8

Suisun Marsh Today: Agents of Change

Stuart W. Siegel

Suisun Marsh has changed, is changing, and will continue to change. The principal subject of this book—the future of Suisun Marsh—is about looking forward with the intention of directing that change toward a positive outcome in the future. The problem, of course, is that beauty is in the eye of the beholder, so one person's positive outcomes can be another person's bad dreams. Therefore, debate and dialogue among those who care about the Marsh are vital to looking forward with intention. Decisions about the future of the Marsh must be well informed if they are to have positive and predictable outcomes. Previous chapters have described historical changes to the Marsh, the status of its present flora and fauna, and physical processes that control ecological functions. Those chapters provide the starting point for planning the Marsh's future.

This chapter summarizes key agents of change: the diverse factors acting upon Suisun Marsh, their mechanisms, and further changes they are likely to bring about. We know more about some of these than we do others, resulting in varying degrees of speculation and uncertainty. To develop scenarios for alternative futures of the Marsh (see chapter 9), we need to understand the separate and combined effects of the following agents of change:

1. climate change
2. reduced sediment supply
3. invasive alien species
4. warmer temperatures
5. earthquakes and seismic risk
6. large-scale tidal marsh restoration
7. watershed land-use change
8. Delta water operations
9. salinity management
10. managed wetlands operations
11. management of endangered species
12. public policy and institutions

CLIMATE CHANGE

Climate change is anticipated to affect Suisun Marsh physically through three main mechanisms: sea-level rise, salinity intrusion, and storm frequency and intensity. Projections for all three mechanisms carry uncertainty, which increases as conditions further in the future are considered (Cayan et al. 2008, 2009). Projections are sensitive to complex atmospheric physical and chemical processes and to future human action or inaction to mitigate climate change.

Sea-level Rise

Sea-level rise is not new. Since 1850, mean sea level at the Golden Gate has risen approximately 0.25 m (0.8 ft) (see chapter 3). Projections for future climate-change-induced sea-level rise predict that the rate of rise will increase, and that the total rise will be 0.3–0.45 m (1–1.5 ft) by 2050 and 1.4 m (4.6 ft) by 2100 (Bay Conservation and Development Commission 2011; Bay Delta Conservation Plan [BDCP] 2013). Recent work comparing measured to projected sea-level rise suggests that the actual rise has been higher than predicted, which suggests a low bias in projections by the Intergovernmental Panel on Climate Change (IPCC) on which the local projections are based (Intergovernmental Panel on Climate Change 2007; Cayan et al. 2012; National Research Council 2012; Rahmstorf et al. 2012). Sea-level rise will continue beyond 2100 even if there is a drastic change in human interactions with the planet.

A key effect of sea-level rise is that the water surface will reach any given elevation with increased frequency, from daily low tides to extreme tide events, driving the 100-year tidal floodplain ever higher (figure 8.1). For example, what is today's 100-year flood stage could be the 1- or 5-year flood stage in the future.

For Suisun Marsh, sea-level rise can manifest its effects in many ways. First, it exacerbates problems created by subsidence. If land surface elevations are too low when areas are flooded, disturbance from wind-wave regimes will prevent sites from developing into emergent marsh. As sea level rises, additional flooded low-lying lands will be converted to open water rather than to emergent marsh (see map 9 in color insert and associated chart).

Higher projected salinities would add to this challenge, given plants' physiological limits to growth in saline intertidal waters (see chapters 3 and 4). Second, managed wetlands will face more frequent dike overtopping and be less able to drain by gravity. Third, tidal-marsh vegetation community succession will take place. Fourth, greater erosion along slough banks will affect dikes, increasing flooding of diked marshlands. Fifth, there will be a greater flood risk in surrounding communities and along Highways 12 and 680, and the Fairfield–Suisun City Wastewater Treatment Plant will have greater difficulty utilizing gravity drainage for its discharges.

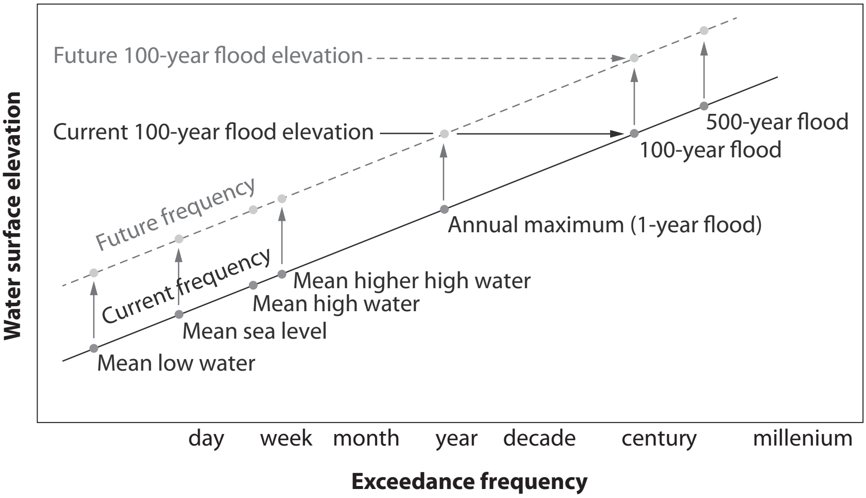

FIGURE 8.1. Diagram of tidal-water surface-elevation exceedance frequency today and with sea-level rise. *Exceedance frequency* is defined as how often a given event occurs (e.g., mean high water-surface elevation occurs once or twice a day, whereas the one-year flood event happens once a year) (source: Heberger et al. 2009).

Salinity Regime

Continuing sea-level rise will bring more saline ocean waters through the Golden Gate (chapter 3), resulting in higher Suisun Marsh salinities. Fall salinity increases may be most pronounced because fall is the driest time of year, and fall outflows of the Sacramento–San Joaquin Delta are unlikely to be increased by water operations to offset increased oceanic salinity. During winter and spring, shorter periods of low salinity are anticipated because precipitation will fall more as rain than as snow and arrive in fewer, more intense storms. With an overall increase in salinity, the Marsh will experience less spatial variability in salinity and could experience less intra- and inter-annual variability. If climate change creates more large flood events, however, high intra-annual variability could occur more often than today.

Increased salinity in Suisun Marsh will have several ramifications. Diked managed wetlands, which commonly are managed for low-salinity conditions, will have greater difficulty achieving those low salinities. Increased salinity will result in a plant community shift to more salt-tolerant species and reduced foraging habitat for most ducks and geese. A similar shift toward more salt-tolerant species would also occur in all other biotic communities, including aquatic communities (chapter 7). These shifts will ripple upward through the food web, altering the fish, wildlife, invertebrate, and plant species that the Marsh will be able to support. Key tidal salt-marsh species, such as salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsoletus*), may benefit because conditions are likely to shift more toward the center of these species' ecological requirements.

Storm Frequency and Intensity

California is projected to retain its Mediterranean climate of cool and wet winters and warm and dry summers, including high variability in interannual precipitation amounts (Cloern et al. 2011). However, total precipitation (rain and snow combined) is generally projected to decline, or at least not increase, as is the total number of storms. While storms will likely be fewer, storm intensities are projected to increase, as are frequencies of extreme events (Cloern et al. 2011). Projections also suggest longer storm surges of salt water from the ocean (Cayan et al. 2008, 2009, 2012; Heberger et al. 2009). Even without climate change, storms that are orders of magnitude larger than ones experienced in recent decades, akin to the storm of 1861–62 when it rained for 43 days, will likely turn the Central Valley into a vast lake and make San Francisco Bay fresh; such storms have historically occurred once every 100–200 years (Dettinger and Ingram 2013).

For Suisun Marsh, the primary effects of these events would be increased flooding, by both salt water and fresh water, more levee damage, and greater intra-annual salinity variability. Longer and higher storm surges and more intense storm events will result in greater likelihood of overtopped dikes and of damage to those levees. To maintain the status quo, greater efforts to protect against, respond to, and repair storm damage will be needed, exacting an economic as well as an environmental cost. Eventually, the fight to maintain diked wetlands may be abandoned in many areas, resulting in tidal wetlands and open water (chapter 9).

REDUCED SEDIMENT SUPPLY

Sediment transport, supply, and deposition in Suisun Marsh have undergone major changes in the past 150 years (chapter 3). The first major change took place following the discovery of gold in the Sierra Nevada in 1848 with the commencement of hydraulic placer mining. This mineral extraction process released billions of cubic meters of sediment into the rivers and San Francisco Estuary, including Suisun Marsh—an estimated ninefold increase over premining levels (Gilbert 1917). Schoellhamer (2011) found that this pulse of sediment has now passed through its lowest estuarine position, San Pablo Bay, so projections today are of net sediment loss in the shallow bays of the Estuary. Although the primary pulse of mining sediment has moved through the Marsh system, remnant terrace deposits with some potential for erosion remain in many watersheds (Meade 1982; James 1991). While recent estimates of river sediment supply to the Delta are substantially higher than Gilbert's (1917) premining estimate, sediments have nevertheless continued to decrease since the mid-1950s, indicating ultimate exhaustion of remnant mining-derived deposits (Wright and Schoellhamer 2005).

The next major change in sediment supply resulted from the construction, beginning in the 1930s, of a vast network of dams and reservoirs for the Central Valley Project and State Water Project, alongside numerous smaller dams, throughout the Central Valley watershed. These dams collectively have trapped sediments in the upper watersheds. Although channels immediately downstream from the dams eroded to new equilibria (Porterfield et al. 1978), providing a short-term sediment source, the long-term effect has been to further decrease sediment supply to the Estuary (Williams and Wolman 1984). Dams also affected flow regimes, typically reducing high flows in most years and increasing low flows (Singer 2007), which together have the effect of reducing downstream sediment supply.

The reduction of hydraulic-mining sediment transport and construction of dams led to a 50% decrease in sediment supply from the Sacramento River between 1957 and 2004 (Wright and Schoellhamer 2004). Ganju and Schoellhamer (2010) suggested that sediment exchange between embayments of the San Francisco Estuary may become more significant sources of sediment as watershed sediment loads continue to decrease. The ability of those embayments to resuspend bottom sediments, however, is expected to decrease with increasing depth from sea-level rise (Schoellhamer 2011).

Schoellhamer (2011) provides evidence that the Estuary crossed a sediment supply threshold in 1999 when erodible sediment on its bottom became depleted. This sediment historically was resupplied by storm contributions from local watersheds and from Central Valley discharges flowing through the Delta, and then resuspended by tidal and wind-wave currents. The decline in external sediment inputs is expected to result in lower rates of sediment accretion in the Marsh. Increased water depths in restored wetlands due to sea-level rise increases the potential for wind-wave resuspension of deposited sediment. These two changes can preclude restoration sites from accreting sediment and produce low sedimentation rates.

This reduction of sediment supplies particularly affects estuarine marsh restoration sites. Most land suited for tidal-marsh restoration is former tidal marshland that subsided as a result of land-use practices. The subsidence reversal essential to reestablishing vegetated tidal marshlands and their ecological functions can come about through two mechanisms: accumulation of sediment deposited from the tidal water column, and accumulation of plant organic matter as both above- and belowground biomass. The reduced supply of suspended sediment for Suisun Marsh leaves organic-matter accumulation as a more critical mechanism for reversing subsidence. Plant biomass production is lower for saline-tolerant species, so shifts of the plant community to lower-productivity species in response to sea-level rise will lead to lower rates of organic-matter accumulation. The ultimate result is a much slower rate of subsidence reversal. Sea-level rise will exacerbate this problem. For more subsided restoration sites, where wind-wave resuspension outweighs sediment retention, these factors could act to keep them permanent open-water habitats. Active efforts to rebuild plant biomass prior to restoring tidal action may become an important design feature for restoration, especially for the more subsided sites.

Another effect of reduced sediment loads is increased water clarity and, thus, deeper light penetration into the water column. More light equates to a larger photic zone, which enables greater total phytoplankton productivity, potentially increasing support for aquatic food webs that lead to fish, assuming that the increased productivity is not all consumed by benthic bivalves. Greater light penetration can also allow increased growth of submerged aquatic vegetation, such as sago pondweed, benefiting waterfowl in shallow bays and sloughs (chapter 4).

INVASIVE ALIEN SPECIES

As shown in chapters 4, 6, and 7, Suisun Marsh now supports a large number of alien species; additional species are continually invading. Changes in hydrologic conditions will tend to favor already established alien species, especially those preferring estuarine or marine habitats. Predicting future invasions is possible to some extent (e.g., Lund et al. 2007), but there is a strong unpredictable component due to the rapid and continued movement of humans and commerce around the globe. The most definitive statement that can be made about future invasions is that they will occur unless stringent prevention measures are in place, and human intervention to avoid or control invasions may work in some cases but not in others.

Once a species invades the Marsh, its abundance and potential harmful effects depend on its ability to adapt to variable conditions. Wetland vegetation is sensitive to salinity during late winter–early spring germination periods, as evidenced by past periods of salinity changes (Clark and Patterson 1985; Clark 1986; Beare and Zedler 1987). Decreases in tidal-marsh salinity during seedling establishment can increase the spread of invasive plant species, such as the alien perennial pepperweed (*Lepidium latifolium*). Under normal conditions, salinity variation generally promotes dynamic plant communities by influencing interactions of dominant native perennial species and annuals or short-lived perennials that have adapted to varied levels of soil salinity (Callaway et al. 1990; Allison 1992). However, well-established invaders also can persist through less-than-favorable high-salinity conditions (Zedler 1983). Salinity regime also exerts an important influence on the abundance of alien invertebrates such as the overbite clam (*Corbula amurensis*) and four species of alien "jellyfish" (Hydrozoa) (Wintzer et al. 2011), as well as affecting the abundance of various fishes (chapter 7).

A persistent issue for restoration is the widespread extent of dominant alien plants (chapter 4) believed to interfere with desired ecological functions that are already established within a highly salinity-regulated marsh system. Such species are expected to be a continued problem in restoration areas, especially when established nearby. Successive years of high salinity stress are hypothesized to be an important factor controlling the spread and establishment of invasive plant species (Suisun Ecological Workgroup 2001).

In aquatic habitats of Suisun Marsh, biotic communities are mixtures of native and alien fishes and invertebrates, with little evidence of native species being driven to extinction by alien invaders. In fact, Matern and Brown (2005) could find little evidence that the invasion of shimofuri goby had harmful effects on any native species, despite its high abundance in the Marsh. In general, higher salinities also tend to favor native fishes (chapter 7). By contrast, the invasion of overbite clam caused major changes to food webs in the Estuary, including lower Suisun Marsh (Kimmerer et al. 1994; Feyrer et al. 2003), and its failure to invade the upper Marsh has increased the value of the Marsh as a refuge for native species (chapter 7).

Overall, Suisun Marsh biotic communities will continue to be mixtures of native and alien species. A basic management conundrum is how to favor desirable native species in the presence of aggressive invasive species, given that eradication of alien species is unlikely. Climate change is likely to create conditions more favorable to many alien species, as well as different assemblages of native species, requiring new and creative management strategies.

WARMER AIR AND SURFACE-WATER TEMPERATURES

Under virtually all realistic climate scenarios, the water in the Estuary and Marsh will have mean annual temperatures several degrees warmer than they are today. Cloern et al. (2011) projected the effects of climate change on the Delta using two very different models from the IPCC (2007) report. Scenario B1 is an optimistic scenario that assumes major reduction in greenhouse gases by 2050. Scenario A1 assumes continual increase in greenhouse gases, which is presumably more realistic but not necessarily the most extreme scenario possible. Under the B1 scenario, mean annual water temperatures would rise 1–2°C (to around 18°C) and the number of days when temperatures exceed 25°C would rise to 15–20 days per year. Under the A2 scenario, mean annual temperatures would rise 3–4°C (to around 20°C), with 80–100 days per year 25°C or above. Under A2, temperatures would keep rising sharply (Cloern et al. 2011). Although the moderating effect of rising sea level, wind, and ocean fog on temperatures in the Marsh is uncertain, temperatures are likely to rise to some extent, regardless. This means that many organisms that require cool water, such as delta smelt, will likely find the Marsh increasingly inhospitable from a temperature perspective.

EARTHQUAKES AND SEISMIC RISK

Suisun Marsh is underlain by a small number of seismic faults, located mostly around the margins of the Marsh (Graymer et al. 2002). Located along the western margin of the Marsh, the Green Valley fault, part of the Concord–Green Valley fault system, is the dominant mapped fault (Graymer et al. 2002) and appears to be the most active. The last large earthquake on this fault occurred 200–500 years ago, but a magnitude 3.2 earthquake occurred on October 8, 2012 (U.S. Geological Survey 2012), indicating that the fault is active. It is possible, even likely, that an earthquake large enough to shake down dikes in the Marsh will occur in the next 100 years, increasing the vulnerability of marshlands to sea-level rise.

LARGE-SCALE TIDAL MARSH RESTORATION

Large-scale tidal marsh restoration for Suisun Marsh in the near future seems increasingly likely. It is called for in the Suisun Marsh Plan (U.S. Bureau of Reclamation [USBR] et al. 2011), the BDCP, the Delta Plan, the Ecosystem Restoration Program (ERP) Stage 2 Conservation Strategy, the U.S. Fish and Wildlife Service (USFWS) San Francisco Estuary Tidal Marsh Recovery Plan, and the USFWS Delta Smelt Biological Opinion for water-project operations. The 2000 CALFED Record of Decision identified Suisun Marsh restoration to be in the range of 20 to 28 km^2 (5,000 to 7,000 acres). In the prior year, the Baylands Habitat Goals Report recommended 70 to 90 km^2 (17,000 to 22,000 acres). The Suisun Marsh Plan calls for the CALFED Record of Decision target, and BDCP and the Delta Plan may call for greater area.

Effects of Restoration

The primary effect of these proposed restoration projects, beyond benefits to native species, will be to alter tidal hydrodynamics within Suisun Marsh and beyond, by redirecting flow patterns and absorbing estuarine tidal energy (see chapter 3). Hydrodynamic modeling for the Suisun Marsh Plan has demonstrated that restoring tidal action to large areas of subsided lands absorbs significant tidal energy and reduces tidal range in nearby areas. The models suggest that mean low water may be up to 0.5 m higher than it is with the current channel configuration (USBR et al. 2011). Raising the elevation of low tides makes intertidal and subtidal lands lower in relation to the tides. The exact magnitude of this effect will depend on where tidal marsh restoration efforts are located. Areas that are less subsided will see less of an effect and will recover faster. As restoration sites fill in through mineral sedimentation and plant-matter accumulation, their tidal prisms will decrease and the effects of large-scale restoration on tidal ranges will diminish.

Large-scale tidal marsh restoration efforts can also have a variety of other effects, positive and negative. For example, they can promote invasive species, alter waterfowl distribution, and alter other ecosystem functions that support both resident and migratory species. Restoration can also promote the recovery of a large range of listed species. But changes caused by restoration projects in the Marsh will also be affected by large-scale changes to the Delta, such as flooding of subsided islands. These changes will absorb estuarine tidal energy and alter tidal ranges in the Marsh, the magnitude of effects depending on the location and timing of the changes. Together, the scale of Delta tidal island flooding and marsh restoration projects could be huge—in the many tens of thousands of acres. However, the role of the Marsh in this change will depend on the extent, timing, and geography of Delta restoration actions.

Regardless of Delta–Marsh interactions, wetland restoration projects will take considerable time to produce noticeable results. Tidal marsh restoration is an evolutionary process. Restoration sites take years to evolve from conditions on the day of a levee breach to a future "quasi-equilibrium" high marsh roughly akin to those on Brown's Island or Rush Ranch. In those intervening years, conditions typically change gradually, as do the associated ecological functions that a restoration site provides. Key step-changes can occur when process thresholds are crossed, such as when sediment accretion raises site elevations to heights where emergent vegetation can colonize. These complexities show why potential modifications to the Marsh should be placed in a comprehensive ecological framework that allows for a more nuanced approach to large-scale restoration.

Conceptual Models

A good way to understand factors that affect tidal marsh restoration is to develop conceptual models of potential interactions among factors. The initial conditions in the models presented here reflect baseline site elevation, substrate characteristics, and the composition of emergent vegetation (Siegel et al. 2010). Once diked lands are opened to tidal action, the many physical and biological processes that control site evolution take over. Ecological functions are tied very strongly to the progress of a restoration site along this evolutionary trajectory (Siegel et al. 2010). Figure 8.2 shows the relationship between Suisun Marsh elevation and inundation regime, which exerts a major influence over all aspects of site ecology.

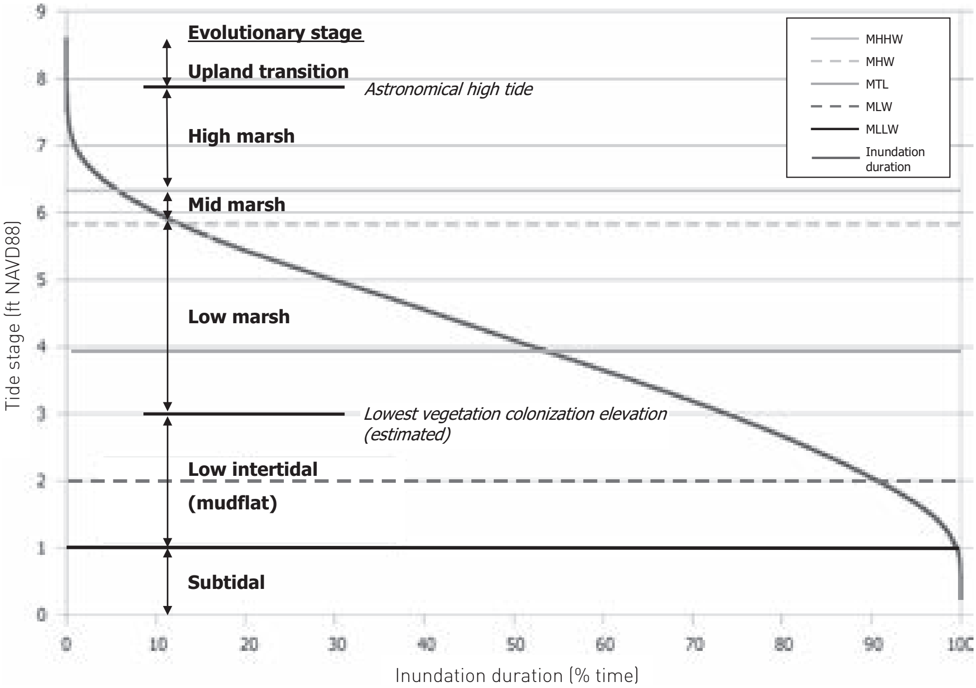

FIGURE 8.2. Inundation regime, marsh elevation, and habitat trajectories. Inundation duration (cumulative percentage of total time of submergence) is shown as a function of tide stage (curved line). When applied to tidal restoration, the elevation of the initial restoration site dictates the extent of tidal submergence, which controls habitat types and ecological functions. The lowest tidal elevation of emergent vegetation is driven by salinity and hydroperiod and is lower for freshwater species. In the Marsh, the lowest elevation of vegetated tidal marsh may extend a little below mean tide level. As a restoration site regains elevation through sediment and biomass accumulation, its vegetation communities, amounts of open water vs. vegetation, and ecological functions will shift upward through the habitat stages (subtidal to low intertidal to low marsh, etc.) (source: Siegel et al. 2010).

The rate of evolution is controlled predominantly by the relative influences and magnitudes of the four major drivers of restoration outcome: initial elevation (figure 8.2), hydrodynamic energy (chapter 3), sediment supply (chapter 3), and salinity and its associated control of vegetation community composition (chapter 4). Table 8.1 summarizes the directionality that each of these four drivers exerts upon the evolution of tidal marsh restoration.

Figure 8.3 illustrates processes that affect the rate at which tidal marsh restoration sites evolve toward high-elevation marsh. The interactions of these processes,

TABLE 8.1 Drivers of the rate (faster or slower) at which tidal marsh restoration evolves.

Driver	High magnitude	Low magnitude
Sediment supply	More sediment = faster	Less sediment = slower
Hydrodynamic energy	More energy = slower	Less energy = faster
Initial elevation	Higher elevation = faster	Lower elevation = slower
Salinity and vegetation	Higher salinity = slower	Lower salinity = faster

and the resulting rates of marsh accretion, control the range of ecological functions provided by restoration efforts. Figure 8.3 illustrates the general relationships among the many physical and biological processes and characteristics and the ecological functions provided by tidal marshlands. Together these conceptual models inform how restoration efforts will evolve as geomorphic elements of Suisun Marsh and how they will provide a range of ecological functions.

WATERSHED LAND-USE CHANGE

Growth of Fairfield and Suisun City continues, as does development on unincorporated county lands to the west and north of Suisun Marsh, converting open space, abandoned industrial sites, and agricultural lands to urban and industrial uses.

The primary effects of local land-use change are increases in impervious surfaces leading to greater storm-water runoff that drains untreated to Suisun Marsh, an increase in treated wastewater discharge, and a change in types and amounts of nonpoint-source contaminants. In addition, more residences located near the Marsh increase the demand for mosquito control, which can be accomplished through water management in the diked managed wetlands, hydrologic modifications in the tidal marshes, and treatment with approved chemicals—all of which have ecological implications.

Farther upstream in the watershed are agricultural and open lands, including annual and perennial crops and cattle grazing. The main changes in these upstream land uses will likely be in the type, quantity, and timing of fertilizer, herbicide, fungicide, and insecticide applications. These changes will bring increased volumes of treated wastewater discharge from the Fairfield–Suisun City Wastewater Treatment Plant, adjacent to the northwest Marsh. That facility operates part of the year without discharge to the Marsh, via field irrigation to support cattle feed. Additionally, the facility is permitted to discharge up to 16 million gallons per day and has infrastructure to discharge tertiary-treated effluent into three diked managed wetlands and into Boynton and Peytonia sloughs. The cumulative consequences of these land-use changes include increased loads of a wide range of nonpoint-source pollutants and wastewater constituents, small

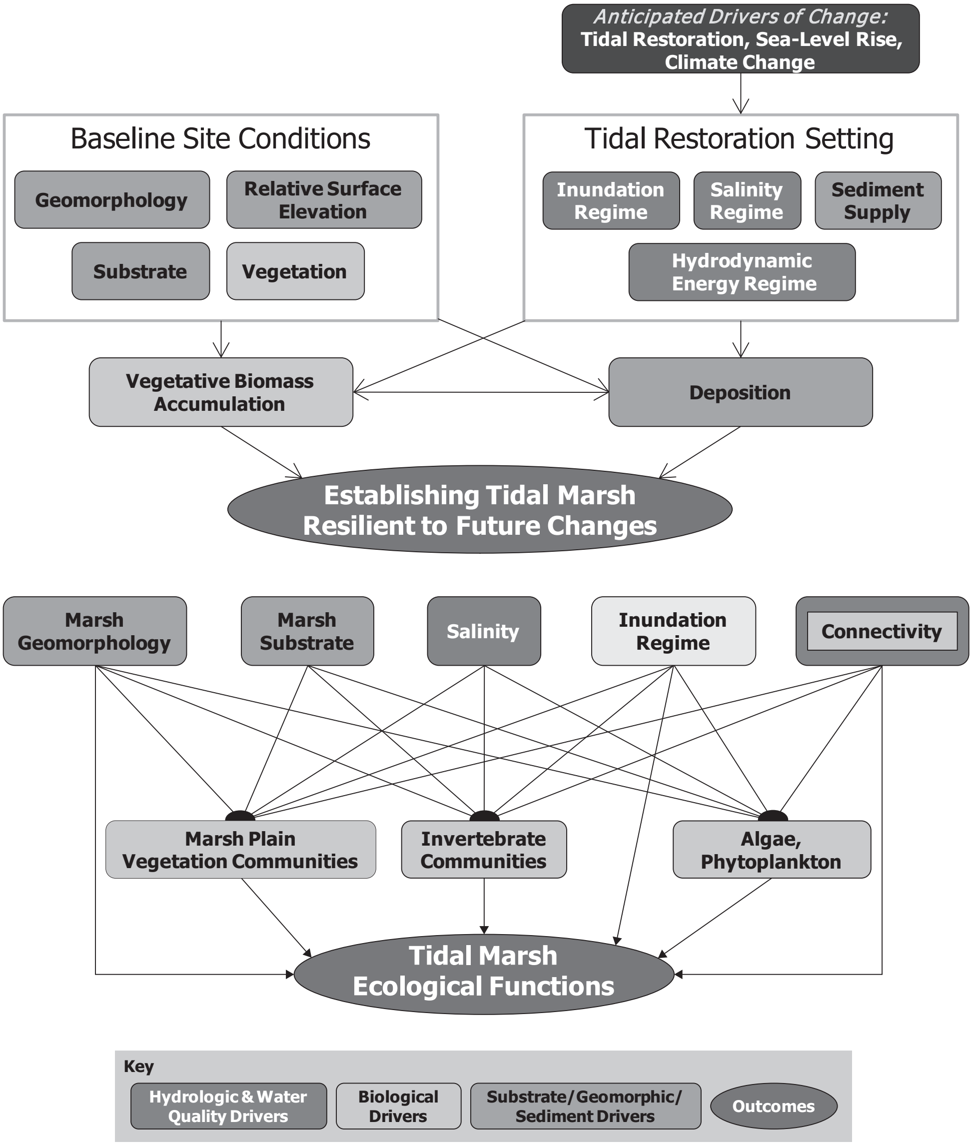

FIGURE 8.3. Conceptual models. (Top) Factors influencing tidal marsh restoration. Where a site "starts" (baseline conditions) and its position in relation to physical and biological processes (restoration setting) largely control how restoration progresses toward higher-elevation tidal marsh and may maintain functions as future changes arrive. (Bottom) Factors influencing tidal-marsh ecological functions. Physical processes and connectivity (upper boxes) control the biology (middle boxes) that yield target tidal-marsh ecological functions (bottom box). (Siegel et al. 2010).

increases in dry-season runoff from landscape irrigation, and loss of adjacent open habitats used by a variety of wildlife species.

DELTA WATER OPERATIONS

Water diversions from the Delta and its inflowing rivers cause changes in the complex flow dynamics in the Delta and Suisun Marsh that affect migration and movement of fish and other aquatic organisms, limit access to suitable habitats, and alter water quality. Together, the state and federal export facilities in the south Delta pump approximately 7.4 billion m^3 (6 million acre-feet) of water annually, and at times effectively reverse flows in the Old and Middle rivers, two major outflow channels in the south Delta. Other water diversions and consumptive water use within the Delta (over 2,000 diversions) use an additional 2.1 billion m^3 (1.7 million acre-feet) (Bay Institute 1998; Herren and Kawasaki 2001; Healey et al. 2008). Variability in flow regime and seasonal flooding were historically important drivers of ecosystem structure and processes in the Delta and the Marsh. Native plant and animal species evolved under flow regimes of high inter- and intra-annual variability that differed strongly from the current managed regime. Water storage and flow control have dampened such variability across seasons and years, which has greatly changed estuarine hydrodynamics, circulation patterns, and nutrient exchanges and has negatively affected resident species adapted to this natural variability (Moyle et al. 2010).

As a result of the severe ecological impacts that have resulted from large-scale water diversions and replumbing of the Delta, three key efforts aim to remedy these conflicts: the BDCP, the Delta Plan, and revisions to flow criteria that are part of the State Water Resources Control Board's water-rights agreements. These efforts have numerous political and scientific complexities and are unlikely to result in dramatic changes to existing Delta outflow regimes in the short term. However, as these regulatory efforts mature into projects that are implemented on the ground, the status quo could very well change. The stated intent of these efforts, as embodied in the Delta Reform Act of 2009, is to both provide a reliable water supply and restore the ecological integrity of the Delta, in which Suisun Marsh is often included.

The mostly likely changes to water operations will be in the magnitude, duration, and timing of Delta outflow, a major driver of physical processes and ecological functions in the Marsh (see chapter 3). These changes can affect vegetation community composition in the tidal marsh, occurrence and control of invasive species, aquatic food-web productivity, operations of diked managed wetlands, water-quality suitability of the Marsh for fish and aquatic organisms, sediment supply, and, consequently, the ability of ecological restoration activities to yield benefits to listed species and natural communities.

SALINITY MANAGEMENT

Salinity management within Suisun Marsh (described in chapter 3) is predicated on the maintenance of primarily freshwater conditions during winter and spring to facilitate managed duck hunting operations. Management is achieved by managing Delta outflows, operating salinity management infrastructure (especially large tidal gates located in Montezuma Slough), and controlling water operations in individual managed wetlands. Salinity will change in the Marsh as (1) Delta water operations introduce a new flow regime; (2) sea-level rise brings oceanic waters farther up the Estuary; (3) tidal marsh restoration alters hydrodynamics; and (4) flooded islands, tidal marsh restoration, and other changes in the Delta alter hydrodynamics. The future component most difficult to predict is human response to these changes. Will Suisun Marsh's salinity management infrastructure continue to be operated to maintain current conditions? Will new regimes be established as these changes come into play? Changes in magnitude and timing of salinity regimes, and associated human responses, will likely determine the magnitude of subsequent ecological change observed in existing and restored tidal marshes, in tidal aquatic ecosystems, and in associated species and natural communities that use these ecosystems (see chapter 3).

MANAGED WETLANDS OPERATIONS

The Suisun Marsh Plan (USBR et al. 2011) prescribes a range of actions for managing Suisun Marsh over the next 30 years. A majority of these actions fall into two categories: managed wetland operations and tidal marsh restoration. The plan calls for restoration of 20–28 km^2 (5,000–7,000 acres) of diked lands to tidal marsh; enhancement of 160–200 km^2 (40,000–50,000 acres) of diked, managed wetlands through improving interior water circulation and exterior water exchange; and allowing a return to tidal slough dredging for sediment to maintain diked marsh levees. These actions, upon receipt of all necessary regulatory authorizations, are designed to allow for a continuation of diked wetlands management over a 30-year period, consistent with operations and waterfowl habitat objectives in place for the past several decades. Duck club managers assume that these actions will take place, allowing continuation of the status quo for duck club marshland management (chapter 5).

Diked wetlands in Suisun Marsh are managed mostly to facilitate production of resident waterfowl and to attract and support migratory waterfowl for hunting; thus, they are managed as seasonally inundated, nontidal wetlands. Nevertheless, diked wetlands also provide a range of habitats that benefit many desirable native species, contributing greatly to diversity and ecological function. For example, several areas, totaling 10 km^2 (2,500 acres), are managed explicitly to provide habitat for the federally protected salt marsh harvest mouse (chapter 6).

Unfortunately, management of current diked wetlands also has adverse effects. Drying of seasonal wetlands causes peat soils to oxidize, resulting in land subsidence. Soil oxidation also produces carbon dioxide, contributing to greenhouse gas emissions. Ongoing subsidence increases the difficulty of managed wetlands operations because it makes gravity drainage less effective. It also increases the difficulty of restoration by increasing the need for subsidence reversal. Prior to the 1990s, spoils from dredging of tidal sloughs were used for levee maintenance. When regulations to protect endangered fishes prohibited this dredging, many managed wetlands borrowed soil internally in large quantities in order to maintain their levees. This practice has greatly lowered internal elevations. Diked wetlands also modify wetland geomorphology in ways that are designed to benefit their management but may make subsequent tidal marsh restoration more difficult. Seasonal wetland management in portions of Suisun Marsh also causes depletion of dissolved oxygen in sloughs that receive drainage water from the diked marshes, through the anoxic decomposition of plant matter and soil carbon. These same conditions also produce methylmercury (Siegel et al. 2011). Low-dissolved-oxygen events most commonly occur during “fall flood-up,” when the wetlands shift from dry to saturated conditions, and to some degree in late winter during flood-and-drain cycles to leach salt from soils. In the smaller sloughs, these discharges limit habitat for many aquatic species and, in severe instances, result in fish kills. Methylmercury, a neurotoxin, can accumulate in the aquatic food web (Alpers et al. 2008) and result in human exposure through fish consumption. Suisun Marsh is one of many locations in California with posted public health warnings about methylmercury and fish consumption. The ecotoxicological effects of methylmercury exposure are less clearly understood (Alpers et al. 2008).

Ongoing managed wetlands operations thus present several consequences for the future of Suisun Marsh. Benefits to waterfowl are high. However, management for waterfowl needs to be more compatible with reducing or stopping soil subsidence, with maintaining good water quality in tidal sloughs that support diverse fish populations, and with decreasing creation of methylmercury. The most challenging effects of ongoing managed wetlands operation are subsidence and soil salt leaching. Subsidence will, over time and in combination with sea-level rise, create less effective gravity drainage and increase the need for pumps. Soil salt leaching, if it continues its reliance on low-salinity applied water, will become less practicable as surface water salinities increase with sea-level rise and, perhaps, with changes to Delta water operations. Shifts in the vegetation community to more salt-tolerant plant species will also result. Thus, continuation of current management practices will ultimately lead to less desirable conditions for waterfowl in diked wetlands.

MANAGEMENT OF ENDANGERED SPECIES

Suisun Marsh has a fairly long history of accommodating species listed under state and federal endangered species acts (ESAs) (chapters 6 and 7). Key ESA drivers of landscape-scale management have included salt marsh harvest mouse, California clapper rail, delta smelt, and salmonids and other fishes; several other species, including some plants, are being considered.

Approximately 10 km^2 (2,500 acres) of diked wetlands in the Marsh are geared toward recovery of the salt marsh harvest mouse. Were these lands to be considered for tidal marsh restoration, their mouse habitat function would have to be reestablished elsewhere in the Marsh. Importantly, the Marsh is on the eastern fringe of this species' range. Thus, because habitat quality would be marginal under natural conditions, most conservation is done on diked rather than tidal marsh, where more suitable conditions can be carefully maintained.

Protections for resident and migratory fishes have been major drivers of fish-screen installation, diversion restrictions on diked wetlands, and the cessation of slough dredging for diked wetland levee maintenance. The Suisun Marsh Plan, when fully implemented, will allow slough dredging for levee maintenance, thereby reducing or eliminating degradation of wetland interiors caused by large-scale borrowing of soils from island interiors. Recovery actions for listed fish species can support overall ecosystem restoration and conservation, as long as efforts are not focused solely on the listed species, but instead on ecosystem functions that support a broad spectrum of wildlife. Suisun Marsh is well suited to this purpose because it contains so many manageable features compared with other locations in the Estuary and, especially, the Delta.

PUBLIC POLICY AND INSTITUTIONS

This final section examines the current and proposed public policy arrangements that do or will govern changes in Suisun Marsh management, and how they support or hinder effective change.

Water-Project Biological Opinions

In 2008 and 2009, the USFWS and the National Marine Fisheries Service issued Biological Opinions under the federal ESA for joint operation of the State Water Project and federal Central Valley Project. In 2009, the California Department of Fish and Game (now Department of Fish and Wildlife) issued an Incidental Take Permit under the California ESA for the water projects. Though these actions require a total of 32.3 km^2 (8,000 acres) of tidal marsh restoration in the Delta and Suisun Marsh, only the California Department of Fish and Wildlife's requirement identifies 3.2 km^2 (800 acres) specific to the low-salinity zone of the Estuary. These requirements, all directed to listed fish species (delta smelt, salmon, green sturgeon, and longfin smelt), are intended to "restore tidal and associated subtidal habitats." An obvious target for these restoration efforts is Suisun Marsh, with the likelihood of considerable financial resources being brought to Marsh projects as a consequence. In the near term, fulfillment of these ESA requirements will provide the dominant funding mechanism and implementing entities for tidal marsh restoration in Suisun Marsh.

Bay Delta Conservation Plan

Currently under development, the BDCP would provide the environmental conservation measures associated with issuance of 50-year permits for Delta water exports. Suisun Marsh is identified as one of several geographic "restoration opportunity areas" (BDCP 2013). Similar to the Biological Opinions, the BDCP allows for tidal emergent marsh and tidal aquatic restoration. Although BDCP has a strong fish focus, it also provides some attention to the broader ecosystem. It would support restoration in the Marsh but does not bring financial resources to the table at this time, because its current financing plan relies on future voter-approved general obligation bonds for which the likelihood of passage is unpromising. Were those bonds passed, the entities that would apply these restoration funds are not yet clear, but they may include the Delta Conservancy, Department of Water Resources, Department of Fish and Wildlife, and/or some other as-yet undetermined entity.

Suisun Marsh Plan and Suisun Marsh Preservation Agreement

The Suisun Marsh Habitat Management, Preservation, and Restoration Plan (USBR et al. 2011) provides the current policy framework and environmental, ESA and regulatory compliance for long-term managed wetlands operations and implementation of the regulatory obligations of the state and federal water projects in Suisun Marsh that are incorporated into the Suisun Marsh Preservation Agreement. It also provides environmental assessment, but not regulatory compliance, for tidal marsh restoration of up to 28 km^2 (7,000 acres) of tidal marsh. The Suisun Marsh Plan supports actions that protect listed species and natural communities and that facilitate tidal marsh restoration for a broad range of benefits. However, it also perpetuates and funds management actions, some of which may be detrimental to other ecological functions of the Marsh (e.g., seasonal wetting and drying of marshlands, resulting in subsidence). Though the Suisun Marsh Plan includes some requirements for tidal marsh restoration, funding to fulfill those requirements is not included.

Suisun Marsh Protection Act

Passed in 1977, the Suisun Marsh Protection Act established the basis for Suisun-area conservation through land-use regulation implemented by the San Francisco Bay Conservation and Development Commission in the wetlands and by Solano County in the adjacent uplands. The act established managed wetlands as the primary land use in the Suisun Marsh interior, allowed for exploration and development of natural gas reserves, allowed for the Potrero Hills Landfill, and set aside the Collinsville area as an industrial reserve area. The latter has recently been reduced in size from 10.5 km^2 (2,600 acres) to 0.8 km^2 (200 acres). The Suisun Marsh Protection Act and its implementing regulatory programs are generally supportive of ecological restoration and conservation in Suisun, although some of the implementation policies are outdated and may not adequately accommodate sea-level rise and conservation of the wetland–upland transition zone important to so many species (chapter 4).

Clean Water Act and California Water Rights Decisions

Suisun Marsh water quality is regulated under a number of programs and plans. Salinity has long been regulated, beginning with Water Rights Decision D-1485 in 1978, Decision D-1641 in 1999, and three Water Quality Control Plans of 1978, 1995, and 2006. The San Francisco Bay Regional Water Quality Control Board (RWQCB) regulates beneficial uses of Suisun waterways through its Basin Plan. The RWQCB also maintains the CWA Section 303(d) Impaired Water Bodies list, which, for the Marsh, includes various pesticides, various organic compounds, mercury, selenium, low dissolved oxygen, nutrients, and marsh salinity. As part of the impaired water bodies program, the San Francisco Bay RWQCB (2006) has developed, and the U.S. Environmental Protection Agency has adopted, a mercury Total Maximum Daily Load (TMDL) for San Francisco Bay that covers the Marsh. Collectively, these water-quality criteria and plans establish a complex regulatory overlay that generally supports ecological restoration and conservation in Suisun, though they may pose challenges where restoration and conservation efforts conflict with salinity criteria. The San Francisco Bay RWQCB is currently in the process of developing low-dissolved-oxygen and methylmercury TMDL standards for Suisun Marsh.[1]

ERP Stage 2 Conservation Strategy, Delta Plan, and USFWS Tidal Marsh Recovery Plan

The ERP Stage 2 Conservation Strategy for the Delta (DFG 2011) was written specifically in anticipation of impending changes to how water is conveyed to the

---

[1] See http://www.waterboards.ca.gov/.

state and federal water export facilities in the southern Delta. This Conservation Strategy will guide the Ecosystem Restoration Program Stage 2 implementation in the Delta and Suisun planning area and is incorporated into the Delta Plan adopted by the Delta Stewardship Council in 2013. The Delta Stewardship Council also has a quasi-regulatory role wherein restoration-project proponents must file "consistency determinations" demonstrating how the project is consistent with the Delta Plan through application of "best available science." The Delta Science Program is anticipated to have a role in supporting development and application of best available science. Efforts to develop a Delta Science Plan are underway as of the publication of this book. The Draft Tidal Marsh Recovery Plan (USFWS 2010) is a formal ESA-guided plan to chart recovery of tidal marsh–dependent species from Suisun Marsh through the San Francisco Estuary and along the Central California Coast. It contains specific restoration recommendations and targets for Suisun Marsh. Taken collectively, these three plans and programs support ecosystem conservation in Suisun Marsh and provide strong scientific foundations for restoration efforts.

Oversight Gap

There is an absence of clear statements on the leadership and authority of the many agencies that have responsibility in Suisun Marsh management. Under the Suisun Marsh Plan, tidal marsh restoration is "to happen," and whichever entities choose to pursue it have a prescribed set of procedures to follow in planning in order to utilize the environmental coverage the plan provides. The Suisun Marsh Plan establishes an Adaptive Management Advisory Team (AMAT), but it does not prescribe any linkage to science or adaptive management of the Delta Plan and the Delta Science Program that are the repository and guiding body for the vast stores of scientific knowledge on Suisun Marsh. The Delta Plan, adopted in 2013, mandates science engagement with the Delta Science Program through its quasi-regulatory "Covered Actions" consistency determinations; restoration in Suisun Marsh, for example, is a Covered Action. The Delta Science Plan, which is anticipated to be established in 2014, will provide guidance on the means by which the best available science should be incorporated into restoration efforts. The AMAT has not, to date, formed or prescribed procedures for establishing projects and designs within a strong science-based framework, nor announced how it will meet Delta Plan Covered Action requirements. The Suisun Marsh Plan's directed adaptive management program is geared mainly toward objectives that are a subset of larger policy directives described above. The plan does identify reducing uncertainties as an important priority. Adaptive management monitoring is defined for impacts of the managed-wetland levee-maintenance dredging program. Monitoring restoration benefits to listed species is deemed "potential," and no monitoring is geared toward ecosystem-level benefits. The plan does not establish a science oversight entity on par with the Delta Independent Science Board. Instead, it recommends that restoration projects seek "input of other science based work groups . . . as applicable." Such issues need to be resolved before effective adaptive management can happen.

SUMMARY AND CONCLUSIONS

Many and varied forces will continue to be acting upon the Suisun Marsh of the future, which should place land managers and resource planners in an adaptive management role. Our best opportunity is to plot futures of Suisun Marsh that take advantage of these forces where possible, and design a system that is as resilient to change as possible. For example, the Marsh may become well suited to interim wetland uses such as carbon sequestration, helping in a small way to mitigate climate change while preparing the Marsh for more effective restoration to tidal marsh through early subsidence reversal. Other forces are within our grasp to alter if we choose (chapter 9). In practice, it will be very challenging, if not impossible, to retain some of today's ecosystem functions and physiographic features, because we will be dealing with novel ecosystems (chapter 9).

Chapter 3 notes that the most critical challenges for tidal marsh restoration in Suisun Marsh are sea-level rise, sediment supply, land subsidence, and, to a lesser extent, tidal energy. Though sea-level rise and sediment supply are outside our control, two forces are fully within our control: land subsidence and tidal energy distribution. Land subsidence, an effect of diked wetland management, can be addressed through alteration of diked wetland management. Understanding tidal energy distribution, which would be altered by planned restoration efforts, requires complex two- and three-dimensional hydrodynamic models to examine a wide range of possible Marsh-wide restoration scenarios. These tools exist, and the challenge is to describe a number of different alternatives, each reflecting a mix of large-scale tidal marsh restoration in the Delta, the Marsh, and northern San Francisco Bay, in combination with options for Delta water conveyance and floodplain enhancement in Yolo Bypass and the San Joaquin River.

To move forward, we need several ingredients. We need to apply our best technical savvy, including the range of information presented throughout this book, to execute tidal marsh restoration, improve diked wetlands management, and improve water quality. We need the many public institutions involved in Suisun Marsh management to function effectively with leadership, authority, and responsibility. We need adequate funding with a reasonable degree of certainty. Perhaps most importantly, we need private landowners to become partners in charting the long-term future of Suisun Marsh. Many changes will be coming in the years and decades ahead. As illustrated in the following chapter, what the future Suisun Marsh looks like will depend on actions taken today.

REFERENCES

Allison, S.K. 1992. The influence of rainfall variability on the species composition of a northern California salt marsh plant assemblage. Vegetation 101:145–60.

Alpers, C.N., C. Eagles-Smith, C. Foe, S. Klasing, M.C. Marvin-DiPasquale, D.G. Slotton, and L. Windham-Myers. 2008. Mercury ecosystem conceptual model. Delta Regional Ecosystem Restoration Implementation Plan. http://www.science.calwater.ca.gov/drerip/drerip_index.html.

Bay Conservation and Development Commission. 2011. Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline. Approved on October 6. San Francisco Bay Conservation and Development Commission, San Francisco.

Bay Delta Conservation Plan. 2013. Bay Delta Conservation Plan. Revised administrative draft. March 2013. ICF 00343.12. http://baydeltaconservationplan.com/Library/DocumentsLandingPage/BDCPDocuments.aspx.

Bay Institute. 1998. From the Sierra to the Sea: The Ecological History of the San Francisco Bay–Delta Watershed. Novato, California: Bay Institute.

Beare, P.A., and J.B. Zedler. 1987. Cattail invasion and persistence in a coastal salt marsh: the role of salinity reduction. Estuaries and Coasts 10: 165–170.

California Department of Fish and Game. 2011. Draft Ecosystem Restoration Program Conservation Strategy for Restoration of the Sacramento–San Joaquin Delta Ecological Management Zone and the Sacramento and San Joaquin Valley Regions. California Department of Fish and Game, Sacramento.

California Department of Water Resources. 1995. Sacramento–San Joaquin Delta Atlas (July). California Department of Water Resources, Sacramento.

Callaway, R.M., S. Jones, W.R. Ferren, Jr., and A. Parikh. 1990. Ecology of a Mediterranean-climate estuarine wetland at Carpenteria, California: plant distributions and soil salinity in the upper marsh. Canadian Journal of Botany 68: 1139–1146.

Cayan, D.R., P.D. Bromirski, K. Hayhoe, M. Tyree, M.D. Dettinger, and R.E. Flick. 2008. Climate change projections of sea level extremes along the California Coast. Climatic Change 87 (Supplement 1): S57–S73.

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.

Cayan, D.M. Tyree, D. Pierce, and T. Das. 2012. Climate Change and Sea Level Rise Scenarios for California Vulnerability and Adaptation Assessment. Publication No. CEC-500–2012–008. California Energy Commission, Sacramento.

Clark, J.S. 1986. Late-holocene vegetation and coastal processes at a Long Island tidal marsh. Journal of Ecology 74: 561–578.

Clark, J.S., and W.A. Patterson III. 1985. The development of a tidal marsh: upland and oceanic influences. Ecological Monographs 55: 189–217.

Cloern, J.E., N. Knowles, L.R. Brown, D. Cayan, M.D. Dittinger, T.L. Morgan, D.H. Schoellhamer, M.T. Stacey, M. van der Wegen, R.W. Wagner, and A.D. Jassby. 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.

Cohen, A.C., and J.T. Carlton. 1995. Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. U.S. Fish and Wildlife Service and National Sea Grant Report No. PB96–166525.

Delta Stewardship Council. 2012. Preliminary Staff Review Draft. Final Staff Draft Delta Plan. Delta Stewardship Council, Sacramento.

Dettinger M.D., and D.L. Ingram. 2013. The coming megafloods. Scientific American 398(1): 64–71.

Feyrer, F., B. Herbold, S.A. Matern, and P.B. Moyle. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion into the San Francisco Estuary. Environmental Biology of Fishes 67: 277–288.

Ganju, N.K., and D. Schoellhamer. 2010. Decadal-timescale estuarine geomorphic change under future scenarios of climate and sediment supply. Estuaries and Coasts 33: 1559–2723.

Gilbert, G.K. 1917. Hydraulic mining debris in the Sierra Nevada. U.S. Geological Survey Professional Paper 105.

Graymer, R.W., D.L. Jones, and E.E. Brabb. 2002. Geologic map database of northeastern San Francisco Bay region, California. U.S. Geological Survey Miscellaneous Field Studies Map MF-2403.

Healey, M.C., M.D. Dettinger, and R.B. Norgaard, eds. 2008. The State of the Bay–Delta Science. CALFED Science Program, Sacramento.

Heberger, M., H. Cooley, P. Herrara, P.H. Gleick, and E. Moore. 2009. The impacts of sea level rise on the California Coast. California Climate Change Center, CEC-500–2009–024-F. Pacific Institute, Oakland, California. http://www.pacinst.org/reports/sea_level_rise/report.pdf.

Herren, J.R., and S.S. Kawasaki. 2001. Inventory of water diversions in four geographic areas in California's Central Valley. Pages 343–355 *in* Contributions to the Biology of Central Valley Salmonids, vol. 2 (R.L. Brown, ed.). California Department of Fish and Game Fish Bulletin No. 179.

Intergovernmental Panel on Climate Change. 2007. Climate Change 2007—Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge: Cambridge University Press.

James, L.A. 1991. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. Geological Society of America Bulletin 103: 723–736.

Kimmerer, W.J., E. Gartside, and J.J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. Marine Ecology and Progress Series 113: 81–93.

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

Matern, S.A., and L.A. Brown. 2005. Invaders eating invaders: exploitation of novel alien prey by the alien shimofuri goby in the San Francisco Estuary, California. Biological Invasions 7: 497–507.

Meade, R.H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. Journal of Geology 90: 235–252.

Moyle, P.B., W.A. Bennett, W.E. Fleenor, and J.R. Lund. 2010. Habitat variability and complexity in the upper San Francisco Estuary. San Francisco Estuary and Watershed Science 8(3): 1–24. http://escholarship.org/uc/item/0kf0d32x.

National Research Council. 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, D.C.: National Academies Press.

Porterfield, G., R.D. Busch, and A.O. Waananen. 1978. Sediment transport in the Feather River, Lake Oroville to Yuba City, California. U.S. Geological Survey Water-Resources Investigations 78–20: 73.

Rahmstorf, S., G. Foster, and A. Cazenave. 2012. Comparing climate projections to observations up to 2011. Environmental Research Letters 7: 044035. doi:10.1088/1748–9326/7/4/044035.

Sacramento–San Joaquin Delta Conservancy. 2012. 2012 Strategic Plan. Delta Conservancy, West Sacramento, California.

San Francisco Bay Regional Water Quality Control Board. 2006. Mercury in San Francisco Bay: proposed basin plan amendment and staff report for revised total maximum daily load (TMDL) and proposed mercury water quality objectives. San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Schoellhamer, D.H. 2011. Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. Estuaries and Coasts 34: 885–899.

Siegel, S., P. Bachand, D. Gillenwater, S. Chappell, B. Wickland, O. Rocha, M. Stephenson, W. Heim, C. Enright, P. Moyle, and others. 2011. Final evaluation memorandum, strategies for resolving low dissolved oxygen and methylmercury events in northern Suisun Marsh. SWRCB Project No. 06–283–552–0. Prepared for the State Water Resources Control Board, Sacramento, California.

Siegel, S., C. Toms, D. Gillenwater, C. Enright. 2010. Suisun Marsh tidal marsh and aquatic habitats conceptual model, chapter 3: tidal marsh. Suisun Marsh Habitat Management, Preservation, and Restoration Plan. http://www.fws.gov/sacramento/es/documents/Tidal_marsh_2010/Tidal_CM_Ch3_Tidal_Marsh.pdf.

Singer, M.B. 2007. The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. River Research and Applications 23: 55–72.

Suisun Ecological Workgroup. 2001. Final report to the State Water Resources Control Board. California Department of Water Resources, Sacramento.

U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, and California Department of Fish and Game. 2011. Suisun Marsh Habitat Management, Preservation, and Restoration Plan. Final environmental impact statement/environmental impact report. U.S. Bureau of Reclamation, Sacramento.

U.S. Fish and Wildlife Service. 2010. Draft recovery plan for tidal marsh ecosystems of northern and central California. U.S. Department of Interior, Fish and Wildlife Service, Sacramento. http://www.fws.gov/sacramento/ES/Recovery-Planning/Tidal-Marsh/es_recovery_tidal-marsh-recovery.htm.

U.S. Geological Survey. 2012. Magnitude 3.3 earthquake 3km south-southwest of Green

Valley, California, October 8, 2012. U.S. Geological Survey Earthquake Hazards Program. http://comcat.cr.usgs.gov/earthquakes/eventpage/nc71855125#summary.

Williams, G. P., and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper No. 1286.

Wintzer, A. P., M. H. Meek, and P. B. Moyle. 2011. Life history and population dynamics of *Moerisia* sp., a non-native hydrozoan, in the upper San Francisco Estuary (U.S.A.). Estuarine and Coastal Shelf Science 94:48–55.

Wright, S. A., and D. H. Schoellhamer. 2005. Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento–San Joaquin River Delta. Water Resources Research 41: W09428.

Zedler, J. B. 1983. Freshwater impacts in normally hypersaline marshes. Estuaries 6: 346–355.