, these same changes in flow may increase the sublethal effects of some contaminants. Additionally, increases in nutrients (particularly ammonia/ammonium) may enhance conditions favorable to invasive species that disrupt food webs (Glibert et al. 2011) and promote the growth of toxic algae such as *Microcyctis* (Lehman et al. 2008).

Habitats affected: Discharge contaminants have been documented in all major aquatic habitats in the Delta and Suisun Marsh. Upstream water diversions have increased contaminant concentrations, and current export pumping practices exacerbate poor water quality conditions in altered habitats. Agricultural discharges have made the San Joaquin River far saltier than it was naturally**.**

Major species directly affected: All native fishes of the Delta are affected, directly or indirectly, by harmful discharges. However, the magnitude of these effects is not well known (Luoma et al. 2008). The best-studied effects are those of the four pelagic species that have been part of the pelagic organism decline studies—the delta smelt, longfin smelt, threadfin shad, and juvenile striped bass—which are presumed to be affected by contaminant discharges through direct toxicity or disruption of food webs (Baxter et al. 2010).

Major actions to reduce stressor effects: In conjunction with other agencies, the State Water Resources Control Board and the regional boards can reduce the impact of discharges through a mix of oversite and regulatory actions that 1) discourage the use of harmful contaminants and encourage safer alternatives, 2) promote land use practices that reduce the introduction of harmful contaminants into waterways, and 3) modify flows to reduce the impacts of contaminants on specific species or habitats.

2. Fisheries Management

Description: The management of fisheries within the Delta watershed directly affects native fish populations. Current activities fall into two categories: harvest and hatchery operations. It should be noted that throughout much of California's history, many fish species (e.g., striped bass) were intentionally introduced into the Delta watershed to enhance recreational and commericial fishing, but this practice no longer occurs and thus is not included in our discussion of fisheries actions.

Harvest operations consist of sport/subsistence fisheries and commercial fisheries. Sport fisheries focus primarily on resident alien fishes, such as largemouth bass, striped bass, and various catfishes, as well as native salmon, steelhead, and sturgeon. These fisheries, with their attendant guide services, boats, and gear, are an important element in the Delta economy, although growth in this sector appears to have leveled off with the recent recession (Delta Protection Commission 2012). Subsistence fisheries in the Delta harvest a broad range of resident alien and native fishes, including carp, catfish, sunfish, largemouth bass, striped bass and sturgeon. Reliable data on subsistence fishing are not available, but as Shilling et al. (2010) note, this practice appears to be increasing along with the growth in ethnic groups that have a tradition of harvesting local fish. (The consumption of Delta fish containing high levels of mercury is of particular concern in the case of subsistence fisheries.) Illegal fishing, or poaching—a subset of sport and subsistence fishing—also appears to be increasing, although no comprehensive data exist on this practice. Commercial fisheries no longer exist in the Delta itself, but conditions there are important for different life stages of salmon, which support commercial ocean fisheries.

Hatcheries have been used within the Delta watershed since the late 19th century to mitigate the effects of overfishing, habitat destruction from mining, and, most recently, the loss of spawning habitat for salmon and steelhead following the construction of dams. Salmon hatcheries have proved to be a mixed blessing. They have sustained fisheries for decades, but this has occurred at the expense of wild populations. Because hatcheries focused on the easy-to-rear fall-run Chinook salmon, the three other runs in the Delta watershed were largely ignored until two were listed under the Endangered Species Act in 1989 and 1999 (Moyle 2002). Further declines in wild populations have been associated with high levels of straying among adult hatchery salmon, which displace or interbreed with wild fish (Williams 2006). Since hatchery fish are less well adapted for reproducing or surviving in the wild, this displacement or interbreeding contributes to the reduction of the wild population. And because hatchery salmon are fairly uniform in genetics and behavior, they are much more vulnerable to unfavorable environmental conditions than mixed stocks of wild salmon, resulting in such unexpected events as the recent crash of the salmon fisheries (with virtually no fishing allowed in 2008 and 2009 and a tightly constrained fishery in 2010).

Who's responsible: The California Department of Fish and Game (DFG) has the mandate to manage the state's fisheries, although the U.S. Fish and Wildlife Service is involved in hatchery management and management for endangered species. The National Marine Fisheries Service (NMFS) has primary responsibility for determining the status of threatened salmonid populations. NMFS works with the Pacific Fishery Management Council and DFG to manage ocean fisheries, including salmon, as well as threatened salmon and steelhead species (for which fisheries are closed).

Major interactions: Insofar as other stressors harm fish populations, they affect the condition of fisheries and have implications for fisheries management. But beyond this obvious link, there is a complex relationship between invasive species and fisheries. Some alien species, such as striped bass and largemouth bass, support popular sport fisheries in the Delta. Conditions that favor largemouth bass (clear, warm, low salinity) are not favorable for many resident and migratory natives. Predation by aliens may also affect salmon and steelhead populations, but recent discussions may have overstated the importance of predation (Moyle 2011). And as noted above, domesticated salmon originating from hatcheries suppress wild populations of salmon, increasing their vulnerability to environmental change.

Habitats affected: All major aquatic habitats in the Delta are used by native and alien fishes subject to harvesting. However, restorative efforts are increasingly focusing on improving habitat for native fishes, including salmon, in the Yolo Bypass-Cache Slough-lower Sacramento River-Suisun Marsh corridor.

Major species directly affected: All species large enough to be eaten by humans are potentially affected by fisheries and activities to protect them. This includes a wide array of salmonids (native), catfish, centrarchid bass and sunfish, striped bass, American shad, and a variety of cyprinids such as splittail (native) and common carp. Other species of fish that these species prey upon are also affected.

Major actions to reduce stressor effects: To date, it is has not been shown that fishery-related activites within the Delta are a major stressor for native fish species, with the possible exception of poaching on sturgeon populations. Maintaining laws and oversight to manage in-Delta sport harvest and poaching can prevent this from becoming an issue. The same applies to commericial ocean fisheries for salmon and sport harvest of salmon and steelhead upstream of the Delta.

In addition, policies governing salmon and steelhead hatcheries need to be reformed to make fisheries sustainable and to maintain wild populations. This reform may involve separating the production functions of hatcheries to support fisheries from the conservation functions to sustain natural populations (Hanak et al. 2011). This may entail reducing or eliminating hatchery production, allowing for only wild salmon spawning in the rivers of the Central Valley. The consequences of shut a shutdown would be large for commercial fisheries, and might be mitigated by moving hatcheries to coastal rivers and streams.

3. Flow Management

Description: Flow management involves the diversion, retention, or manipulation of water flows within and upstream of the Delta to support water supply needs, flood management, or ecosystem improvement. Flow management is broadly inferred to create stress when it 1) changes aspects of the historic flow regime that support life history traits of native species, 2) limits access to or quality of critical habitat, or 3) promotes conditions better suited to invasive non-native species at the expense of native species.

The two sources of water movement in the Delta—freshwater inflows and tides—provide the water that supports and connects dynamic habitats. These flows also supply sediment and the energy needed to shape these physical habitats, and they control salinity gradients and water temperatures. Native species of the Delta are adapted to and depend on variable flow conditions. This variability occurs along all dimensions: local hydraulics, regional salinity, temperature and flow gradients between riverine and tidal conditions, and the dramatic seasonal and interannual variation of California's Mediterranean climate. This nested, multiscale variability is summarized in a few flow metrics affected by flow management: timing (seasonality), magnitude, duration, frequency, and rates of change.

Water management has fundamentally changed the flow regime of the Delta, affecting every aspect of its flows. The largest effects are the modification of winter and spring inflows and outflows of the Delta and the introduction of net cross-Delta and net reverse flows in some Delta channels that has led to high fish entrainment rates at the export pumps (Fleenor et al. 2010; State Water Resources Control Board 2010; National Research Council 2012).

Prevailing ecological theory argues that the magnitude of these alterations can be linked to declining native species, either directly or through changes to habitat, water quality, and food webs (Poff, Richter, and

Arthington, et al. 2010). Direct and circumstantial evidence, such as species declines during droughts, supports this conclusion (Moyle, Katz, and Quiñones 2011; National Research Council 2012), which serves as the basis for the State Water Resources Control Board's (2010) flow criteria for the Delta ecosystem.

Who's responsible: Responsibility for the negative effects lies with 1) the construction, location, and operation of infrastructure that impounds or removes water upstream of the Delta for farming and municipal uses, 2) in-Delta water users, and 3) water export operations of the federally-run Central Valley Project (CVP) and the state-run State Water Project (SWP). Regulatory responsibilities lie with the State Water Resources Control Board , California Department of Fish and Game, National Marine Fisheries Service, U.S. Fish and Wildlife Service, and U.S. Environmental Protection Agency. Management responsibilities lie with the entities that remove water from the Delta, either directly or through upstream diversions, including the U.S. Bureau of Reclamation (for the CVP) and the Department of Water Resources (for the SWP), and with large local utilities (e.g., the Modesto Irrigation District, Turlock Irrigation District, Yuba County Water Agency, Contra Costa Water District (CCWD), East Bay Municipal Utilities District, and San Francisco Public Utilities Commission, all through upstream diversions except for the CCWD).

Major interactions: Flow in the Delta drives all ecosystem functions and interacts with all of the other groups of stressors. The most notable interaction is between flow and physical habitat. Landscape changes resulting from reclamation and flood management infrastructure have, in combination with changes in flow, eliminated the historical hydrologic connectivity of floodplains and aquatic ecosystems in the Delta and its tributaries, degrading and diminishing Delta habitat for native plant and animal communities. The large reduction of hydrologic variability and physical complexity has, in turn, supported invasions of alien species that have further degraded conditions for native species. Flow regime changes have also accentuated the effects of degraded water quality on native ecosystems. The combination of these factors makes today's Delta a novel ecosystem that appears to have undergone an ecological regime shift unfavorable to native species (Moyle and Bennett 2008; Baxter et al. 2010).

Habitats affected: Flow management affects all major aquatic and terrestrial habitats in the Delta and Suisun Marsh. In the northern, eastern, and southern Delta, flow management has reduced the area and quality of riverine, riparian, freshwater marsh, and floodplain habitats. In the western Delta and Suisun Marsh, where tides dominate flow conditions, flow management has altered water quality, temperature, and salinity gradients. And all water diversions in the Delta have some direct effects on fish populations through entrainment of larval and juvenile fish. Water exports also change flow patterns in adverse ways. Upstream of the Delta, flow management reduces spawning and rearing habitat for migratory species that travel through the Delta.

Major species directly affected: Changes in water flows have disrupted conditions for most native fishes in the Delta (Moyle 2002). The major species harmed include delta smelt, longfin smelt, Sacramento hitch, Sacramento splittail, white sturgeon, juvenile Chinook salmon, and various species of shrimp. Changes in flow also appear to support multiple alien species, including largemouth bass, bluegill, red ear sunfish, and golden shiner.

Major actions to reduce stressor effects: Many options exist for improving habitat conditions by changing water management: for example, promoting winter flood and spring snowmelt pulses through coordinated flow releases from dams, managing temperature and salinity through export and inflow coordination that maximizes habitat in the western Delta, and increasing seasonal and interannual hydrologic variability to suppress invasive species and promote native populations. Because of the complex nature of these changes and their interactive effects, they would have to be undertaken in an adaptive management context, with careful monitoring of effects and a willingness to modify activities that do not appear to be working. (For a discussion of adaptive management as it might apply in the Delta see Moyle et al. 2012.)

4. Invasive Species

Description: Invasive species are alien plants and animals that negatively affect native species or the ecosystem. Most of the established alien species in the Delta have minor impacts on the ecosystem. A few, however, have caused major disruptions to ecological conditions, earning the sobriquet "invasive." These species can be grouped into two categories: ecosystem engineers and food-web disruptors.

Ecosystem engineers physically alter ecosystem processes, degrading habitat for native species. This degradation typically involves changes in flow, water quality, substrate, light penetration, turbidity, or other aspects of physical habitat. An example of an ecosystem engineer is the Brazilian waterweed, *Egeria densa*. This plant grows in dense beds that clog Delta sloughs and channel margins, slowing flows, trapping sediment, increasing water clarity, and providing habitat for alien species such as predatory largemouth bass.

Food-web disruptors are species that significantly alter food webs, making them less able to support native species. Some alien species replace natives in food webs, reducing the quality of food for native fishes. An example is the widespread replacement of native copepods, an important food source for juvenile fish, by *Limnoithona*, which has less nutritional value. Other food web disruptions occur when alien species reduce the amount of food available for native fishes. Two small clams, *Corbula amurensis* and *Corbicula fluminea*, are such efficient grazers that they can remove most phytoplankton from the water where they live. Corbula has an especially pernicious effect on food webs in the low salinity zone in the western Delta and Suisun Bay, diminishing the food available for zooplankton and mysid shrimp, which become scarcer and which, in turn, diminishes the food supply for fish that rely upon them, such as the delta smelt and striped bass.

Who's responsible: Invasive species enter the region in a variety of ways, most prominently through ballast water discharged from ships, boating activities, and illegal introductions by anglers. Quagga and zebra mussels are expected to soon enter the Delta by attaching themselves to boat hulls trailered from infested waters. Occasionally, sport fishermen introduce invasive game fish, as in the case of the northern pike, which recently inhabited Lake Davis before its assumed extermination by the Department of Fish and Game.

Water management operations also bear some indirect responsibility for fostering alien species. Withdrawals that alter flow regimes (upstream and within the Delta) and the inflow of contaminants and nutrients favored by alien species tend to favor non-native residents. For instance, low flow-rates, high temperature, and low salinity in the western Delta favor largemouth bass, a species that tends to prey upon smaller native fishes. Inputs of ammonium and other nutrients, increases in water clarity, and declines in dissolved oxygen may favor species that can persist in these environments, while doing little to support native species of fish.

No one agency has lead responsibility for managing invasive species. The Department of Fish and Game is responsible for preventing new introductions of alien species and for managing non-native fishes that may harm native populations, but the agency lacks sufficient funds and personnel for thoroughly undertaking these responsibilities. The Department of Boating and Waterways is responsible for controlling certain aquatic weeds. The U.S. Coast Guard regulates shipping and, in theory, ballast water discharge. An official California Aquatic Invasive Species Management Plan was adopted in 2008 (www.dfg.ca.gov/invasives/plan), but the plan requires complex coordination among agencies for its implementation, as well as considerable funding, and thus has had arguably little effect so far.

Major interactions: Invasive species in the Delta are favored by the changes occurring in other major groups of stressors. Reduced hydrologic variability, lost and degraded physical habitat, and changes in water quality resulting from upstream and in-Delta discharges have contributed to a "regime shift" in the Delta, with its ecosystem increasingly resembling that of a warm-water lake, dominated by largemouth bass, sunfishes, Mississippi silverside, and other alien species (Moyle and Bennett 2008; Baxter et al. 2010).

Habitats affected: All major aquatic habitats in the Delta and Suisun Bay have been affected by invasive species, which have altered food webs and habitat structure. The least affected areas in the Delta are edge habitats strongly influenced by the Sacramento River (such as the Cache Slough region) and habitats where environmental variability is high, such as Suisun Marsh.

Major species directly affected: Negative effects occur for native fish species, including northern anchovy, delta smelt, longfin smelt, striped bass, threadfin shad, Sacramento hitch, Sacramento splittail, white sturgeon, and juvenile Chinook salmon. Positive effects occur for a suite of alien fishes, including largemouth bass, bluegill, red ear sunfish, and Mississippi silversides.

Major actions to reduce stressor effects: Although future invasions are inevitable (Lund et al. 2007), actions can be undertaken to limit the introduction and establishment of invasive species. For instance, enforcement and expansion of state and federal laws managing ballast water discharge can slow the rate of introductions. Similarly, mandatory inspection and cleaning of boat hulls may slow the spread of quagga and zebra mussels in the Delta watershed. Indirect methods, such as increasing variability in the salinity regime over large areas, may help to reduce clam populations, while nutrient management—of both amount and chemical form—may play a role in managing submerged and free-floating invasive aquatic macrophytes (Glibert et al. 2011). Experimental control methods may also prove useful, such as current efforts to control water hyacinth with South American plant hoppers (*Sacramento Bee*, August 11, 2011). Modeling the responses of current and potential invasive species to likely future changes in the estuary may help determine what types of controls may be needed and the extent to which modifications can be made in the physical structure of the estuary to favor native species.

5. Physical Habitat Loss or Alteration

Description: The physical habitat of the Delta has been dramatically altered since statehood in 1850. Most of this alteration occurred during the immense land reclamation of the late 1800s and early 1900s, when hundreds of thousands of acres of tidal, riparian, and floodplain habitat were converted to farms and pasture (Thompson 1957).

Reclamation led to the loss of roughly 95 percent of the Delta's original tidal marsh and floodplain habitat (Bay Institute 1998; Whipple et al. forthcoming). Today, the remaining habitat is dominated by relatively deep channels, with disconnected remnants of historical tidal marsh and floodplain and some mid-channel islands. To stabilize the channels, the 1,100 miles of Delta levees have been lined with rock ("riprap"), further degrading native fish habitat. Maintenance of these levees to meet federal and state requirements also requires removal of most riparian vegetation.

The scale of alteration in the Delta landscape is an underappreciated stressor in current debates over the Delta ecosystem, which tend to focus principally on flows (Lund et al. 2010; National Research Council 2012). Land reclamation has fundamentally altered the historical connection between land and water in the Delta. The reduced hydrologic connectivity between primary aquatic habitat and areas that were periodically flooded by tides and spring flows has reduced the abundance of key habitats for native aquatic species and diminished important habitat gradients. In addition, land reclamation has "simplified" all Delta habitats, eliminating the physical complexity that characterized native habitats and supported diverse populations (Lund et al. 2007). The characteristics of the earlier Delta that are likely gone forever include: (1) physical habitat appropriate for species that tend to rely on shallow water and structure for refuge and feeding; (2) food aggregation that long, complex sloughs and channels provide through increased production and retention; and (3) cooling functions that adjacent wetlands provide for small water bodies such as sloughs, which provide refuge for fishes during summer heat spells.

Who's responsible: The reclamation of the Delta and Suisun Marsh began in the 1850s and was complete by the 1930s (Thompson 1957). Today, most activity is focused on maintaining or upgrading the existing levee network to support interrelated land and water use activities. These include farms and duck clubs on Delta islands and in Suisun Marsh, infrastructure and existing and proposed urban developments and legacy towns, and Central Valley Project and State Water Project water exports. For the portion of the levee network within the Sacramento–San Joaquin Flood Control Project (nearly 400 miles), the Department of Water Resources provides most of the oversight, and permits are issued by the U.S. Army Corps of Engineers and the Central Valley Flood Protection Board. Portions of the "non-project" levee network are overseen by DWR and local reclamation districts. Water exports by the SWP and CVP benefit from the maintenance and upgrading of western Delta levees.

Major interactions: Loss or disruption of physical habitat in the Delta interacts with and amplifies other stressors. The largest interaction is with flow management. Water flow management to support native species is less effective if there is insufficiently extensive hydrologic connectivity and habitat complexity to support flow changes. The limitations are most apparent in efforts to improve winter and spring pulse flows, which rely on floodplain and marsh habitat to multiply their effect. Simplified habitats, in conjunction with altered flows, improve conditions for many invasive plants and fishes. Finally, the loss of hydrologic connectivity and physical complexity amplifies the effects of poor water quality (particularly from the San Joaquin River) because the natural water quality improvements derived from wetlands are no longer available.

Habitats affected: The effects of land reclamation and land conversion vary by location. Land reclamation has reduced or degraded: 1) freshwater tidal marsh habitat in the north and south Delta, 2) floodplain and wetland habitat in the north and south Delta and its tributaries, 3) brackish water tidal marsh habitat in Suisun Marsh, 4) open water/channel habitat throughout the Delta, and 5) riparian habitat throughout the Delta.

Major species directly affected: Juvenile salmon, juvenile and spawning-adult Sacramento splittail, tule perch, Sacramento blackfish, and other native resident fishes. Delta smelt and longfin smelt are indirectly affected by the loss of physical habitat.

Major actions to reduce stressor effects: Land use changes behind the levees constrain environmental management options. In the central and western Delta, oxidation of organic-rich soils on Delta islands has led to widespread land subsidence (Mount and Twiss 2005). Deeply-subsided areas cannot be restored to tidal marsh within a reasonable timeframe. These areas may be suitable for open water tidal habitat following flooding of islands, but the benefits for native species remain uncertain (Moyle 2008). Shallowly-subsided areas have more potential to be restored through subsidence reversal (e.g., by growing tules) to support tidal marsh habitat. In the north and south Delta, there is considerable potential for restoring marsh, riparian, and floodplain habitat. Levee breaching, setback, or removal to restore hydrologic reconnection, coupled with flow management, can improve conditions for native populations that rely on floodplains and tidal marsh habitat. However, the outcomes of tidal marsh restoration are somewhat uncertain, since some efforts may promote invasive submerged aquatic vegetation and fishes at the expense of natives.

Conclusions

The populations of many native fishes in the Delta have been in a long-term decline. Decades of monitoring and research indicate that a diverse range of factors—multiple stressors—have contributed to this situation (National Research Council 2012). Some promising approaches to assessing the effects of multiple stressors include conceptual and population models, supported by process-oriented field and laboratory studies. To date, however, these efforts are either incomplete or have not been structured to support environmental policymaking.

To meet the near-term need for policies that will help reduce the damage stressors are causing for the Delta's native fish popuulations, it is necessary to simplify the inherent complexities of stressors and their interactions. Complexity and uncertainty have often been used as an excuse to avoid action (Lund et al. 2010). Additionally, any single action, even if deemed beneficial for the fish, is usually confronted by a stakeholder or interest group opposed to its realization, thus making collective actions even more difficult. Yet maintaining the status quo appears to be the least likely avenue to successfully managing the Delta's native biodiversity.

Stressors currently affecting native species can be grouped into five categories that facilitate allocation of responsibility and prioritization of responses. In alphabetical order, these include stress caused by 1) discharges altering water quality, 2) fisheries management activities, 3) flow regime alterations, 4) invasive species, and 5) physical habitat disruption and removal.

These stressors affect many resident and anadromous native fish species, including delta smelt, longfin smelt, Sacramento splittail, white sturgeon, and juvenile Chinook salmon, as well as various species of shrimp that serve as an important food source in the Delta. Changes in water quality, loss of habitat, and alteration of flow regime appear to have the broadest and most direct impact on native species. However, other contributors of stress include the many invasive species that are damaging the food webs and physical habitats of native species, and the practices of fisheries management (and in particular the hatcheries) that are damaging wild populations of salmon.

Responsibilities for this damage to the Delta's ecosystem vary, and in some cases are more general than others. For example, in the case of habitat loss due to land reclamation, much of the consequence can be traced to past economic activity. Yet current economic activity benefits from and continues to depend upon this historical occurrence—and thus bears some responsibility for its continuation. Other forms of stress, such as declining water quality due to contaminants or alteration of flows, are primarily a function of current activities, allowing for more direct allocation of responsibility. And certainly the stress introduced into the Delta from fisheries management is the direct responsibility of agencies that manage fisheries. In yet other cases, it is difficult to assign specific responsibility. Take, for example, the introduction and management of invasive species in the Delta. Still, the effects of this stressor can be reduced through the better management of other activities, such as flow changes, that amplify the effects of this stressor.

In future work, we hope to use this classification of stressors and potential remedies to inform discussions on how to prioritize ecosystem investments and to allocate responsibility for supporting these investments. Both issues present major policy challenges for California, and solutions to these challenges are needed to support a more promising future for the Delta's aquatic ecosystem.

References

Adams, S. M., ed. 2002. *Biological Indicators of Aquatic Ecosystem Stress*. Bethesda, MD: American Fisheries Society.

Baxter, R., R. Breuer, L. Brown, L. Conrad, F. Feyrer, S. Fong, K. Gehrts, L. Grimaldo, B. Herbold, P. Hrodey, A. Mueller-Solger, T. Sommer, and K. Souza. 2010. *2010 Pelagic Organism Decline Work Plan and Synthesis of Results*. Interagency Ecological Program for the San Francisco Estuary. Available at www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf.

Bay Institute. 1998. *From the Sierra to the Sea: The Ecological History of the San Francisco Bay-Delta Watershed*. Available at www.bay.org/publications/from-the-sierra-to-the-sea-the-ecological-history-of-the-san-francisco-bay-delta-waters.

Bennett, W. A., and P. B. Moyle. 1996. “Where Have All the Fishes Gone? Interactive Factors Producing Fish Declines in the Sacramento–San Joaquin Estuary.” In *San Francisco Bay: The Ecosystem*, ed. J. T. Hollibaugh (San Francisco, California: Pacific Division of the American Association for the Advancement of Science).

Bennett, W.A., W. J. Kimmerer, and J. R. Burau. 2002. “Plasticity in Vertical Migration by Native and Exotic Estuarine Fishes in a Dynamic Low-Salinity Zone.” *Limnology and Oceanography* 47: 1496–1507.

Central Valley Regional Water Quality Control Board. 1998. *The Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board Central Valley Region*. Available at www.swrcb.ca.gov/rwqcb5/water_issues/basin_plans.

Cloern J. E., N. Knowles, L. R. Brown, D. Cayan, and M. D. Dettinger. 2011. “Projected Evolution of California’s San Francisco Bay-Delta-River System in a Century of Climate Change.” *PLoS ONE* 6 (9): e24465. DOI: 10.1371/journal.pone.0024465.

Conaway, C. H., F. J. Black, T. M. Grieb, S. Roy, and A. R. Flegal. 2008. “Mercury in the San Francisco Estuary.” *Reviews of Environmental Contamination and Toxicology* 194: 29–54.

Delta Protection Commission. 2012. *Economic Sustainability Plan for the Sacramento–San Joaquin Delta*. www.delta.ca.gov/res/docs/ESP_P2_FINAL.pdf.

Feyrer, F., K. Newman, M. Nobriga, and T. Sommer. 2010. “Modeling the Effects of Future Outflow in the Abiotic Habitat of an Imperiled Estuarine Fish.” *Estuaries Coasts* 34: 120–28.

Fleenor, W., W. Bennett, P. Moyle, and J. Lund. 2010. “On Developing Prescriptions for Freshwater Flows to Sustain Desirable Fishes in the Sacramento–San Joaquin Delta.” Submitted to the State Water Resources Control Board regarding flow criteria for the Delta necessary to protect public trust resources. Davis, California: University of California, Davis, Center for Watershed Sciences.

Glibert, P. M., D. Fulerton, J. M. Burkholder, J. C. Cornwell, T. M. Kana. 2011. “Ecological Stoichiometry, Biogeochemical Cycling, Invasive Species, and Aquatic Food Webs: San Francisco Estuary and Comparative Systems.” *Reviews in Fisheries Science* 19 (4): 358–417.

Hampton, S.E., and D.E. Schindler. 2006. “Empirical Evaluation of Observation Scale Effects in Community Time Series.” *Oikos* 113: 424–39.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. *Managing California’s Water: From Conflict to Reconciliation*. San Francisco: Public Policy Institute of California.

Healey, M. C., M. D. Dettinger, and R. B. Norgaard, eds. 2008. *The State of Bay-Delta Science, 2008*. Sacramento, CA: CALFED Science Program.

Ives, A. R., B. Dennis, K. L. Cottingham, and S. R. Carpenter. 2003. “Estimating Community Stability and Ecological Interactions from Time-Series Data.” *Ecological Monographs* 73: 301–30.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. “Isohaline Position as a Habitat Indicator for Estuarine Populations.” *Ecological Applications* 5 (1): 272–89.

Lehman, P. W., G. Boyer, M. Satchwell, and S. Waller. 2008. “The Influence of Environmental Conditions on the Seasonal Variation of Microcystis Cell Density and Microcystins Concentration in San Francisco Estuary.” *Hydrobiologia* 600: 187–204.

Lindley, S. T. and M. S. Mohr. 2003. “Modeling the Effect of Striped Bass (*Morone saxatilis)* on the Population Viability of Sacramento River Winter-Run Chinook Salmon (*Onchorhyncus tshawytscha*).” *Fisheries Bulletin* 101: 321–31.

Lucas, L.V., J. E. Cloern, J. K. Thompson, and N. E. Monsen. 2002. "Functional Variability of Habitats within the Sacramento–San Joaquin Delta: Restoration Implications." *Ecological Applications* 12: 1528–47.

Lund, J., E. Hanak, W. Fleenor, R. Howitt, J. Mount, and P. Moyle. 2007. *Envisioning Futures for the Sacramento–San Joaquin Delta*. San Francisco: Public Policy Institute of California.

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: University of California Press and Public Policy Institute of California.

Luoma, S., S. Anderson, B. Bergamaschi, L. Holm, C. Ruhl, D. Schoellhamer, R. Stewart. 2008. "Water Quality." In *The State of Bay-Delta Science, 2008*, ed. M. C. Healey, M. D. Dettinger, and R. B. Norgaard (Sacramento, CA: CALFED Science Program).

Mac Nally, R., J. R. Thomson, W. J. Kimmerer, F. Feyrer, K. B. Newman, A. Sih, W. A. Bennett, L. Brown, E. Fleishman, S. D. Culberson, and G. Castillo. 2010. "Analysis of Pelagic Species Decline in the Upper San Francisco Estuary Using Multivariate Autoregressive Modeling." *Ecological Applications* 20: 1417–30.

Maunder, M. N., and R. B. Deriso. 2011. "A State-Space Multistage Life Cycle Model to Evaluate Population Impacts in the Presence of Density Dependence: Illustrated with Application to Delta Smelt (*Hyposmesus transpacificus)*." *Canadian Journal of Fisheries and Aquatic Science* 68: 1285–1306.

Mount, J. F., and R. Twiss. 2005. "Subsidence, Sea Level Rise, Seismicity in the Sacramento–San Joaquin Delta." *San Francisco Estuary and Watershed Science* 3 (1).

Moyle, P. B. 2002. *Inland Fishes of California*. Revised and expanded. Berkeley: University of California Press.

Moyle, P. B. 2008. "The Future of Fish in Response to Large-scale Change in the San Francisco Estuary, California." In *Mitigating Impacts of Natural Hazards on Fishery Ecosystems,* ed. K. D. McLaughlin (Bethesda, MD: American Fishery Society, Symposium 64).

Moyle, P. B. 2011. "Striped Bass Control: The Cure Worse than the Disease?" Available at http://californiawaterblog.com/2011/01/31/striped-bass-control-the-cure-worse-than-the-disease.

Moyle, P. B., and W. A. Bennett. 2008. "The Future of the Delta Ecosystem and Its Fish." Technical Appendix D. *Comparing Futures for the Sacramento–San Joaquin Delta*. San Francisco: Public Policy Institute of California.

Moyle, P. B., J. V. E. Katz, and R. M. Quiñones. 2011. "Rapid Decline of California's Native Inland Fishes: A Status Assessment." *Biological Conservation* 144: 2414–23.

Moyle, P. B., W. Bennett, J. Durand, W. Fleenor, B. Gray, E. Hanak, J. Lund, and J. Mount. 2012. *Where the Wild Things Aren't: Making the Delta a Better Place for Native Species.* San Francisco: Public Policy Institute of California.

National Research Council. 2012. *Sustainable Water and Environmental Management in the California Bay-Delta*. Washington DC: National Academies Press.

Poff, N. L., B. D. Richter, A. H. Arthington, et al. 2010. "The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards." *Freshwater Biology* 55: 147–70.

Rose, K. A., E. S. Rutherford, D. McDermott, J. L. Forney, and E. L. Mills. 1999. "An Individual-Based Model of Walleye and Yellow Perch in Oneida Lake, New York." *Ecological Monographs* 69: 127–54.

Scheinter, S. M. and J. Gurevitch, eds. 1993. *The Design and Analysis of Ecological Experiments*. New York: Chapman & Hall.

Shilling, F., A. White, L. Lippert, and M. Lubell. 2010. "Contaminated Fish Consumption in California's Central Valley Delta." *Environmental Research* 110: 334–44.

Sommer, T., C. Armor, R. Baxter, R. Breuer, L. Brown, M. Chotkowski, S. Culberson, F. Feyrer, M. Gingras, B. Herbold, W. Kimmerer, A. Mueller-Solger, M. Nobriga, and K. Souza. 2007. "The Collapse of Pelagic Fishes in the Upper San Francisco Estuary." *Fisheries* 32: 270–77.

State Water Resources Control Board. 2010. *Final Report on Development of Flow Criteria for the Sacramento–San Joaquin Delta Ecosystem*. Available at www.swrcb.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/final_rpt.shtml.

Thompson, J. 1957. "Settlement Geography of the Sacramento–San Joaquin Delta." Ph.D. dissertation. Stanford, CA: Stanford University.

U.S. Environmental Protection Agency. 2011. *Water Quality Challenges in the San Francisco Bay/Sacramento–San Joaquin Delta Estuary*. Available at www.federalregister.gov/articles/2011/02/22/2011-3861/water-quality-challenges-in-the-san-francisco-baySacramento-san-joaquin-delta-estuary.

Whipple A. A., R. M. Grossinger, D. Rankin, et al. Forthcoming. "Sacramento–San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process" (working title). Richmond, CA: San Francisco Estuary Institute-Aquatic Science Center.

Williams, J. G. 2006. "Central Valley Salmon: A Perspective on Chinook and Steelhead in the Central Valley of California." *San Francisco Estuary and Watershed Science* 4 (3): Article 2. Available at http://repositories.cdlib.org/jmie/sfews/vol4/iss3/art2.

Acknowledgments

We thank the following reviewers for their helpful comments on an earlier draft: Cliff Dahm, Greg Gartrell, Anthony Saracino, Lynette Ubois, and one reviewer who wished to remain anonymous. We also thank Gary Bjork for editorial support. We alone are responsible for the views expressed herein and for any errors or omissions.

About the Authors

William Bennett is a professional researcher in fish ecology with the John Muir Institute of the Environment at the University of California, Davis. His research has focused primarily on understanding the population dynamics of fishes in the San Francisco Estuary and the near-shore marine environments in California. He has worked extensively with the Interagency Ecological Program and the CALFED Bay-Delta program to investigate the delta smelt and striped bass populations in the San Francisco Estuary, and his work with the Pacific Estuarine Ecosystem Indicator Research Consortium has focused on tidal-marsh goby populations. He also has studied the relative influences of fishing intensity and climate change on the near-shore rockfish fishery.

John Durand has been researching and teaching about the ecology of the San Francisco Estuary for much of the past decade. His current work, supported by grants from the Delta Science Program, investigates the way in which estuaries support native fishes and food webs. Before returning to research, he had a career as a science school teacher and environmental education non-profit director. He holds an M.S. in Ecology from San Francisco State University and will receive his Ph.D. in Ecology from UC Davis in 2012.

William Fleenor is a professional research engineer in the Civil and Environmental Engineering Department at the University of California, Davis. He holds a bachelor's degree in mechanical engineering from the Rose-Hulman Institute of Technology and a master's degree in environmental engineering and Ph.D. in water resources from UC Davis. He has been involved with numerous hydrodynamic and water quality research projects involving the Delta.

Ellen Hanak is a senior policy fellow at the Public Policy Institute of California. Her career has focused on the economics of natural resource management and agricultural development. She launched PPIC's research program on water policy in 2001 and has published numerous reports and articles on California's water management challenges and opportunities. Other areas of expertise include infrastructure finance and climate change. Before joining PPIC, she held positions with the French agricultural research system, the President's Council of Economic Advisers, and the World Bank. She holds a Ph.D. in economics from the University of Maryland.

Jay Lund holds the Ray B. Krone Chair in Environmental Engineering and is director of the Center for Watershed Sciences at UC Davis. He specializes in the management of water and environmental systems. He served on the Advisory Committee for the 1998 and 2005 California Water Plan Updates, is a former editor of the *Journal of Water Resources Planning and Management*, and has authored or co-authored more than 200 publications.

Jeffrey Mount is a professor in the Geology Department at the University of California, Davis, where he has worked since 1980. His research and teaching interests include fluvial geomorphology, conservation and restoration of large river systems, flood plain management, and flood policy. He holds the Roy Shlemon Chair in Applied Geosciences at UC Davis, is the founding director of the UC Davis Center for Watershed Sciences, and is a member of the Delta Independent Science Board. He is author of *California Rivers and Streams: The Conflict between Fluvial Process and Land Use* (1995).

Peter Moyle has been studying the ecology and conservation of inland fishes of California since 1969 and the San Francisco Estuary since 1976. He was head of the Delta Native Fishes Recovery Team and a member of the Science Board for the CALFED Ecosystem Restoration Program. He has authored or coauthored more than 200 scientific papers and 10 books, including *Inland Fishes of California* (2002) and *Protecting Life on Earth* (2010, with M. Marchetti). He is a professor of fish biology in the Department of Wildlife, Fish, and Conservation Biology at UC Davis, and is associate director of the UC Davis Center for Watershed Sciences.

PPIC | PUBLIC POLICY INSTITUTE OF CALIFORNIA

PUBLIC POLICY INSTITUTE OF CALIFORNIA
500 Washington Street, Suite 600
San Francisco, California 94111
phone: 415.291.4400
fax: 415.291.4401
www.ppic.org

PPIC SACRAMENTO CENTER
Senator Office Building
1121 L Street, Suite 801
Sacramento, California 95814
phone: 916.440.1120
fax: 916.440.1121`