Public Interest Energy Research (PIER) Program

White Paper

EFFECTS OF CLIMATE CHANGE ON THE INLAND FISHES OF CALIFORNIA:

With Emphasis on the San Francisco Estuary Region

A White Paper from the California Energy Commission's California Climate Change Center

Prepared for: California Energy Commission

Prepared by: University of California, Davis

UC DAVIS CENTER FOR WATERSHED SCIENCES

JULY 2012

CEC-500-2012-029

Peter B. Moyle
Rebecca M. Quiñones
Joseph D. Kiernan

Center for Watershed Sciences
University of California, Davis

DISCLAIMER

ACKNOWLEDGEMENTS

Funding for the analysis was provided by the California Energy Resources Conservation and Development Commission Instream Flow Assessment Program (Grant No. IFAP-01). Discussions with Jeffrey Mount and Jay Lund (University of California Davis Center for Watershed Sciences) and Ellen Hanak (Public Policy Institute of California) were very helpful. We appreciate the useful comments on the drafts by various reviewers. We also appreciate the guidance and comments by Guido Franco, Myoung-Ae Jones, and other California Energy Commission staff, and by Mark Wilson.

PREFACE

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the California Climate Change Center to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions.

For more information on the PIER Program, please visit the Energy Commission's website http://www.energy.ca.gov/research/index.html or contract the Energy Commission at (916) 327-1551.

ABSTRACT

California's native inland fish fauna is in steep decline, a pattern which is reflected in the status of fishes native to streams flowing into the San Francisco Estuary and in the estuary itself. Climate change will further reduce the distribution and abundance of these mostly endemic fishes and expand the distribution and abundance of alien fish species. The decline and likely extinction of many native fishes reflects dramatic shifts in the state's aquatic ecosystems; shifts which are being accelerated by climate change. Fishes requiring cold water, such as salmon and trout, will especially suffer from climate change impacts of warmer water and reduced summer flows. Additionally, desirable species living in the San Francisco Estuary and the lower reaches of its streams will have to contend with the effects of rising sea level along with changes in flows and temperature. This paper: (1) briefly describes the environment of California and its fish fauna, (2) summarizes the projected general effects of climate change on its aquatic environments, (3) discusses likely interactions of climate with other stressors of fish populations, (4) describes possible effects on fishes of the San Francisco Estuary, and (5) suggests elements of a conservation strategy for the native fish fauna, focusing on the San Francisco Estuary.

Keywords: freshwater fishes, Salmonidae, Cyprinidae, invasive species, extinction

Please use the following citation for this paper:

Moyle, Peter B., Rebecca M. Quiñones, and Joseph D. Kiernan (University of California, Davis). 2012. ***Effects of Climate Change on the Inland Fishes of California: With Emphasis on the San Francisco Estuary Region.*** California Energy Commission. Publication number: CEC-500-2012-029.

TABLE OF CONTENTS

LIST OF TABLES

Section 1: Introduction

The fishes that inhabit the fresh and estuarine waters of California are expected to be strongly affected by climate change because most scenarios project not only increasing water temperatures, but also much more variable hydrologic conditions, with more frequent and severe flood and drought conditions (Knox and Scheuring 1991; Anderson et al. 2008; Cayan et al. 2009). In addition, rising sea level will alter estuarine ecosystems, as well as the lower reaches of streams and rivers.

Yet because of California's large size and diverse topography, its well-documented fish fauna, and the high degree of alteration of its waterways, the state also presents many opportunities to learn how climate change will affect inland fish populations in a changing world and how we, and the native fishes, can adapt to this change. The fishes of San Francisco Estuary (SFE) and its surrounding watersheds are particularly vulnerable to climate change effects because the SFE is an urbanized estuary that ecologically depends on fresh water from the highly modified Sacramento and San Joaquin rivers, as well as from numerous smaller streams. Together these rivers and streams drain by far the largest watershed in the state, so geographically broad climate change effects (e.g., reduced snowfall in the Sierra Nevada) have disproportionate impacts on the SFE (Knowles and Cayan 2002; Dettinger and Culberson 2008). Thus, the aquatic ecosystems of the SFE will be strongly affected by increased variability in freshwater inflows, diversions of water, increases in water temperature, and flooding of shallow marshland areas by sea level rise. These changes are taking place in concert with changes in the terrestrial ecosystems to which the aquatic systems are closely linked.

This review paper (1) briefly describes the physical environment of the state and its fish fauna, (2) describes the SFE as fish habitat, (3) summarizes the likely effects of climate change on aquatic environments in California and the SFE, (4) discusses likely interactions of climate with other stressors of fish populations, (5) describes potential effects of climate change on SFE habitats, focusing on fishes, and (6) suggests elements of a conservation strategy for the native fish fauna of the SFE region.

Section 2: California's Environment and Fishes

California is large (411,000 square kilometers [km^2]), long (1,400 km from Mexico to Oregon, spanning 10 degrees of latitude), and topographically extremely diverse, including both the highest and lowest points in the lower United States. It can be divided into 50 distinct watersheds, in which native fishes have evolved independently and which have independent histories of introductions of alien (non-native) fishes (Moyle 2002; Moyle and Marchetti 2006). While the climates of these watersheds range from extremely dry to extremely wet, most of the state follows a Mediterranean climatic pattern, in which precipitation occurs mainly in winter and spring, followed by long, dry summers. This climate results in rivers that naturally have high annual and seasonal variability in flows (Mount 1995), so the native fishes are adapted to live with hydrologic extremes. This is especially true of fishes of the SFE and its watershed. The SFE is the largest estuary on the Pacific Coast of North America and is subject to the vagaries of flow from two of its largest rivers, as well as to constantly changing ocean conditions.

Of California's 129 native inland fishes (those species which breed in fresh water), 63 percent are endemic to the state, and 19 percent are found also in just one adjacent state (Moyle 2002; Moyle et al. 2011). Thus, California's native fishes largely (82 percent) live within coinciding political and zoogeographic boundaries (Moyle 2002). Mixed with this diverse native fauna are 49 species of introduced fishes, often dominating the more altered aquatic habitats (e.g., reservoirs). The freshwater fishes of the SFE region include about 25 percent of California's native inland fishes and 60 percent of the alien fishes, so this region's fishes are representative of fishes found throughout the state. Our understanding of the biology and status of these species, while far from complete, is better than most comparable areas of the world (Moyle 2002; Moyle et al. 2008; Moyle et al. 2010), making it possible to conduct semi-quantitative analyses of trends and of factors affecting these trends (e.g., Moyle and Marchetti 2006).

The highly variable and often harsh conditions found in California's waterways favor fishes that migrate between fresh and salt water (i.e., anadromous fishes; 24 percent of total native fauna), as well as fishes that thrive in isolated or extreme environments such as desert springs, intermittent streams, and alkaline lakes (Moyle 2002). Most species, however, live in watersheds of the Central Valley and North Coast, where water is usually abundant and habitats diverse. Unfortunately for the fishes, humans find California a pleasant place to live, so the rivers, lakes, springs, and creeks of the state have been greatly altered, even in remote places (Hundley 2001).

As a consequence, native fishes have been in steady decline since the mid-nineteenth century, so by 1989, 7 species (5 percent) were regarded as extinct, 15 (13 percent) were formally listed as threatened or endangered, and 51 (43 percent) were regarded as imperiled [1] (Moyle and

[1] By "imperiled" we mean species that are either in decline, with extinction likely in 100 years or less if present trends continue, or that have restricted geographic ranges, so that relatively small, localized events could result in extinction. In either case, intensive management is needed to prevent extinction.

Williams 1990). By 1995, the numbers of listed and imperiled species had risen to 18 (16 percent) and 51 (44 percent), respectively (Moyle et al. 1995).

Today, of 129 kinds of native fishes, 7 (5 percent) are extinct, 31 (24 percent) are listed, and 69 (53 percent) are imperiled (but not listed); meaning that 82 percent of California's native fishes are now listed, imperiled, or extinct (Moyle et al. 2011). For the majority (62 percent) of the listed or imperiled (54 percent) are imperiled (but not listed), meaning that 82 percent of California's native fishes are now listed, imperiled, or extinct (Moyle et al. 2011). For the majority of listed or imperiled species, climate change is one of the factors accelerating their decline and will most likely[2] contribute to extinction by the end of the twenty-first century (Moyle et al. 2011). Thus, climate change is a growing stressor, which is acting on an already-stressed fish fauna.

The Sacramento-San Joaquin watershed (encompassing about 40 percent of California by area) drains most of northeastern California, the west side of the Sierra Nevada, much of the east side of the Coast Range, the Central Valley, and the SFE region. Forty-seven (38 percent) of California's extant inland fishes are found in the watershed, with 33 (27 percent) of these species found in rivers and streams flowing into the SFE (Leidy 2007). Of these 33 species, 20 (61 percent) are deemed imperiled (Moyle et al. 2011).

In addition, the thicktail chub (*Gila crassicauda*), tidewater goby (*Eucyclogobius newberryi*), coho salmon (*Oncorhynchus kistuch*), and Sacramento perch (*Archoplites interruptus*)—once common fishes in the SFE—are now extirpated from the SFE, and the chub is globally extinct (Moyle 2002; Leidy 2007). Thus, the patterns of decline and extinction of inland fishes seen throughout California and the Central Valley also characterize the SFE. It is worth noting that these patterns apply only to fish that spend at least part of their life cycle in fresh water; the largely marine fish fauna of San Francisco Bay is less dramatically altered, thanks to the constant replenishing of fish populations from the Pacific Ocean.

The importance of this discussion is that most inland California fishes are already on a slide toward extinction, pushed by the abundant alien species. Climate change is thus an additional factor contributing to their vulnerability to extinction.

[2] We use the terms *likely* and *very likely* in the sense that the Intergovernmental Panel on Climate Change (IPCC) (2010) uses them, where *very likely* means a 90 to 100 percent probability of occurrence and *likely* means a 66 to 100 percent probability of occurrence.

Section 3: Effects of Climate Change on Aquatic Environments in California

Three major aspects of climate change affect fish distribution and abundance: temperature, precipitation, and sea level rise. The interaction among these effects will be particularly strong in the SFE.

Temperature. There are diverse climate change models for the future of California, but they generally converge on scenarios that assume that within 50–100 years, if not sooner, winter and summer air temperatures will average between 1°C–4°C (1.8°F–7.2°F) and 1.5°C–6°C (2.7°F–10.8°F) warmer, respectively, and precipitation will be more variable, although not necessarily less in amount on average (Miller et al. 2003; Cayan et al. 2009). Further, annual snowpack in the Sierra Nevada and Cascade ranges is expected to diminish greatly, so stream flows will be increasingly driven by rainfall events. An increase in the ratio of rain to snow will result in more peak flows during winter, increased frequency of high flow events (floods), diminished spring pulses, and protracted periods of low (base) flow. In addition, there will be more extended droughts, as well as series of extremely wet years, albeit with dry summers. These conditions will translate into warmer water temperatures at most elevations, reflecting both increases in air temperatures and reduced summer flows.

The region of the state with the greatest uncertainty regarding the future effects of climate change is the North Coast, including the San Francisco Bay region, because of uncertainties in future changes in ocean temperature, coastal currents, and other factors. If summer fog does not diminish (Diffenbaugh et al. 2004), then many coastal streams may stay cool, if with reduced summer flows. However, observations of foggy day frequency indicate that fog is already decreasing on the coast (Johnstone and Dawson 2010), increasing stream temperatures and decreasing summer flows.

From a fish perspective, the impacts of climate change are likely to be most severe on species requiring cold water (<18°C–20°C, or 64°F–68°F) for persistence, especially the iconic salmon and trout (Salmonidae). The ability of waters of the United States to support cold-water fishes is projected to decrease by 4 to 20 percent by 2030 and by as much as 60 percent by 2100 (Eaton and Scheller 1996), with the greatest loss projected for California because of its naturally warm summer climate (O'Neal 2002; Preston 2006). Warming (more days with maximum temperatures > 20°C or > 68°F) of the more freshwater regions of the SFE is regarded as an additional threat to declining endemic species such as delta smelt (*Hypomesus transpacificus*) (Wagner et al. 2011).

California's rivers and streams have presumably already been affected by increases in air temperature. Summer water temperatures may have increased, on average, 0.5°C–1.0°C (0.9°F–1.8°F) in the past 20 years or so (e.g., Bartholow 2005). While such increases may seem small, they can push already marginal waters over thresholds for supporting cold-water fishes. In the Klamath River, where summer temperatures often exceed 22°C (72°F) (McCullough 1999; CDEC 2008), small temperature increases are making the mainstem increasingly inhospitable for

Pacific salmon (*Oncorhynchus* spp.) and steelhead trout (*O. mykiss*) that use the river in summer and fall. Likewise, Butte Creek, a tributary to the Sacramento River in Tehama County, will likely lose its salmonid fishes in the next 50–100 years as the result of temperature changes (Thompson et al. *in press*). Similarly, streams tributary to the SFE are increasingly losing their ability to support salmonid fishes as water temperatures warm, although the degree to which cold-water habitat will be lost depends on the interactions among stream flow (including cold-water releases from dams), urbanization, and effectiveness of restoration efforts (Leidy 2007).

Precipitation. Models for precipitation indicate that precipitation in California will become more variable, with more falling as rain and less as snow (Cayan et al. 2009). Generally, the total amount of precipitation by 2100 is projected to be less, although the extent of the loss is highly uncertain (Cayan et al. 2009). From a fish perspective, present rainflow streams will respond somewhat differently than snowmelt streams, although as temperatures rise, the hydrologic character of snowmelt streams will become more like those of rainflow-derived streams.

Snowmelt streams are mainly characteristic of the Sierra Nevada and Cascade mountain ranges. Historically, they had extended spring flows to which local fish were adapted and which helped to keep the Sacramento-San Joaquin Delta (Delta), in the upper SFE, as a largely freshwater system (Moyle et al. 2010). However, the effects of snowmelt streams have been greatly reduced by the capture of the spring recessional flows by dams. In general, the streams will be become more variable in flow, with warmer summer and fall temperatures as the result of lower flows and shallower depths (Allan and Castillo 2007). The latter are caused by the reduced snowpack, increased frequency of rain storms, and reduced seasonal retention of water in soils and other natural reservoirs (Hayhoe et al. 2004; Stewart et al. 2004, 2005; Hamlet et al. 2005). Elevations below 3000 meters (m) will likely suffer the most (80 percent) loss of snowpack (Hayhoe et al. 2004), as well as reduction in water content of the remaining snow (e.g., Van Kirk and Naman 2008). Earlier snowmelt has already moved the timing of high flows forward by 10 to 30 days on average (Stewart et al. 2005), with annual peak discharges especially occurring earlier (Cayan et al. 2001, 2009). These changes dramatically affect flow of low-elevation rivers in the Central Valley and operation of reservoirs which affect the flow. In the SFE, this change in river flow regime is likely to result in a Delta with more variable salinity, especially during dry years, when less water is available to be released from reservoirs, reducing outflows.

Streams that are already dependent on rain, such as those of the SFE region, will become even more variable, with greater extremes in high and low flows, leading to drying up of long reaches of stream on occasion. In interior and south-coast California, such streams already show highly variable flow regimes, with "flashy" flows in winter in response to rain events (e.g., Cosumnes River; Moyle et al. 2003) and extremely low flows in summer, maintained mainly by water stored in subsurface gravel deposits and similar short-term ground water storage areas. Winter rains have already created some of the most extreme flow events ever recorded for California, such as the major floods of 1955 and 1964 in the Eel and other coastal rivers (e.g., Yoshiyama and Moyle 2010).

Overall, the amount of water carried by streams in California (and the rest of the western United States), if present trends continue, will decrease by 10 to 50 percent during the drier months (e.g., Cayan et al. 2001). More important, extreme high- and low-flow events are projected to increase by 15 to 20 percent (Leung et al. 2004), especially in the northern Sierra Nevada and southern Cascade Range (Kim 2005). This increased incidence of extreme events will test the adaptive ability of native stream fishes, including those in streams tributary to the San Francisco Estuary.

Sea level rise. Projections of the rate of sea level rise are changing, usually upwards, as better information becomes available. Cayan et al. (2009) project a rise in sea level of 35–50 centimeters (cm) in the next 50 years, while Knowles (2010) projects a rise of as much as 150 cm by 2100. Other scenarios range from optimistic projections of 45–70 cm by 2100 to pessimistic projections of 1500 to 3500 cm (Knowles 2010). Accompanying the mean rise of sea level will be an increase in major events that enhance effects of the rise, such as high tides, storm surges, and coincidence of high tides with high outflows from rivers (Cayan et al. 2009). For fishes, a major consequence of sea level rise will be the reduction or loss of tidal marsh habitat, important throughout the SFE (Moyle et al. *in press*), although all habitats will change substantially, including an increase in deep open water habitat in the Delta (Moyle 2008).

When effects of sea level rise, more variable precipitation, and increased water temperatures are considered together, the picture that emerges is of a very different SFE, with major changes in fish habitat, resulting in a large increase in the number of endangered species by 2100. The effects of such change, of course, will be exacerbated by interactions with other anthropogenic factors that cause stress to the SFE ecosystem and its inhabitants, including fish.

Section 4: Interactions Between Climate Change and Anthropogenic Stressors

The many human-made factors that affect aquatic ecosystems, as reflected in fish populations and assemblages, are reviewed in Moyle (2002) and will only be briefly covered here, to relate them to climate change. The factors can be placed in five broad categories: (1) dams and diversions, (2) land use practices, (3) pollution, (4) alien species, and (5) harvest.

4.1 Dams and Diversions

Dams and diversions have both upstream and downstream effects on fishes. A major upstream impact in California and the SFE has been denial of access to spawning and rearing areas of migratory fishes such as salmon and lampreys (Petromyzontidae). The blockage both diminishes total populations of these fishes and eliminates nutrient subsidies that migratory fishes provide to upstream ecosystems, making the ecosystems more diverse and robust. Reservoirs upstream of dams are also a completely different habitat, typically with warm surface waters that favor alien fishes, including species that are predators of native fishes (and can move into above-dam reaches that might otherwise act as refuges). These now-isolated, altered upstream ecosystems have increased vulnerability to climate change effects, as warmer temperature and reduced flows stress natural fish assemblages, increasing their vulnerability to alien predators and increasing local extinction rates, with reduced opportunities for recolonization.

Downstream effects of dams can be both positive and negative. On the positive side, many reservoirs behind dams stratify in summer, creating extensive pools of cold water that, if released judiciously, can be used to maintain cold-water flows in low-elevation streams, perhaps countering climate change effects. For example, release of cold water from Shasta Dam is essential for maintaining winter-run Chinook salmon (*O. tshawytscha*), which no longer have access to their historic cold-water habitat in the McCloud River, upstream of the dam (Moyle 2002). On the negative side, dams and diversions typically deprive rivers and streams of much of their water, leaving dry streambeds in some cases (e.g., San Joaquin River) and much diminished rivers in others. If not seriously augmented with cold-water releases, the downstream rivers turn into warm-water streams supporting mainly alien species (e.g., Putah Creek; Marchetti and Moyle 2001). A major problem with dependence on cold-water releases from dams, however, is that cold-water pools in reservoirs may disappear during extended periods of drought, leaving salmon and other fish without refuges.

The problems created by dams are exacerbated by the location of large pumping stations in the south Delta, in the upper San Francisco Estuary. These stations, one operated by the state (California Department of Water Resources) and one operated by the federal government (U.S. Bureau of Reclamation) provide water for farms in the southern Central Valley and for urban areas of southern California. They are a key part of California's water delivery system. Water is retained behind dams in winter and spring and then released down the rivers of the Sacramento Valley in summer and fall to be exported by the south Delta pumps. The steady increase in exports (until recently) is associated with a major shift in the Delta ecosystem that favors alien species and endangers a number of native species, especially fish (Feyrer et al. 2007; Moyle and Bennett 2008; Lund et al. 2010). Climate change and sea level rise will cause further changes to the ecosystem (Moyle 2008), as discussed below.

4.2 Land Use Practices

Whatever happens on land affects the waterways that drain the land. Logging, agriculture, and urbanization, for example, typically accelerate runoff into streams, carrying debris from land (especially sediment) into the stream. Because accelerated runoff often results in flooding in downstream areas, there is a tendency for humans to build levees to contain flood flows; not always successfully. Regardless, all this activity greatly alters streams, making them more vulnerable to climate change effects.

Take, for example, the situation in the Eel River, the third largest watershed in California, which once supported runs of up to a million salmon and steelhead each year. Recent monitoring shows only a few thousand fish a year ascending the river (Yoshiyama and Moyle 2010). While the decline has multiple causes, the single biggest cause is undoubtedly the heavy logging that took place on the basin's fragile hillsides. When record rains hit the watershed, the damaged hillsides, often denuded of vegetation, washed into the river, filling deep pools and creating a wide shallow meandering river in summer, exposed to the sun. This new, warmer river then became perfect habitat for predatory Sacramento pikeminnow (*Ptychocheilus grandis*), introduced into an upstream reservoir by bait fishermen (Moyle 2002). The pikeminnow are a major factor suppressing remaining salmon and steelhead populations, although even without pikeminnow much of the river continues to be marginal or unsuitable summer habitat for salmonids (Yoshiyama and Moyle 2010). Such complex interactions are likely to become more common as climate change further stresses both water and landscapes. In the case of the Eel River, return to cool water conditions needed for salmonids becomes less likely with climate change, even if there is substantial recovery of channel and forest conditions.

In streams tributary to SFE, the abundance of alien fishes is a good indicator of how stressed the environment is. Thus, native fishes are least abundant and alien fishes most abundant in warm, low-gradient reaches of stream close to the estuary that are highly degraded by water diversion, pollution, channelization, and other by-products of urbanization (Leidy 2007). In the estuary itself, there is a distinct gradient of abundant alien species in the Delta down to mostly native species in San Francisco Bay (see below). Climate change will alter fish abundance and distribution in the SFE in many, often unpredictable, ways.

4.3 Pollution

Most waters in California are regarded as impaired under the federal Clean Water Act, by warm temperatures, siltation, contaminants, or some combination of factors. Pollution can result from point-source discharges (e.g., sewage treatment plants), non-point source discharges (e.g., runoff or return water from streets and farms), and legacy effects (e.g., mercury from Gold Rush-era mining). The negative effects of pollution on fish are expressed as direct fish kills, avoidance of once-important habitats such as migratory corridors, increased incidence of disease, reduced ability to avoid predators and other potential causes of death, and reduced reproductive capacity. Thus, streams and portions of the SFE subject to pollutants tend to have fewer fish and lower species richness, and be dominated by tolerant alien species. Brown (2000) found that the heavily contaminated lower San Joaquin River (upper south Delta) was inhabited almost exclusively by small, highly tolerant alien species such as Mississippi silverside (*Menidia audens*) and red shiner (*Cyprinella lutrensis*). The added stress of climate change, with warmer temperatures, reduced flows, and increased concentration of pollutants will result in expansion of such fishes, unless input of pollutants is greatly reduced and flows through the Delta are increased.

4.4 Alien Species

The inland waters of California have been successfully invaded by 49 fish species (Moyle and Marchetti 2006) and many species of invertebrates and aquatic macrophytes. These species dominate many waters, especially reservoirs and lowland rivers. The result has been increased homogenization of the aquatic biota of streams and lakes, and declines in native species (Moyle and Marchetti 2006), especially in waterways heavily altered by human activity. These alien species are largely those that are tolerant of high temperatures, low dissolved oxygen concentrations, and low-flow or lake-like conditions. Examination of the characteristics of alien species listed in Marchetti et al. (2004) suggests that 36 (73 percent) of the species are likely to expand their ranges under most climate change scenarios. New invaders are also highly likely to become established, further exacerbating problems for native fishes.

4.5 Harvest

Historically, many species of California fish were harvested at unsustainable levels, leading to declines; however, the effects of overharvest were often difficult to separate from other causes of decline, such as river alteration (Moyle 2002). This was particularly true in the SFE, where nineteenth-century commercial fisheries for Chinook salmon, white sturgeon (*Acipenser transmontanus*), Sacramento perch (*Archoplites interruptus*), and other species reduced their populations to low levels (Moyle 2002). However, the declines were generally regarded as undesirable, leading to responses such as tighter regulation of fisheries, construction of hatcheries to supplement reproduction of wild fish, and provision of cold-water flows below dams (Moyle 2002). Unfortunately, while such efforts produced a hiatus in declines of salmon and sturgeon populations, declines have continued in recent years in part because “fixes” such as hatcheries have not been able to adequately replace or mitigate for loss of natural habitat. This situation will only become worse under climate change without drastic measures such as dam removal, although demand for harvestable fish will continue to drive many water management decisions related to climate change.

Section 5: Effects on SFE Fishes

The San Francisco Estuary is arguably the most important waterway in California because it is a major node for water supply, a regional center of international shipping, the focus of a large and expanding urban area, the largest and most complex estuary on the West Coast, and an important region for aquatic biodiversity, including abundant and diverse fishes. It is also one of the most altered estuaries in the world (Nichols et al. 1986; Lund et al. 2007). Thus, climate change effects on the SFE and its biota affect the well-being of the entire state. The SFE has three ecologically (and geographically) distinct aquatic regions: the Delta, Suisun Bay and Marsh, and San Francisco Bay (Moyle 2002; Moyle et al. *in press*). In addition, the streams flowing directly into the SFE, not including the Sacramento and San Joaquin Rivers, represent another major aquatic habitat type.

5.1 Sacramento-San Joaquin Delta

The Sacramento-San Joaquin Delta is the freshwater portion of the SFE and historically was a giant wetland fed by flows of the Sacramento, San Joaquin, and lesser rivers, with many complex channels and ponds. Today the Delta is a collection of diked islands (polders) intersected by deep tidal channels that carry water that is polluted to varying degrees (Lund et al. 2007). Most of the polders in the south and central Delta are 2–7 m below sea level, and the dikes (levees) protecting them are highly vulnerable to failure (Suddeth et al. 2010). As indicated above, the Delta is also the center of California's water supply system, with large quantities exported from the south Delta annually, in ever-increasing amounts until recently, altering water flow patterns and water quality.

The Delta has also been invaded by a wide array of alien species, some of which have had major effects on ecosystem function. Not surprisingly, there have been long-term changes in fish populations of the Delta, with many desirable species in severe decline (Feyrer et al. 2007). Six native fishes that depend on the Delta are listed as threatened or endangered, including the delta smelt, which is endemic to the estuary. Moyle and Bennett (2008) show that the export-focused hydrology in combination with other factors has resulted in a "regime shift" in the Delta ecosystem, away from a variable estuarine system and toward more lake-like conditions. Consequently, the fish fauna (and the rest of the aquatic biota) has also shifted from riverine and estuarine species toward mostly alien warm-water lake and slough species.

Today, the Delta ecosystem is faced with another regime shift caused by climate change, especially sea level rise (Lund et al. 2007; Moyle 2008; Lund et al. 2010). Many of the polders are highly likely to be flooded because they are below present-day sea level and protected by structurally weak dikes. Flooding is inevitable under predicted levels of sea-level rise and the increase in major flood events predicted under most climate change scenarios. Earthquakes, of course, just increase probability of flooding through large-scale dike failure. Flooding of islands will dramatically change the nature of the Delta's aquatic ecosystem (as well as the ability to export water from it, if the flooding is mostly salty water). While the exact nature of the potential changes are unknown, increased volume of open, brackish water could improve habitat for declining pelagic species such as delta smelt and striped bass (*Morone saxatilis*) (Moyle 2008; Grimaldo et al. 2009). Moreover, increased variability in salinity, flow, habitat, and other factors likely to result from climate change (at least initially) could favor some desirable species of fish and other organisms (Moyle et al. 2010).

As Lund et al. (2007, 2010) document, the physical, chemical, and biological characteristics of the future Delta will depend on how Californians decide to manage the polders and their shaky dikes, flows of inflowing rivers, exports from the south Delta, sources of pollution, species invasions, and other factors. Regardless, climate change will dramatically alter the nature of solutions possible, with considerable economic impacts. For example, decisions to repair Delta dikes or to build a new conveyance system to deliver Sacramento River water south will cost billions of dollars. To a certain extent such decisions can ameliorate (e.g., improve habitat variability) or exacerbate (e.g., build higher dikes) Delta ecological problems (Lund et al. 2010).

5.2 Suisun Bay and Marsh

Suisun Marsh is a large managed marsh along the northern edge of Suisun Bay; a large, shallow, highly productive region that connects the Delta to Carquinez Straits and San Francisco Bay. Both marsh and bay are usually brackish (salinities < 15 parts per thousand [ppt] for much of the year), but they can range from fresh to salty (> 20 ppt) depending on river inflows and the effects of tides. Suisun Bay has long been regarded as a crucial rearing area for larval fish from the Delta and San Francisco Bay, although this role has been greatly diminished by the invasion of the overbite clam (*Corbula amurensis*) which consumes much of the pelagic productivity.

Suisun Marsh is the largest estuarine marsh remaining on the west coast of the contiguous United States. Most of the marsh area is diked wetlands managed for waterfowl, with the rest of the acreage consisting of tidally influenced sloughs (California Department of Water Resources 2001). The marsh's central location in the SFE and its abundance of relatively natural habitat make it an important rearing area for a mixture of freshwater, estuarine, and marine fishes (O'Rear and Moyle 2010; Moyle et al. *in press*). Most of the Suisun Marsh channels are shallow (typically 0–3 m in depth) and lined with tules (*Schoenoplectus* spp.) and other brackish-water marsh plants. The salinities in the channels range from 0 ppt in wet winters to 20 ppt in early autumn of dry years, with water temperatures ranging from about 9°C to 22°C (48°F to 72°F) on an annual basis (O'Rear and Moyle 2010).

Many of the same factors that affect the Delta also affect Suisun Bay and Marsh. In particular, exports from the south Delta alter freshwater inflows into both areas. In an effort to counter these effects, the Suisun Marsh Salinity Control Gates, built across upper Montezuma Slough where Sacramento River water flows in, are operated to inhibit saltwater intrusion into the marsh during flood tides and thereby provide fresh water for diked wetlands (California Department of Water Resources 2001). These wetlands are managed largely for waterfowl hunting. Numerous diversions, most of which are unscreened for fish, are located throughout the marsh; they are most commonly operated in early fall for flooding wetlands to attract wintering waterfowl.

While the fish fauna of this region is represented by a mixture of freshwater, marine, and brackish species, those species that can tolerate a wide range of salinity (i.e., euryhaline species) such as striped bass and splittail tend to be most abundant. The composition of the fish fauna is constantly changing, however, with seasonal and annual shifts in salinity and temperature, as well as with longer-term changes to the San Francisco Estuary.

This can be seen by examining the changing fish fauna of Suisun Marsh (O'Rear and Moyle 2010; Moyle et al. *in press*). Since 1980, monthly surveys have collected 55 species of fish, of which 25 have been alien species (O'Rear and Moyle 2010), although the catch is usually dominated by just 10–12 species. Catches generally declined in the first 15 years of the study (1980–1994), but during 1995–2006, catch numbers vacillated around a relatively stable mean (O'Rear and Moyle 2010). However, during 2006–2008 catch declined substantially, apparently reflecting lower Delta outflows and consequent higher salinities, but rose again slightly in 2009. The decreased catch of native fish has been more precipitous and less variable than that for alien fishes (O'Rear and Moyle 2010). Catches of individual alien species have been highly variable over the study's history, reflecting new invasions (e.g., shimfuri goby [*Tridentiger bifasciatus*], shokihazi goby [*T. barbatus*], overbite clam, and Siberian prawn [*Exopalaemon modestus*]), as well as presumed uncertain responses of alien species to environmental variability (Moyle et al. 2010). Nevertheless, the proportion of alien fishes has generally increased over the years.

Sea level rise will cause dramatic changes to both the marsh and bay and their fishes. If even conservative estimates of sea level rise hold true, most of Suisun Marsh will become tidal or subtidal habitat by 2100 (Knowles 2010). Worst-case scenarios will push sea level into urban areas that fringe the northern edge of the marsh, presumably resulting in massive dike-building efforts to protect the cities and making the marsh largely subtidal habitat. While marsh managers can delay the inevitable by simply letting their marshes flood during high tides or high outflow, repairing the internal dikes and then draining them, significant raising of dikes is unlikely because of cost and poor substrate to support heavy materials. Depending on how rapidly sea level rises and where sediment is deposited, developing tidal areas could maintain large areas of tules and other emergent plants with tidal channels running through them, supporting diverse fish and invertebrates. If increased variability in salinity occurs, which is highly uncertain, alien clam populations may be suppressed, increasing zooplankton productivity in open areas, and thereby increasing production of plankton-eating fish such as delta smelt and striped bass.

The effects of sea level rise and climate change on the open waters of Suisun Bay are a bit more uncertain. While depth should increase in proportion to sea level rise, the magnitude of tidal currents that move water, fish, nutrients, and sediment may depend on the volume of flooded islands in the Delta and, to a lesser extent, in Suisun Marsh. Large volumes of water will dissipate tidal energy (C. Enright, personal communication). On the other hand, the projected increase in large floods and long droughts will create more variable conditions over the years (fresh in flood years, very salty in drought years) which could favor native fishes (Moyle et al. 2010). This is all rather speculative, however.

5.3 San Francisco Bay

San Francisco Bay is the marine part of SFE; it includes highly diverse habitats. There are large tidal marshes around the mouths of the Napa and Petaluma rivers, the somewhat brackish open waters of San Pablo Bay, the rushing tidal regions around the Golden Gate that carry huge volumes of cold salt water in and out of the bay, and the warm, shallow, sometimes hypersaline waters of South Bay with its fringing salt marshes. Except in wet, high-outflow years, the fishes of San Francisco Bay are largely a select group (*ca*. 44 common species) of the same species that are found in the Pacific Ocean outside the bay (Hieb and Fleming 1999). Only the fish faunas of Napa and Petaluma marshes resemble that of Suisun Marsh upstream (Moyle et al. *in press*).

The assemblages of fish and macroinvertebrates in San Francisco Bay show high variability from year to year, depending on complex interactions among salinity, temperature, river outflow, and other factors (Hieb and Fleming 1999). There are also shifting abundances among species that are resident in the bay all year around versus those that migrate into the bay from the ocean, often as small juveniles. Cloern et al. (2010) found that the groups of species in San Francisco Bay tracked fluctuations of the two dominant current-driven climate patterns of the Pacific Ocean: the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation. Shifts in these patterns resulted in synchronous shifts in abundance of most fishes and macroinvertebrates in San Francisco Bay.

According to Cloern et al. (2010, p. L2106) "…population fluctuations of key marine species in SFB are tightly tied to climate-driven variability in the coastal ocean. Therefore, ecological forecasts of estuarine responses to climate change must consider how altered patterns of atmospheric forcing across ocean basins will influence both watershed hydrology and coastal oceanography." In other words, climate change effects on the ocean, still poorly understood, can have major impacts on the biota of inland waters, especially estuaries such as SFE. Because ocean currents can strongly influence regional climatic patterns, their strength and position can alter patterns of precipitation, fog, and other factors that in turn can affect river flows and estuarine fishes.

5.4 Bay Area Streams

The fishes of the 23 watersheds tributary to the SFE are perhaps the best documented for any region in California. Leidy (2007) recorded 33 native species from the streams, although only 24 had reproducing populations, and three species were extinct with no hope of recovery. About 30 species of alien fishes were present. Leidy (2007) found that native species persisted mainly in headwater and mid-elevation portions of the watersheds where streams had permanent flows, were unpolluted, and had reasonably intact channels and riparian zones. The more evidence of human disturbance, the more likely the stream was to be dominated by alien species, especially at lower elevations or in larger streams (Leidy 2007). Thus, heavily urbanized streams tended to support mainly small numbers of very tolerant alien fishes, if fish were present at all.

As indicated above, these streams flow mainly as the result of rainfall, including groundwater sources that allow them to be perennial. Urban runoff contributes some water as well, but mainly makes flows following rain events more extreme. This makes these streams and the fish assemblages they support highly susceptible to climate change, and many are likely to go dry during periods of drought without artificially enhanced flows (from reservoirs and ponds). As Leidy (2007) points out, conservation measures for these streams to counter effects of climate change are badly needed.

Section 6: Conclusions

The native fishes and aquatic ecosystems of California and the SFE region are already being stressed by many factors, from water diversions to pollution. If present trends continue, climate change will accelerate the loss of aquatic species and cause dramatic changes to the ecosystems that make California's waterways so distinctive. Changes in temperatures and flows will greatly reduce distribution and abundance of endemic fishes and expand distribution and abundance of alien fish species (Table 1). The native species suffering the most are likely to be the valuable salmon and trout, which require cold-water habitats, and estuarine-dependent species, such as delta smelt. As more native species become listed as threatened or endangered, conflicts over water allocation for fish versus other uses can only increase (Moyle et al. 2010; Hanak et al. 2011). Fish are presently being listed at the rate of one species per year, a rate which could increase, and extinction for multiple species is certain without dramatic action.

If we assume that the causes of global warming are not going to change dramatically in the next century, then we need to develop regional strategies that will conserve most native aquatic species that are likely to disappear otherwise. The goal of each regional strategy would not be to create a series of pristine reserves (which is simply not possible, given how much California has already changed) but to have waterways or watersheds managed on a philosophy of reconciliation (Rosenzweig 2003; Hanak et al. 2011). Reconciliation ecology assumes that humans will be part of the ecosystem, as participants and managers, but that the ecosystem will be managed to sustain as many of the native species and other desirable components as possible. Elements of a climate change adaptation strategy for the SFE region should include the following:

1. Recognize that rapid sea level rise is a reality and plan for it, rather than just letting it happen. Determine which areas affected by sea level rise are defensible (and worth defending) in their present state and which are not. For those that are not (e.g., many Delta islands, much of Suisun Marsh) find ways to manage sea level rise effects as a way to improve conditions for desirable species such as Chinook salmon, delta smelt, and splittail.

2. Manage coldwater pools in large reservoirs to favor native fishes. Most rivers in central California are regulated to some degree and most have reservoirs on them that stratify, with cold winter water on the bottom. For reservoirs behind dams such as Shasta or Friant (upper San Joaquin River), the coldwater pool should be regarded as water reserved for fish and the entire reservoir managed accordingly. The benefits of this cold water would extend downstream to the SFE, which is crucial rearing and migration area for anadromous fishes.

3. Improve land management practices along San Francisco Bay Area streams, with the goal of keeping them cooler and having more persistent summer flows. Leidy (2007) provides suggestions of ways to do this.

4. Conduct a climate change "triage" analysis to determine which fish (or other) species in the SFE region are likely to persist in numbers no matter what we do, which species require assistance to persist, and which species are likely to be extirpated no matter what actions we

take. Such an analysis should only be done in the context of a major research program, given that (for example) the physiological requirements of many native fishes are poorly understood.

5. Designate headwater streams and many mid-elevation streams as "climate change refuges" acquiring water rights and improving habitats, using funding from a surcharge on energy and water transactions. The idea is to identify good remaining examples of aquatic ecosystems that could potentially serve as refuges and invest in measures that would protect them from climate change effects as much as possible.

Table 1. Predicted Effects of Climate Change on Major Ecological Groups of Inland Fishes of California, with the Trend Reflecting Likely Impacts of Increases in Stream Temperatures and More Variable Flow Regimes in Streams, with No Special Conservation Measures Taken

Ecological Group	Temperature Tolerances (°C)	Abundance	Distribution	Examples
Coldwater resident species	< 20	Decline	Reduced	Rainbow trout, riffle sculpin
Anadromous species	< 18–20	Major decline, extinctions	Loss of southern populations	Chinook salmon, Pacific lamprey, green sturgeon
Native cool-water stream species	< 24	Decline	Upward shift in elevation where possible	Hardhead, tule perch, threespine stickleback
Widely distributed (tolerant) native species	< 28	Little change	Little change, some upward shifts in elevation	Sacramento pikeminnow, Sacramento sucker
Endemic species with limited distributions	Various	Major decline, extinctions	No change, unless extirpated	Red Hills roach, coho salmon
Alien warm-water species	< 35	Increase	Expansion	Largemouth bass, red shiner, common carp, western mosquitofish
Estuary-dependent species	< 22–24	Major declines, extinctions	No change, unless extirpated	Delta smelt, striped bass
Marine species	< 22	Shifts in species abundances	More southern CA species present in northern CA	English sole, rockfishes

Note: Basic ecological information and scientific names of example species can be found in Moyle (2002). Temperature tolerances reflect the general upward limit of optimal conditions for growth and reproduction, recognizing that tolerances can vary among populations and that each species has different tolerances.

References

Allan, J., and M. Castillo. 2007. *Stream ecology: Structure and function of running waters.* Dordrecht, Netherlands: Springer.

Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson, and R. Snyder. 2008. "Progress of incorporating climate change into management of California's water resources." *Climatic Change* **89**:91–108.

Bartholow, J. 2005. "Recent water temperature trends in the lower Klamath River, California." *North American Journal Fisheries Management* **25**:152–162.

Brown, L. R. 2000. "Fish communities and their associations with environmental variables, lower San Joaquin River drainage, California." *Environmental Biology of Fishes* **57**:251–269.

California Data Exchange Center (CDEC). 2008. Klamath River watershed historical precipitation and outflows. California Department of Water Resources. http://www.cdec.water.ca.gov.

California Department of Water Resources. 2001. *Comprehensive Review Suisun Marsh Monitoring Data 1985–1995.* California Department of Water Resources, Sacramento, California, USA.

Cayan, D., S. Kammerdiener, M. Dettinger, J. Caprio, and D. Peterson. 2001. "Changes in the onset of spring in the Western United States." *Bulletin of the American Meteorological Society* **82**:399–415.

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. *Climate change scenarios and sea level rise estimates for the California 2008 climate change scenarios assessment.* Draft Paper, California Energy Commission CEC-500-2009-014-D.

Cloern, J. E., K. A. Hieb, T. Jacobson, B. Sansó, E. Di Lorenzo, M. T. Stacey, J. L. Largier, W. Meiring, W. T. Peterson, T. M. Powell, M. Winder, and A. D. Jassby. 2010. "Biological communities in San Francisco Bay track largescale climate forcing over the North Pacific." *Geophysical Research Letters* 37: L21601–L21606.

Dettinger, M. D., and S. Culberson. 2008. "Internalizing climate change-scientific resource management and the climate change challenges." *San Francisco Estuary and Watershed Science.* http://escholarship.org/uc/item/64z013q3?query=Internalizing climate change.

Diffenbaugh, N. S., M. A. Snyder, and L. C. Sloan. 2004. "Could CO_2-induced land-cover feedbacks alter near-shore upwelling regimes?" *Proceedings of the National Academy of Sciences* **101**:27–32.

Eaton, J., and R. Scheller. 1996. "Effects of climate warming on fish thermal habitat in streams of the United States." *Limnology and Oceanography* **41**:1109–1115.

Feyrer, F., M. L. Nobriga, and T. R. Sommer. 2007. "Multidecal trends for three declining fish species: Habitat patterns and mechanisms in the San Francisco Estuary, California, USA." *Canadian Journal of Fisheries and Aquatic Sciences* **64**:723–734.

Grimaldo, L., A. R, Stewart, and W. Kimmerer. 2009. "Dietary segregation of pelagic and littoral fish assemblages in a highly modified tidal freshwater estuary." *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **1**:200–217.

Hamlet, A., P. Mote, M. Clark, and D. Lettenmaier. 2005. "Effects of temperature and precipitation variability on snowpack trends in the Western United States." *Journal of Climate* **18**:4545–4561.

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: PPIC. 482 pp.

Hayhoe, K., D. Cayan, C. Field, P. Frumhoff, E. Maurer, N. Miller, S. Moser, S. Schneider, K. Cahill, E. Cleland, L. Dale, R. Drapek, R. Hanemann, L. Kalkstein, J. Lenihan, C. Lunch, R. Neilson, S. Sheridan, and J. Verville. 2004. "Emissions pathways, climate change, and impacts on California." *Proceedings of the National Academy of Sciences* **34**:12,422–12,427.

Hieb, K., and K. Fleming. 1999. Summary. *In*: Orsi, James J., editor. *Report on the 1980–1995 Fish, Shrimp, and Crab Sampling in the San Francisco Estuary, California.* Technical Report 63. Sacramento, California: The Interagency Ecological Program for the Sacramento-San Joaquin Estuary. www.estuaryarchive.org/archive/orsi_1999.

Hundley, N. J. 2001. *The great thirst. Californians and water: A history.* Berkeley, California: University of California Press.

Intergovernmental Panel on Climate Change (IPCC). 2010. DRAFT guidance notes for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties. The IPCC Fifth Assessment Report. Geneva Switzerland.

Johnstone, J. A., and T. E Dawson. 2010. "Climatic context and ecological implications of summer fog decline in the coast redwood region." *Proceedings of the National Academy of Sciences* **107**: 4533–4538.

Kim, J. 2005. "A projection of the effects of the climate change induced by increasing CO_2 on extreme hydrologic events in the western U.S." *Climatic Change* **68**:153–168.

Knowles, N. 2010. Potential inundation due to rising sea levels in the San Francisco Bay Region. San Francisco Estuary and Watershed Science. http://escholarship.org/uc/search?entity=jmie_sfews;volume=8;issue=1.

Knowles, N., and D. R. Cayan. 2002. "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." *Geophysical Research Letters* **29**:1891–1895.

Knox, J., and F. Scheuring. 1991. "Global climate change and California: Potential impacts and responses." Berkeley, California: University of California Press.

Leidy, R. A. 2007. *Ecology, assemblage structure, distribution, and status of fishes in streams tributary to the San Francisco Estuary, California.* San Francisco Estuary Institute Contribution **530**: 1–194.

Leung, L., Y. Qian, X. Bian, W. Washington, J. Han, and J. Roads. 2004. "Mid-century ensemble regional climate change scenarios for the Western United States." *Climatic Change* **62**:75–113.

Lund, J., E. Hanak, W. Fleenor, W. Bennett, R. Howitt, J. Mount, and P. Moyle. 2007. *Envisioning futures for the Sacramento-San Joaquin Delta.* San Francisco: Public Policy Institute of California. 284 pp. www.ppic.org.

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, California: University of California Press.

Marchetti, M. P., and P. B. Moyle. 2001. "Effects of flow regime on fish assemblages in a regulated California stream." *Ecological Applications* **11**:530–539.

Marchetti, M. P., P. B. Moyle, and R. Levine. 2004. "Invasive species profiling: Exploring the characteristics of exotic fishes across invasion stages in California." *Freshwater Biology* **49**:646–661.

McCullough, D. 1999. *A review and synthesis of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon.* U.S. Environmental Protection Agency, Seattle. Washington.

Miller, N. L., K. E. Bashford, and E. Strem. 2003. "Potential impacts of climate change on California hydrology." *Journal of the American Water Resources Association* **39**:771–784.

Mount, J. F. 1995. *California rivers and streams: The conflict between fluvial process and land use.* Berkeley, California: University of California Press.

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

Moyle, P. B., P. K. Crain, K. Whitener, and J. F. Mount. 2003. "Alien fishes in natural streams: Fish distribution, assemblage structure, and conservation in the Cosumnes River, California, USA." *Environmental Biology of Fishes* 68:143–162.

Moyle, P. B. 2008. The future of fish in response to large-scale change in the San Francisco Estuary, California. Pages 357–374 *in* K. D. McLaughlin, editor. Mitigating Impacts of Natural Hazards on Fishery Ecosystems. American Fishery Society, Symposium 64, Bethesda, Maryland.

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 38 pp. www.ppic.org.

Moyle, P. B., P. K. Crain, K. Whitener, and J. F. Mount. 2003. "Alien fishes in natural streams: Fish distribution, assemblage structure, and conservation in the Cosumnes River, California, USA." *Environmental Biology of Fishes* **68**: 143–162.

Moyle., P. B., J. Hobbs, and T. O'Rear. *In press*. Tidal marsh fishes of the San Francisco Estuary *in* A. Palaima, ed. Ecology, conservation and restoration of tidal marshes: The San Francisco Estuary. Berkeley, California: University of California Press.

Moyle, P. B., J. A. Israel, and S. E. Purdy. 2008. Salmon, steelhead, and trout in California: Status of an emblematic fauna. UC Davis Center for Watershed Sciences. 316 pp. http://watershed.ucdavis.edu/pdf/SOS-Californias-Native-Fish-Crisis-Final-Report.pdf.

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* doi:10.1016/j.bicon.2011.06.002.

Moyle, P. B., J. R. Lund, W. A. Bennett, and W. E. Fleenor. 2010. "Habitat variability and complexity in the upper San Francisco Estuary." *San Francisco Estuary and Watershed Science* **8**:1–23.

Moyle, P. B. and M. P. Marchetti. 2006. "Predicting invasion success: Freshwater fishes in California as a model." *Bioscience* **56**:515–524.

Moyle, P. B., and J. E. Williams. 1990. "Biodiversity loss in the temperate zone: Decline of the native fish fauna of California." *Conservation Biology* **4**:275–284.

Moyle, P. B., R. M. Yoshiyama, J. E. Williams, and E. D. Wikramanayake. 1995. *Fish species of special concern of California.* California Department of Fish and Game, Sacramento, California. 2nd edition. 272 pp.

Nichols, F. H., J. E. Cloern, S. N. Luoma, and D. H. Peterson. 1986. "The modification of an estuary." *Science* **231**: 567–573.

O'Neal, K. 2002. *Effects of global warming on trout and salmon in U.S. streams.* Defenders of Wildlife, Washington D.C.

O'Rear, T. A., and P. B. Moyle. 2010. "Long-term and recent trends in fish and invertebrate populations of Suisun Marsh." *Interagency Ecological Program Newsletter* **23**:26–48

Preston, B. 2006. "Risk-based reanalysis of the effects of climate change on U.S. cold-water habitat." *Climatic Change* **76**:91–119.

Rosenzweig, M. L. 2003. *Win-win ecology: How the Earth's species can survive in the midst of human enterprise.* New York: Oxford University Press.

Stewart, I., D. Cayan, and M. Dettinger. 2004. "Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario." *Climactic Change* **62**:217–232.

Stewart, I., D. Cayan, and M. Dettinger. 2005. "Changes toward earlier streamflow timing across western North America." *Journal of Climate* **18**:1136–1155.

Suddeth, R., J. Mount, and J. R. Lund. 2010. "Levee decisions and sustainability for the Sacramento-San Joaquin Estuary." *San Francisco Estuary and Watershed Science* **8**:1–23.

Thompson, L. C., D. R. Purkey, M. I. Escobar, C. M. Mosser, and P. B. Moyle. *In press* Climate change adaptations to prevent loss of aquatic ecosystem services. Case study for Chinook salmon in California. *Journal of Water Resources Planning and Management.*

Van Kirk, R. W., and S. W. Naman. 2008. "Relative effects of climate and water use on base-flow trends in the lower Klamath basin." *Journal of the American Water Resources Association* **44**:1036–1052.

Wagner, R. W., M. Stacey, L. R. Brown, and M. Dettinger 2011. "Statistical models of temperature in the Sacramento–San Joaquin Delta under climate-change scenarios and ecological implications." *Estuaries and Coasts* 34:544–556. DOI 10.1007/s12237-010-9369-z.

Yoshiyama, R. M., and P. B. Moyle. 2010. Historical review of Eel River anadromous salmonids, with emphasis on Chinook salmon, coho salmon and steelhead. Center for Watershed Sciences, UC Davis, Working Paper: 129 pp. http://watershed.ucdavis.edu/library.html.