3. Drivers of Change Within the Delta

"... danger is never so near as when you are unprepared for it."

Francis Parkman (1849), The Oregon Trail

As we have seen in the last two chapters, the Delta has provided an array of services to the people and economy of California for the past 150 years. These diverse services—ranging from water supply to farming to shipping to recreation—have all required some manipulation of the hydrology and the landscape of the Delta. The construction of dikes and the draining of marshlands to support farming is the most regionally significant and visible physical manipulation. Maintaining water quality standards to sustain exports, in-Delta water diversions, and ecosystem needs has required sophisticated hydrologic and landscape engineering. Even low-profile services, such as hunting, fishing, and boating, require significant maintenance interventions.

The development of the Delta has completely transformed the region, leaving no significant remnants of the original landscape (Bay Institute, 1998). This transformation has been both dramatic and, on a geological time scale, instantaneous. When framed within the overall changes in California since the gold rush, the scope and scale of the Delta's transformation is on par with other rapid changes throughout the state, particularly within the major urban centers and the agricultural valleys. The Delta, like many other regions of California, exhibits a complex mix of natural responses to human-induced changes and has experienced numerous unintended and often undesirable consequences. If present trends continue, several uncontrolled hydrologic, ecologic, and landscape changes will occur into the indefinite future and pose great threats to the sustained provision of Delta services. Unfortunately, these changes appear to be outpacing the abilities of both the scientific community and policymakers to keep up.

All naturally evolving landscapes undergo a process of constant feedback between landscape processes and such drivers of landscape change as tectonic activity (changes resulting from movements in the Earth's crust), sea level change, and climate change. This process is particularly pronounced in estuarine, coastal, riverine, and deltaic systems, in which subtle changes in certain landscape drivers, including runoff, sediment supply, and tide and wave energy, are accommodated by corresponding changes in patterns of deposition, erosion, and landscape form (Pethick and Crook, 2000; Reed, 2002). In theory, this kind of feedback maintains a dynamic equilibrium, in which the landscape is in rough balance with the forces acting on it, even as it changes over the long term. In practice, because of human activity, the Delta is in profound and increasing disequilibrium with the forces currently operating on it.

This chapter outlines several key drivers of change within the Delta. The focus here is on natural and human-driven changes that not only affect our ability to benefit from Delta services but are also likely to significantly reduce the quality of these services in the future. The six key drivers, discussed in a recent CALFED report by Mount, Twiss, and Adams (2006), include land subsidence, sea level rise, seismicity, regional climate change, alien species, and urbanization.

Subsidence and Sea Level Rise

The most significant and enduring effect on Delta landscapes has been the conversion of roughly 450,000 acres of freshwater tidal marsh into farmland during the late 1800s and early 1900s. The draining and tilling of the Delta's organic-rich soils initiated a period of subsidence, a rapid lowering of land surface elevations of Delta islands perhaps unmatched in the world. The location and magnitude of subsidence has been and will continue to be the greatest influence on the Delta's landscape and is a fundamental constraint on future efforts to manage the Delta's services.

The exceptional subsidence of the Delta stems from its unique geologic setting and historical land use practices. For more than 6,000 years, the Delta was a freshwater tidal marsh (Shlemon and Begg, 1975; Atwater, 1982) consisting of a complex network of tidal channels, sloughs, "islands" composed of tule marsh plains, complex branching ("dendritic") water channels, and natural levees colonized by riparian forests (Bay Institute, 1998). A slow rise in sea level and gradual regional tectonic subsidence (subsidence of the land resulting from flexure of the Earth's crust) created what geologists refer to as “accommodation space” and made room for the relatively continuous accumulation of large volumes of sediment within the Delta (Atwater et al., 1979; Orr, Crooks, and Williams, 2003). Analysis of core samples by Shlemon and Begg (1975) and Atwater (1982) suggests that as accommodation space was formed by sea level rise over the last 6,000 years, it was quickly filled by the deposition of inorganic sediment from the Sacramento and San Joaquin Rivers and a similar amount of *in situ* production of organic material in the tule marshes. The preservation of this material, as the peat soils of the Delta, benefited from the oxygen-poor conditions within saturated soils of the marshes.

These natural patterns were substantially altered by reclamation in the late 1800s and early 1900s (Mount and Twiss, 2005). As we saw in Chapter 2, to farm the organic-rich soils, farmers needed to drain the islands. This involved constructing levees around the islands, filling most tidal channels and sloughs, and, most important, lowering local groundwater tables below crop root zones by constructing perimeter drains.[1] The draining of Delta soils caused widespread elevation loss.[2] This process was exacerbated by destructive land use practices, including peat burning and tillage, which promoted wind erosion (the most destructive practices are no longer used). The pace of subsidence was exceptional, exceeding four inches per year on some islands with the most intensive practices. Today, all islands of the Delta that contained peat soils and were used for agriculture have subsided; most in the central and western Delta lie more than 10 feet below today’s mean sea level (Figure 3.1).[3]

Modeling Subsidence

The rapid loss of island elevation during the 20th century created a new form of human-induced or “anthropogenic” accommodation space below sea level. This space has no natural analog. It has not filled with either sediment or water, as would occur normally in an estuary capable of natural

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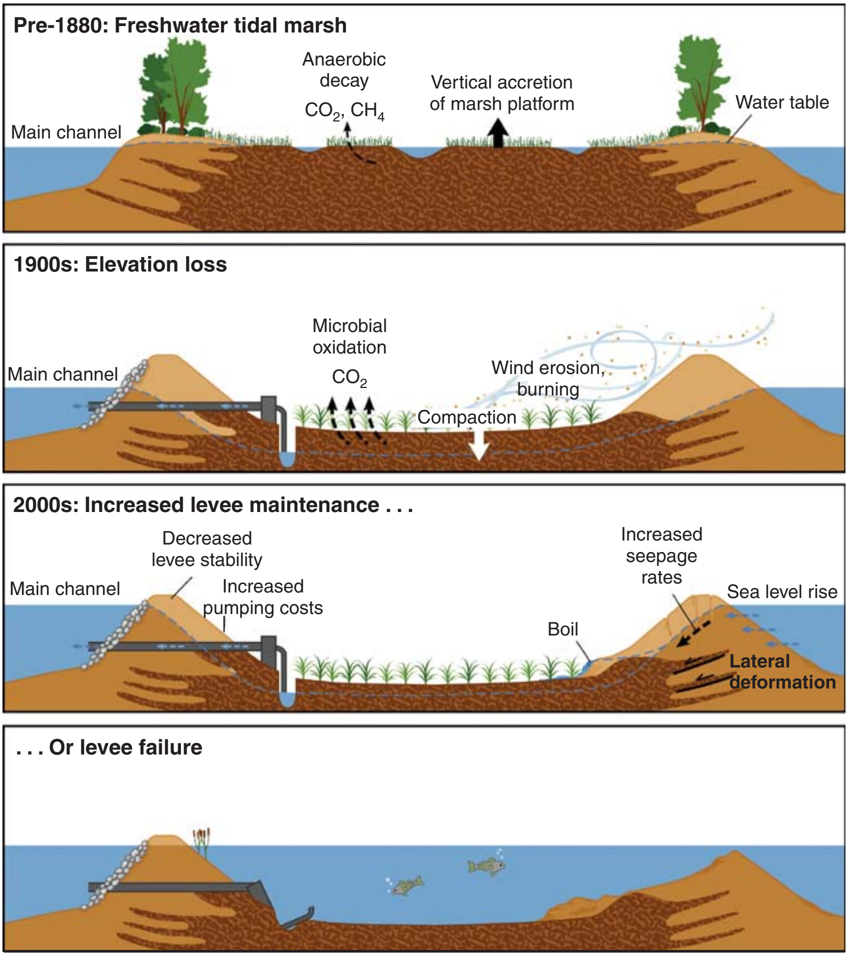
[1]Such drainage systems prevent waterlogging of a property—in this case, the Delta island. For an illustration, see Figure 3.1.

[2]See Deverel, Wang, and Rojstaczer (1998) and Deverel and Rojstaczer (1996). Contributing factors included microbial oxidation of organic matter, consolidation as a result of dewatering, and compaction of underlying soils.

[3]For a map of subsidence levels in the Delta, see Figure 2.4.



SOURCE: Mount and Twiss (2005). Reproduced under the terms of the Creative Commons Attribution License.

Figure 3.1—Conceptual Diagram Illustrating the Historical and Future Trajectory of Island Subsidence in the Delta

adaptation but is instead filled with air (as shown in the second and third panels of Figure 3.1).

Using a simplified geographic model, Mount and Twiss (2005) tracked the formation of this accommodation space in the Delta over the past 100 years. Their results indicate that more than 3.4 billion cubic yards of space has been created, roughly equivalent to 70,000 football fields 30 feet deep, or the volume of material used to construct Rome (Hooke, 2000). Mount and Twiss then used the same model to project future subsidence in the Delta over the course of the next 50 years. This model assumed that the Delta would continue to be farmed and that peat oxidation would continue to generate accommodation space. It also factored in sea level rise over the next 50 years, which magnifies the effect of subsidence by increasing the differential between interior island elevations and water surface elevations.[4] The results, summarized in Figure 3.2, suggest that under business-as-usual conditions, the Delta will generate an additional 1.3 billion cubic yards of accommodation space. However, the patterns of subsidence will change during this time. In the southern Delta and portions of the eastern Delta, where farming practices have completely removed the peat soils, sea level rise is the only driver of new accommodation space. But in the central, western, and northern Delta, if the lands continue to be farmed, subsidence will continue for much of the next century—in other words, agriculture will also drive the creation of accommodation space (Figure 3.3).

Subsidence, Sea Level Rise, and Levee Failure

The creation of accommodation space by human activity has the unintended effect of putting the landscape in considerable disequilibrium. Water is seeking to refill the subsided islands. This state of imbalance is maintained by more than 1,100 miles of artificial levees (Department of Water Resources et al., 2002), which are increasingly subject to failure. Levee failure and subsequent island flooding can have many causes (including such mundane things as burrowing by beavers and ground squirrels), some of which have no direct relationship to the magnitude of land subsidence. However, on a regional and local scale, the difference between interior island elevation and adjacent channel water surface elevation is a useful measure of the relative magnitude of the forces acting on levees. The greater these forces, the greater the potential for water seepage through and under levees—a common cause of levee failure.

Mount and Twiss (2005) developed a simplified measure of levee failure potential in the Delta as a function of island subsidence and sea level

[4]Conservative estimates of sea level rise were factored into the model using values provided by the Intergovernmental Panel on Climate Change (2001).

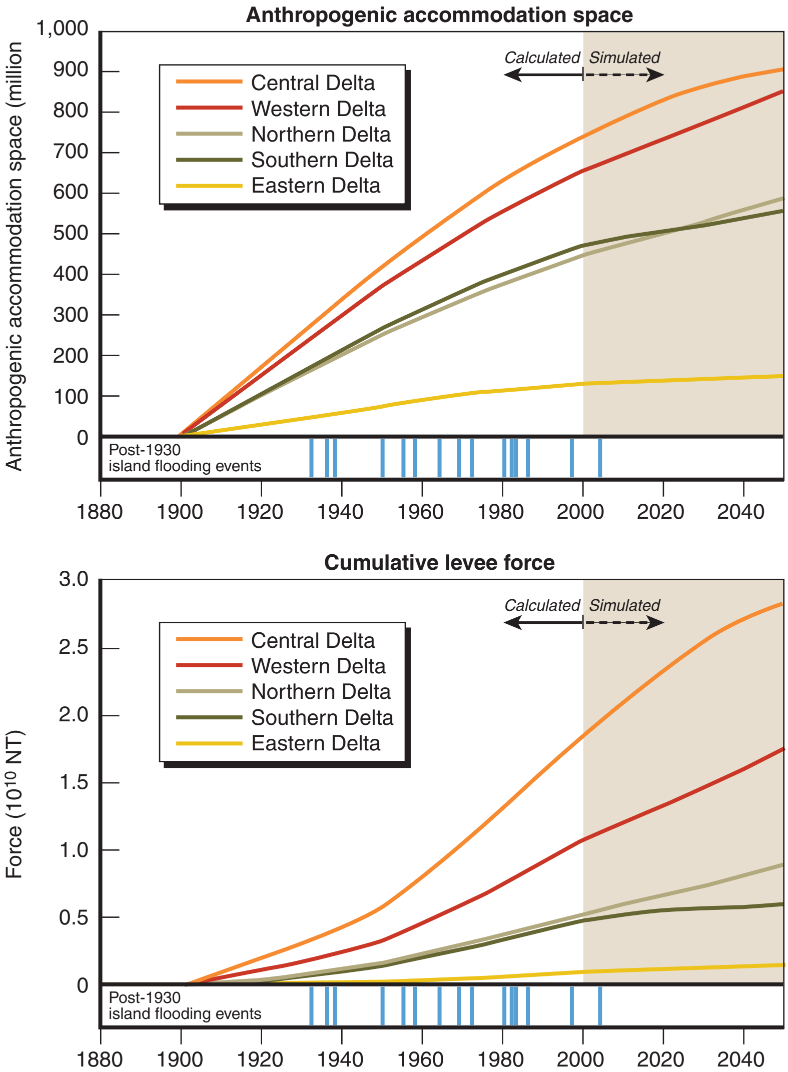


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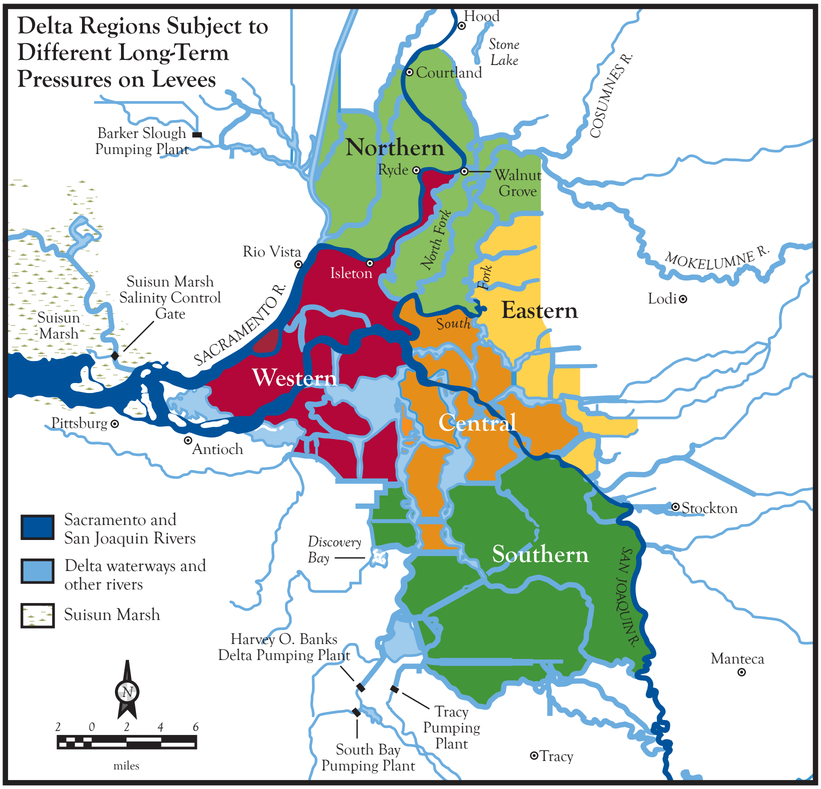
Figure 3.2—Historical and Projected Changes in Anthropogenic Accommodation Space and Cumulative Hydrostatic Force in the Delta

rise over the next 50 years. They calculated the hydrostatic forces (that is, the pressure exerted by water) acting on levees throughout the Delta; these



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NOTE: The regional designations shown here were used to calculate pressures on the levees, as depicted in Figure 3.2. They often differ from areas of the Delta discussed elsewhere in this report. For instance, the "western" region shown here extends farther to the north and east than the area considered for fluctuating Delta salinity in subsequent chapters.

Figure 3.3—Delta Regions Subject to Different Long-Term Pressures on Levees

forces increase with the squared difference between land and water heights. For each island, they estimated total hydrostatic force over the island's entire levee length. Using this approach, they found that deeply subsided islands have a high cumulative hydrostatic force and thus a high potential for failure. Islands with long levee lengths also have a high potential for failure because of the greater opportunity for hydrostatic pressure to exploit local levee weaknesses. Deeply subsided islands with long levee lengths are at the highest risk of future failure. Figure 3.2 depicts the historical and projected changes in cumulative hydrostatic force. These estimates indicate that the central and western Delta, in particular, will be increasingly vulnerable to levee failures and island flooding over the next 50 years and into the indefinite future.

Levee Policy

Although the Central Valley flood control system established in the 1910s set minimum heights for Delta levees, state regulatory involvement in the many privately owned levees remained negligible for most of the 20th century. Following the large 1986 flood in the Central Valley, which exposed the poor condition of Delta levees, the state legislature established new levee standards and launched a program of financial support. Supported by Senate Bill 34, the Delta Levee Subventions Program provided funds to maintain and upgrade levees, with the goal of raising levee crowns to one foot above the estimated 100-year flood stage height to meet State Hazard Mitigation Plan standards (Department of Water Resources, 1995). A long-term goal for the Delta is to meet Federal Public Law (PL) 84-99 standards for agricultural levees.

The subventions program, which dedicated roughly $110 million in state funds and $90 million in local matching funds to Delta levees between 1988 and 2005, has noticeably improved the conditions of many levees. However, it is important to recognize the program's limitations. Upgrading levees to meet the program's target elevation does not guarantee that Delta levees will not fail during a 100-year flood event (100-year floods have a probability of 1 percent of occurring in any given year). The one-foot difference between the estimated 100-year flood stage height and the levee crowns, particularly in a region subject to very high winds during floods, is insufficient to prevent levee failure. Moreover, the subvention program did not address the interior or the foundation of most levees, so seepage under and through levees remains an important threat during high water flows and could cause levees to fail even before they are overrun by floodwaters. Finally, the 100-year standard elevation estimate was based on 1986 hydrology rather than current hydrology, which takes into account changes in runoff conditions (discussed below). The National Flood Insurance Program maps, which have not been updated recently, place the entire Delta into the 100-year floodplain, reflecting the relatively low level of protection that the levees provide. It is reasonable to assume that in the future, large inflows of water into the Delta will inevitably result in multiple island failures.

Seismicity

For more than 30 years, DWR has warned that earthquakes pose considerable risk to Delta levees (Department of Water Resources, 1995). At least five major faults lie within close proximity to the Delta and are capable of producing significant ground accelerations. Poor foundation soils and poor-quality levee construction materials lead to a high risk of failure caused by liquefaction and settling.[5] Multiple seismic risk studies conducted for the Bay Area indicate a very high potential for major quakes in the region in the near future.[6]

In a report prepared for the CALFED Levee System Integrity Program, Torres et al. (2000) showed that ground accelerations from moderate earthquakes (magnitude 6.0, with a probability of recurring on average every 100 years) are capable of causing multiple levee failures. The highest risk of levee failure is in the western Delta, because of deep subsidence, poor foundations, and proximity to several significant seismic sources. However, a medium to high risk of catastrophic levee failures exists for almost all the central Delta as well.

Some local Delta engineers judge that seismicity is not a problem for the Delta because no local levee collapses have occurred from earthquakes in the past. However, there have been no significant ground accelerations in the Delta since the 1906 earthquake, before tall levees were constructed to protect subsided islands. The levees that now protect deeply subsided islands have not yet been tested. Moreover, the State Hazard Mitigation Plan and federal PL 84-99 standards do not address the susceptibility of levees and their foundations to failure during seismic shaking. Upgrading levees to meet PL 84-99 standards—at an estimated cost of roughly

[5]Liquefaction is the tendency of some soils to behave like a liquid when shaken, as happened in the Marina District of San Francisco during the 1989 earthquake.

[6]See http//quake.usgs.gov/research/seismology/wg02/.

$1 billion to $2 billion—will do little to reduce the potential for failure during earthquakes.

Seismicity poses a significant threat to the management and maintenance of current and future services provided by the Delta. Preliminary consequences of a rare, large quake would likely be that 16 or more islands would flood, principally within the central and western Delta (Jack R. Benjamin and Associates, 2005). All modeling to date indicates that this flooding would significantly alter the volume of the tidal prism (i.e., the volume of water moved during each tidal cycle) and local hydrodynamics with severe, prolonged disruptions in water quality and aquatic habitat.

The risk of sudden change in the Delta is quite high. In a simplified review of this risk, Mount and Twiss (2005) evaluated the probability of a major event that would significantly and perhaps permanently change the configuration of the Delta abruptly. Their analysis highlighted two sources of potential dramatic change: major seismic events and floods that are likely to recur every 100 years or less. Their calculations show that the probability is roughly two-in-three that during the next 50 years either a large flood or seismic event will affect the Delta. However, this analysis underestimates the actual probabilities for two reasons. First, strain continues to accumulate on Bay Area faults, increasing the annual risk of seismic activity. Second, current calculations of the size of a 100-year flood in the Delta are based on outdated hydrology data, which neglect the much higher inflows from rivers feeding into the Delta in recent years. In sum, the Delta is likely to change significantly and abruptly during the next generation. Sudden catastrophic change would be a very hard landing indeed for those depending on the Delta.

Regional Climate Change

Approximately 50 percent of California's average annual runoff, derived from roughly 45 percent of its surface area, flows to the Sacramento–San Joaquin Delta. The magnitude, timing, and duration of these inflows are, along with tides, the major influence on the physical and biological conditions that dictate the services that can be derived from the Delta. Regional climate change, driven principally by the Earth's warming in response to increases in greenhouse gasses, is currently affecting inflows to the Delta and will continue to affect them into the indefinite future (Knowles and Cayan, 2004; Hayhoe et al., 2004; Department of Water Resources, 2006).

Since the latter half of the 20th century, there has been a general trend toward increasing hydrologic variability and changes in the timing of runoff in the western United States (Jain, Hoerling, and Eischeid, 2005; Stewart, Cayan, and Dettinger, 2004). This trend has been particularly pronounced for the Sierra Nevada mountains and the Central Valley (Aguado et al., 1992). The region also has witnessed increased frequency and intensity of extreme rainfall events. Additionally, there has been a long-term shift in the seasonal pattern of runoff, with peaks shifting from spring toward winter (Dettinger et al., 2004). These changes in runoff are consistent with the results of regional climate models.[7]

Most modeling efforts predict that in the coming century, California will see a continuation of the hydrologic and climatologic trends established in the latter half of the 20th century (Dettinger, 2005). Warming trends will continue, with an increase in average annual temperatures of 2°F to 5°F by the 2030s and 4°F to 18°F by 2100 (Hayhoe et al., 2004). Recent work suggests significant increased interannual variability (vanRheenan et al., 2004) with the potential for increased frequency of both critically dry and wet years (Maurer, 2006) and significant declines in summer and fall inflows to the Delta because of shifts in the timing of snowmelt runoff (Zhu, Jenkins, and Lund, 2005; Miller, Bashford, and Strem, 2003). Additionally, regional models generally depict significant increases in the number of large winter storms, with associated increases in high winter inflows to the Delta.

The effects of ongoing and future changes in climate and runoff on the Delta have not been well documented to date, but they are the subject of numerous research efforts.[8] Water resource and flood management operations will be able to mute many of the effects of climate change, with the possible exception of increases in water temperature associated with increases in ambient air temperatures (Tanaka et al., 2006). However,

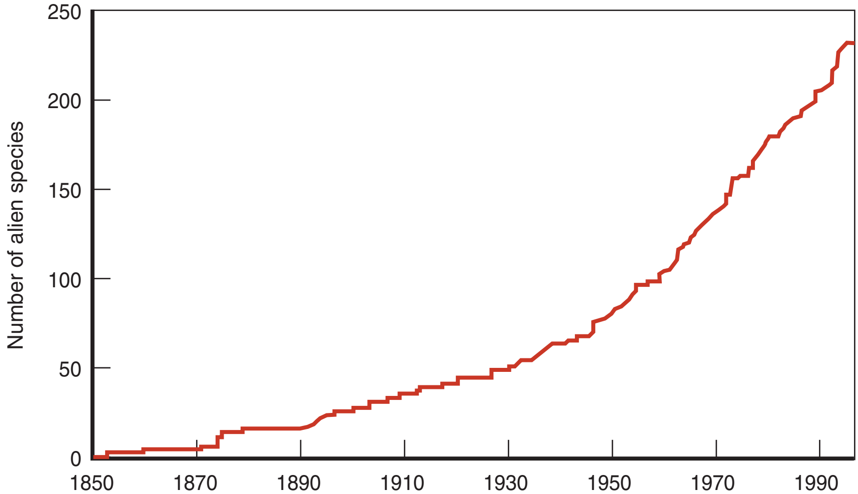
[7] To derive predictions for individual regions such as California, global climate models, known as General Circulation Models (GCM), are "downscaled."

[8] For a summary, see Department of Water Resources (2006).

all changes point toward a long-term, multidecade decline in the quality of Delta services. First, the increased frequency and magnitude of winter floods in the Delta will exacerbate pressures on the levee network, raising the cost of maintenance and increasing the likelihood of widespread, multi-island floods. In principle, reservoir operations can be altered to reduce the peak flood flows. In practice, however, there is likely to be growing conflict between flood control and water supply goals for reservoir management. To make sure that they store enough water for summer use, managers will face pressure to fill reservoirs during the winter rather than during the spring when runoff is likely to be less reliable. Yet such a strategy might increase flood risks, given the growing likelihood and magnitude of winter floods. Second, climate change is likely to introduce significant water quality costs. Currently, during low inflow periods, water quality in the Delta is generally poor, owing to the poor water quality of the San Joaquin River and to salinity intrusions from the Bay, coupled with increases in the influence of tides. Over the course of the next century, the shift in timing of runoff from spring to winter and the increase in frequency of critically dry years suggest long-term declines in Delta water quality, with a wide range of effects.

Alien Species

The San Francisco Bay–Delta is arguably one of the most invaded estuaries in the world (Cohen and Carlton, 1998). More than 250 alien species of aquatic and terrestrial plants and animals have entered the estuary since the first arrival of Europeans, with most indications showing that the pace of invasions has increased in recent decades (Figure 3.4). At least 185 alien species now inhabit the Delta and have profoundly changed Bay-Delta food webs and habitats, generating an array of effects—mostly negative—on native species. They also contribute to levee problems (e.g., burrowing by muskrats and crayfish), impede navigation (e.g., floating mats of water hyacinth), and otherwise cause economic damage. Today and for the indefinite future, we are managing an ecosystem composed of a mix of native and alien species that are in constant flux, as native species decline in abundance, new alien species invade, and established aliens wax and wane in numbers.



SOURCE: Cohen and Carlton (1998).

Figure 3.4—Estimated Number of Alien Species Within the San Francisco Estuary, 1850–1990

Although we have an improved ability to predict the effects of species invasions (e.g., Moyle and Marchetti, 2006), the process of invasion remains highly idiosyncratic in terms of which aliens will be most successful and change the ecosystem they invade. Nevertheless, several alien species not yet established in the Delta, such as the zebra mussel, are likely both to invade and to have large effects (Table 3.1). Invasions of alien species continue because efforts to halt new invasions have been small compared to the magnitude of the problem (e.g., Nobriga et al., 2005). For this reason, invasions by alien species and changes in the abundance of established alien species are another driver of change in the Delta. (Chapter 4 discusses this issue in greater depth.)

Urbanization

Although population growth has slowed in California in recent decades, the absolute population increases anticipated over the coming decades remain dramatic. By 2025, the state is expected to add another nine million residents—more than the population of the state of Ohio—

Table 3.1

Examples of Alien Species That May Invade the Delta in the Near Future

Species	Threat Rating	Invasion Likelihood	Likely Source	Why a Threat	Comments
Fish					
Northern pike	1	1	Lake Davis, California	Predator on salmon, native fish	Eradication program scheduled
White bass	2	1	California reservoirs	Schooling predator on pelagic fish	
Grass carp	2	2	Illegal import from Southern California	Changes aquatic communities	Used for aquatic weed control
Silver carp	2	3	Illegal import from Eastern United States	Plankton feeder	One of three Asian carp species infesting Eastern United States
Invertebrates					
Zebra mussel	1	2	Recreational boats, ballast water	Changes food webs, clogs water supply systems	Spreading rapidly in United States
Spiny waterflea	2	3	Ballast water	Predator on zooplankton	Two species, one fresh, one marine
Atlantic comb-jelly	1	2	Ballast water	Predator on zooplankton	Caused major changes to Black Sea ecosystem
Asian fish tapeworm	2	1	Imported live fish	Kills, weakens native fish	Example of disease/parasite

Table 3.1 (continued)

Species	Threat Rating	Invasion Likelihood	Likely Source	Why a Threat	Comments
Plants					
Oxygen weed	2	2	Aquarium trade	Clogs waterways	Aquatic plant
Water chestnut	2	1	Aquarium and ornamental trade	Forms dense mats	Aquatic plant

SOURCES: References for the species mentioned are as follows: northern pike, white bass, and grass carp (Moyle, 2002); silver carp (Schofield et al., 2005); zebra mussel (Cohen and Weinstein, 1998); spiny waterflea and Atlantic comb-jelly (Lowe, Browne, and Boudjelas, 2005); Asian fish tapeworm (Salgado-Maldonado and Pineda-López, 2003); oxygen weed and water chestnut (L. Anderson, UC Davis, personal communication, 2006).

NOTES: Threat ratings are as follows: 1—High likelihood of causing considerable ecosystem/economic damage. 2—Moderate likelihood of causing ecosystem/economic damage. Invasion likelihood in next 25 years: 1—High. 2—Moderate. 3—Small.

to reach 45 million (Johnson, 2005). The most recent update of the California Water Plan assumes that the population may then double—reaching 90 million residents—by 2100 (Department of Water Resources, 2005c). Following trends of the past two decades, much of this growth is expected to occur in the state's inland areas, including the regions bordering the Delta. Such growth will significantly increase both the demand for Delta services and the effects of human activity on the Delta. A growing and seemingly inevitable consequence has been the conversion of Delta farmlands to subdivisions. Estimates prepared by the California State Reclamation Board suggest that as many as 130,000 new homes are currently in the planning stages within the Delta.

Although urbanization can be controlled through regional land use planning mechanisms, there has been little political will to address the issue. Without a dramatic change in state policy, urbanization will powerfully influence the quality of services provided by the Delta. The effects will be seen in two principal ways. First, unlike most other activities in the Delta, urbanization is generally irreversible, barring a catastrophic event like Hurricane Katrina. Once a Delta island is converted to homes, that land use is fixed in place indefinitely; it also promotes the expansion of such services and infrastructure as transportation, utilities, and water systems. Changes in sea level and runoff conditions and the effects of seismicity are unlikely to reverse urbanization. Instead, it is highly likely that after problems caused by these forces, levees will be repaired and raised, and homes will be rebuilt.

Second, urbanization is self-accelerating. Urbanization in one location significantly increases the value of adjacent lands. This, coupled with declining profit margins for farming, will increase the pressure to convert farmlands to subdivisions. This process is already under way in the Delta's "secondary zone"—the upland areas and exempted lowland areas that were slated for development under the 1992 Delta Protection Act (Figure 3.5). In the future, there will be great pressure to build homes within the Delta's "primary zone," despite the act's intent to maintain this low-lying area for agricultural and recreational uses. The increase in number of homes along the perimeter and within the Delta will inevitably shift priorities for Delta management toward flood control and infrastructure to support urbanization. Without major changes in regional land use policy, this shift

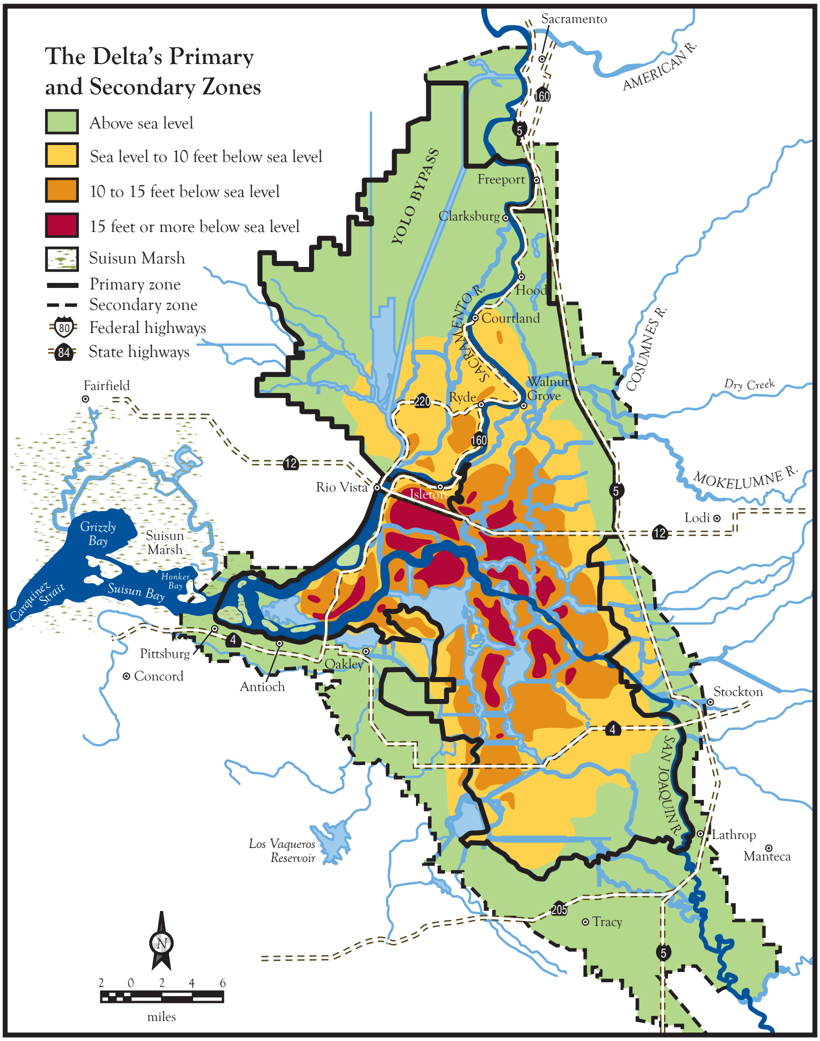


Figure 3.5—The Delta's Primary and Secondary Zones

will come at the expense of habitat protection and other services—such as water quality and water supply—that are important for other parts of California.

Conclusions

The current Delta was developed primarily by creating leveed islands to promote farming in the early days of commercial agriculture. These levees were often constructed with local peat soils and little engineering expertise to protect noncritical land uses—farms that could be restored following any levee failures. Agriculture continues as a major use of the land and as a standard for levee maintenance. However, the use of the Delta both as a conduit for water exports since the 1940s (as described in Chapter 2) and, more recently, as an area of urbanization has increased focus on levee reliability to protect both water quality and urban lands. As described in the next chapter, the Delta's highly altered levee-centric system has been at odds with the aquatic ecosystem, which has experienced a long-term decline in native species and an increased prevalence of undesirable alien species.

The long-term prospects for retaining a levee-centric system for protecting Delta land and water are poor. The existing levee system, even with recently proposed improvements, will be subject to greater probabilities of failure, with sudden and catastrophic consequences for all users of the Delta (Jack R. Benjamin and Associates, 2005). Sea level rise, increasing flood variability, past and continuing land subsidence, earthquakes, and urbanization all contribute to the increasing likelihood of major and multiple levee failures.

When we combine this analysis of the drivers of change in the Delta with a review of our current ecological understanding of the Delta's ecosystem, as described in the next chapter, the current levee-centric strategy for managing the Delta appears unsustainable. Moreover, should the Delta levees fail, the consequences are likely to be sudden and catastrophic for local residents, landowners, Delta species, and water exporters. Currently, the Delta is unsustainable for almost all stakeholders. Responding to the long-term problems of the Delta only after a major catastrophe is unlikely to produce wisely considered or economically prudent policy.