4. Aquatic Ecosystems

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We live in a time of rapid change and rapid discovery in ecosystems of the region. This discovery is changing how we view the Bay-Delta system and its responses, even as the system itself is changing. Knowledge is accumulating rapidly through field studies, laboratory experiments, modeling and analysis of data from a large suite of long-term monitoring programs. Yet key questions central to management and to the future trajectory of the ecosystem remain unanswered.

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This chapter describes the current state of science for the aquatic ecosystem of the upper San Francisco Estuary. It emphasizes processes in the Sacramento-San Joaquin Bay-Delta as part of a habitat continuum between rivers and the Pacific Ocean. Because of the rapid development of the science, this report will soon be overtaken by new discoveries. In addition, with over 500 scientific publications on the estuary in the last decade, this chapter can provide only some examples of recent developments rather than a thorough review. We have therefore chosen to focus on the upper estuary, and to emphasize recent developments on topics relevant to management. We rely principally on published work, using research in progress to indicate potential future directions.

The state of the science in the Bay-Delta is essentially the state of the scientific community's view of the ecosystem. This view has shifted substantially in the last two decades (Lund et al. 2007, Appendix A) because of changes in the legal and societal framework, the multiple problems besetting the estuary, and the breadth of disciplines and backgrounds of the scientists working on the problems. Scientists previously viewed the Delta in isolation as a network of river channels, with striped bass as the key species of interest. The current scientific perspective is broader and more holistic. It conceives of the Delta as part of an estuary with close connections to the watershed and the ocean, numerous species of concern, and a rich and complex physical and biological structure.

There is broad agreement that the Delta is in poor condition. In describing the state of the ecosystem, however, we avoid the term "ecosystem health," which, as a metaphor, implies a normative state that does not exist. As long as there is water, there will be an aquatic ecosystem with a distinct structure and function; it just might not do what society wants. Thus the state of the ecosystem has value only in relation to societal values, particularly the extent to which it provides ecosystem services. These include extractive services such as fishing and water diversions, active and passive recreation, and aesthetic or ethical services, such as maintenance of natural landscapes and endemic species (Daily 1999). The Delta no longer delivers these services as it once did. Science has an important role in explaining why this is happening.

Key Themes for the Ecosystem

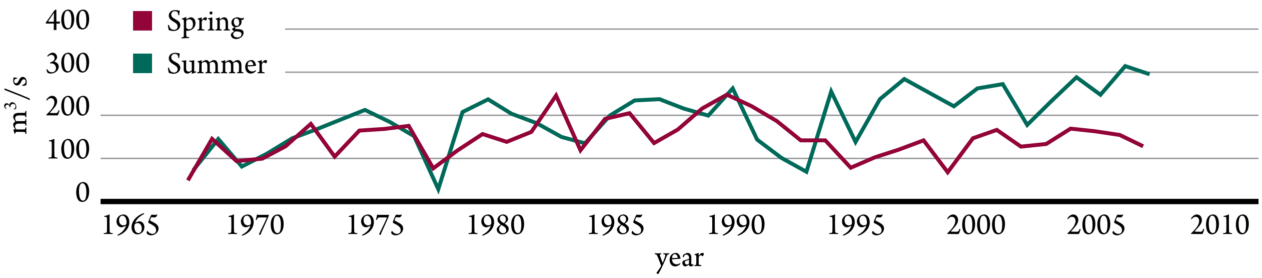
Three themes that underlie this chapter are key to how we learn about the estuarine ecosystem and the context in which that learning occurs:

1) the ecosystem is temporally variable—tides rise and fall, floods come and go, species migrate in and out, and this variability is essential to its function;
2) the ecosystem is spatially variable and is dominated by several spatial gradients that are also essential to ecosystem function; and
3) monitoring and research help us understand the ecosystem, but our understanding will always be incomplete and will always lag behind changes in the system.

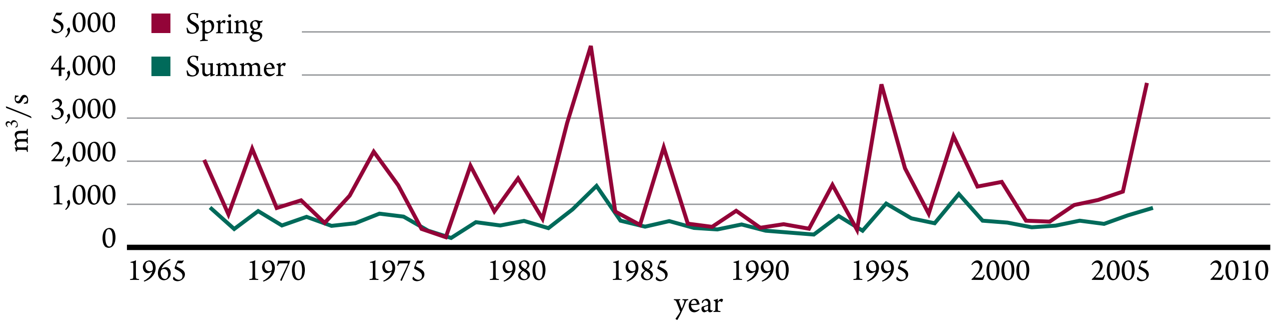
Temporal Variability

Temporal variability has been investigated using data from numerous monitoring stations and natural records of past conditions (see Figure 4.1). Variation in freshwater flow is the most important natural driver of change. Freshwater flow in the rivers varies substantially over time-scales from days to millennia, with evidence for long, deep droughts in the prehistoric record.[1] Variation in flow between years has important consequences for species abundance in the estuary (Jassby et al. 1995), and the seasonal oscillation between winter wet and summer dry conditions, together with seasonal and

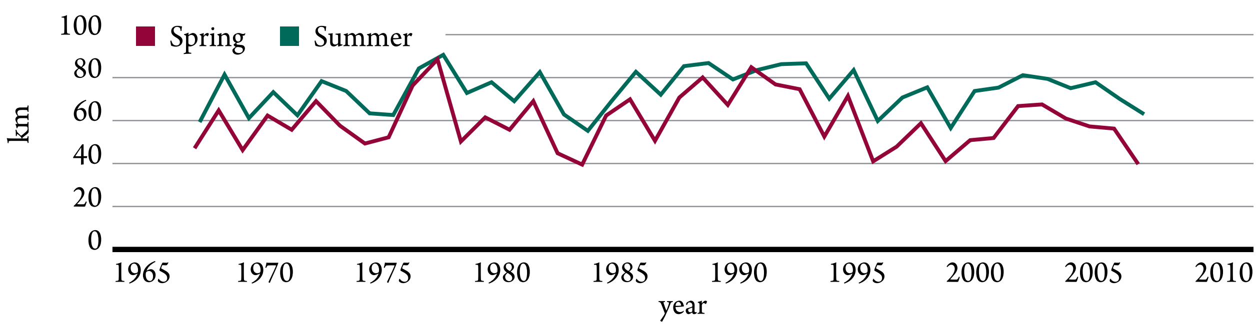
1 Discussed in greater detail in Chapters 2 and 6



Delta Export Flow. Measured in cubic meters per second (m^3/s).



Delta Inflow. Measured in cubic meters per second (m^3/s).



X2. Measured in kilometers from the Golden Gate.

Figure 4.1. Changes in Delta inflow, export flow, and X2 over time. Delta inflow and export flow are measured in cubic meters per second (m3/s) and X2 is measured in kilometers from the Golden Gate. Inflow and export flow are annual means by season. (Source: IEP Dayflow accounting program 2008)

daily patterns of sunlight and temperature, set the stage for biological cycles. Notwithstanding the ecological importance of variation in freshwater flows, the most obvious cause of daily variation in the estuary is the tidal cycle. Variation due to tidal flows must be accounted for in nearly all investigations of estuarine ecology.

The history of the ecosystem is one of high short-term variability (for example, year-to-year variation in fish abundance) overlying a number of long-term trends (for example, increasing numbers of introduced species). Many of the longer-term trends reflect a few brief periods of substantial change (Examples in Figure 4.1). Key among the long-term trends are increasing water clarity, species introductions and resulting changes in ecosystem function, decreases in phytoplankton production in Suisun Bay and the Delta, and decreases in abundance of fish in the northern estuary.

Future sources of temporal variability include deliberate human actions to resolve conflicts as well as the projected influence of changing climate and rising sea level. On a time-scale of decades, large changes are likely to occur through regional human activities, such as the rising demand for water and changes in the configuration of the Delta. Large-scale levee failures due to earthquakes and other factors will likely result in many islands being irreversibly flooded.

Spatial Variability and Gradients

The Delta is an integral part of the Bay-Delta system; a transition zone between inflowing rivers and the ocean. Gradients in elevation, freshwater flow, and tidal influence set the stage for a host of associated physical, chemical and biological gradients (see Figure 4.2). Most notable among these is the strong gradient of increasing salinity as one moves from the rivers to the ocean. Each estuarine species has its own distribution with regard to salinity. These distributions are determined by each species' physiological tolerance for salt, how it responds to estuarine circulation and how it responds to other species such as predators (Kimmerer 2004; 2006). Distributions can change seasonally and with the life-stage of the species.

An additional kind of gradient is the declining influence of many environmental factors with distance. For example, the effects of export pumping are strong near the pumps in the South Delta but weaker far from the pumps in the North and West Delta. In contrast, connections among different regions are mediated by movements of water, substances and organisms. These connections blur the boundaries between regions. For example, the rise and fall of ocean tides is felt far into the Delta, and conditions in the ocean can affect abundance of fish such as salmon that migrate between ocean feeding grounds and freshwater spawning grounds.

Thus, while we can consider the river–estuary system as a continuum of habitats, we can also legitimately isolate portions of it for research, management and restoration. This is one reason for the emphasis on the Delta: it is part of a large, important ecosystem and at the same time the focus of the conflict between water use and ecosystem protection.

Additional, smaller-scale spatial variation and gradients also exist within the Delta. For example, the residence time of water varies greatly between open channels and dead-end sloughs, and habitat for various kinds of fish is distributed very unevenly throughout the Delta. The relative importance for ecological processes of river flow, export flow, and tidal flow vary with location in the Delta (Kimmerer and Nobriga 2008).

Monitoring and Research

We learn about the ecosystem in three main ways. *Monitoring* tracks temporal changes in system properties and allows an assessment of the state of the system. *Laboratory and field research* is used to detect mechanisms, test or compare alternative hypotheses and determine parameter values for models. *Con-*

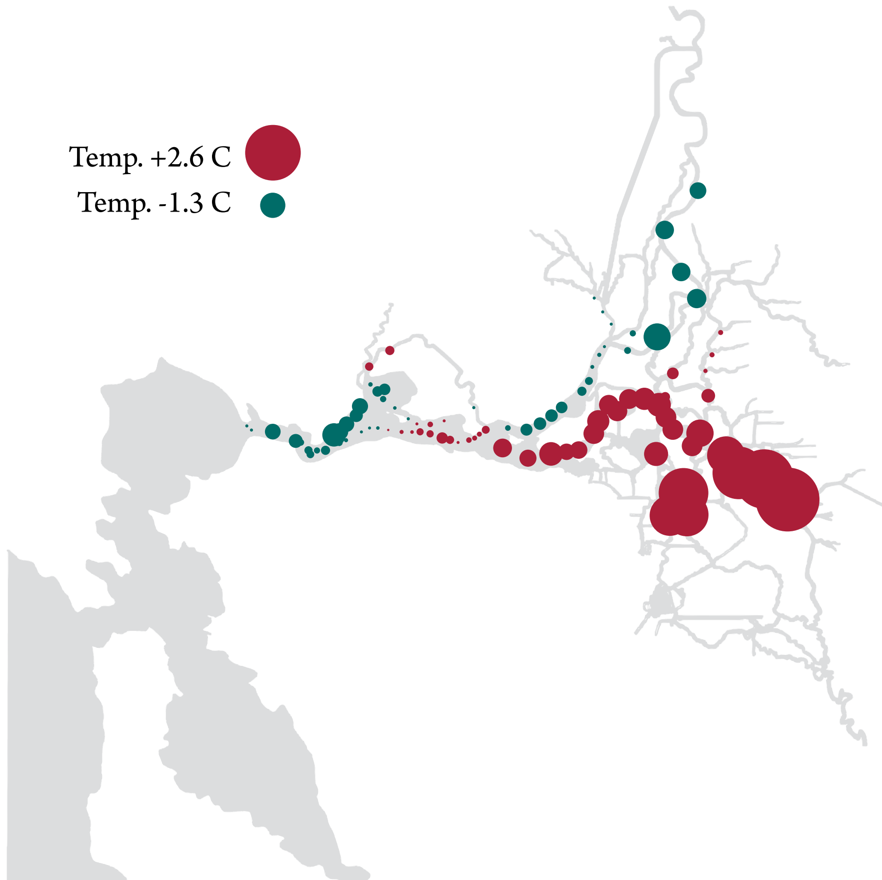


Figure 4.2. Gradient in temperature in the Delta during September based on data gathered during midwater trawl sampling from 1990 to 2001. Many other physical attributes of the Delta also show strong spatial gradients. Red dots show places where temperature was higher than the overall mean for the Delta and green dots show places where temperature was lower than the mean. The size of the dot indicates how much higher or lower the temperature was. The legend in the upper left of the figure gives a scale for the dots in degrees centigrade (i.e., -1.3 C is the lowest temperature and +2.6 C is the highest temperature). From the figure it is apparent that in September the San Joaquin is very warm and cools as it moves toward its confluence with the Sacramento whereas the Sacramento is cool and warms toward the confluence. Suisun Bay and Carquinez Strait are cooler than the Delta. (Source: Kimmerer 2004)

ceptual and simulation modeling are used to organize our understanding about the system and to examine the consequences of alternative concepts or potential management actions. Each of these components is crucial to the success of the scientific enterprise in providing information useful for management.

Monitoring got an early start in the Bay-Delta. Regular salinity monitoring began in 1920, followed by more comprehensive monitoring in the rivers and the estuary by several state and federal agencies, notably the United States Geological Survey. More integrated monitoring in a portion of the estuary began in 1970 under the auspices of the Interagency Ecological Program (IEP), and the San Francisco Estuary Institute's Regional Monitoring Program (RMP) was started in 1993. Temperature, salinity and other properties in the estuary are now recorded by continuous monitoring stations.

Shipboard monitoring programs collect samples for water quality, phytoplankton, zooplankton, benthic communities, and the distribution and relative abundance of fish.

The level and quality of monitoring in the Bay-Delta ecosystem is high, but monitoring alone is inadequate for understanding how the system functions. This was realized early on, and broadly based estuarine research was initiated in the 1960s by the California Department of Fish and Game and IEP workers and their collaborators (Stevens 1966; Turner and Kelley 1966; Arthur and Ball 1979). However, it was only with the substantial infusion of research funds through the CALFED Ecosystem Restoration Program and Science Program that a concerted effort was begun to understand the system, rather than simply document trends. This has been supplemented more recently with the IEP investigations into the Pelagic Organism Decline (POD) (Sommer et al. 2007). Research on the Delta is typically multidisciplinary, with numerous and productive interactions among scientists, engineers and agency staff.

Even with the current high level of monitoring and research, inherent limitations exist in our ability to understand how the ecosystem responds to change, whether natural or man-made. First, biological populations change through dynamic processes of birth, development, growth, death and migration. Yet, most data on populations are from monitoring of distribution and abundance over only part of the life-cycle. Second, water in the estuary is turbid, rendering the aquatic ecosystem effectively invisible. We observe it mainly using nets, which sample a very limited part of the system and lose important information about its spatial structure. This sampling is also expensive, and is never sufficient to provide reliable estimates of the abundance of key species. Third, the system is always changing. New species invade and alter food web structure. More refined data analyses change our understanding of important processes (Jassby et al. 2002). Changing management interests alter the emphasis of monitoring, research and analysis—for example, the change from emphasis on striped bass *(Morone saxatilis)* to Delta smelt *(Hypomesus transpacificus)*. Finally, patterns in a complex and variable system can be detected only over time, with a lot of data and always with considerable uncertainty. As a result, understanding often lags far behind ecological change.

Food Webs

All ecosystems capture nutrients and solar or chemical energy, transform energy and nutrients among living and non-living forms, and consume the energy in metabolism. Energy for growth, metabolism and reproduction of virtually all organisms comes from the sun through photosynthesis by plants. This energy is supplied in the form of organic matter to aquatic ecosystems either directly from phytoplankton or other plants, or indirectly from exogenous sources (for example, marshes, farms). Energy and nutrients are transformed by the feeding of organisms within the estuarine food web. How these transformations occur, and how they are influenced by human activities and the particular geographical and physical context of the estuary, are the principal topics of estuarine ecological research. Research on the food webs and habitats supporting fish in the estuary has been particularly vibrant in the last decade.

Organic Matter Supply

Most of the organic matter in the Delta is non-living material, mostly dissolved in the water, delivered by rivers from upstream (Jassby et al. 2000). However, most of that non-living organic matter is of low food value to consumer organisms in the Delta (Sobczak et al. 2002). Furthermore, to be useful as food to larger consumers such as fish, the energy content of this dissolved organic material must first be consumed by bacteria and other very small organisms, leading to inefficient energy transfer (Sobczak et

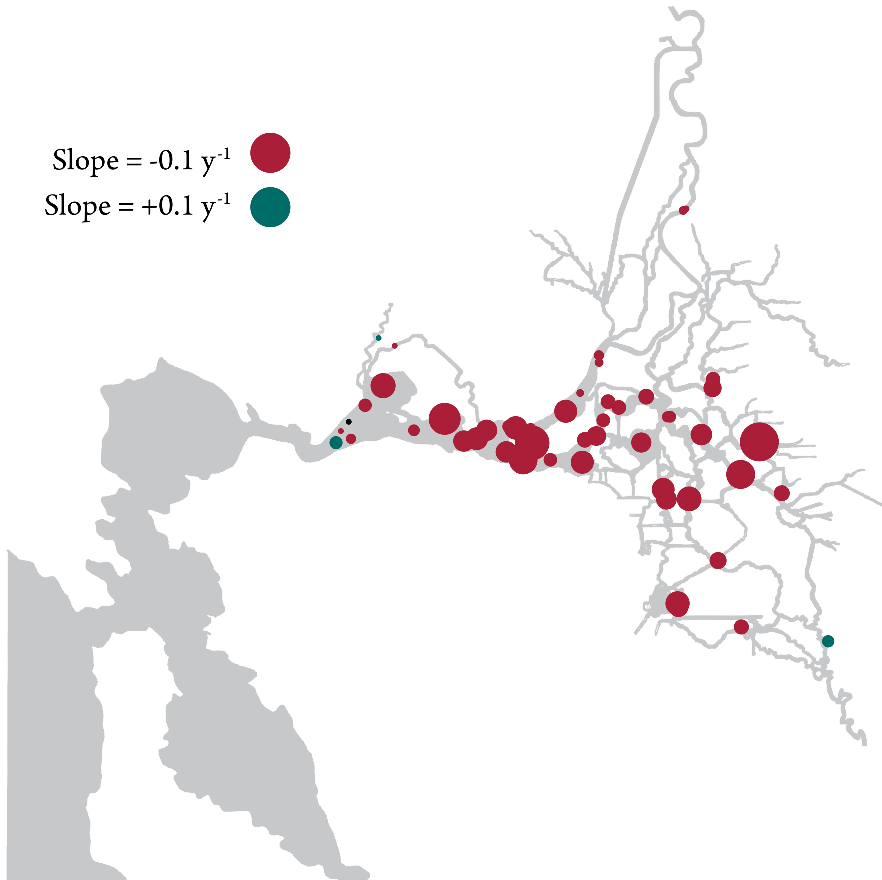


Figure 4.3. Long-term changes in turbidity in the Delta and Suisun Bay. Turbidity has important effects on ecosystem function. Red dots indicate decreases in turbidity over time and green dots indicate increases in turbidity. The size of the dot shows the relative increase or decrease in turbidity. The legend in the upper left of the figure shows the relationship between dot size and the rate of change in turbidity with time. (Source: Kimmerer 2004)

al. 2005). Although much less abundant than the dissolved organic material, phytoplankton (microscopic aquatic plants) is the main source of organic matter for the food webs that support fish (Müller-Solger et al. 2002; Sobczak et al. 2002).

The growth of phytoplankton in the Bay-Delta is often limited by light because high concentrations of suspended sediment make the estuary very turbid, and light often does not penetrate far into the water (Cloern 1999). Because light penetration is so low, phytoplankton grows most abundantly in shallow areas, and deep channels receive a subsidy of phytoplankton from these shallow productive areas (Lucas et al. 1999; Lopez et al. 2006). Water in the Delta has become less turbid over the last three decades (see Figure 4.3). This is because rivers are now carrying less sediment into the estuary (Wright and Schoellhamer 2004), and invasive aquatic weeds are filtering sediment out of water in the Delta. This has led to an increase in phytoplankton growth rate, which may have contributed to a recent increase in the mass of phytoplankton in the Delta (Jassby 2008).

Nutrient concentrations in Delta water are high enough that they probably do not limit phytoplankton growth (Jassby et al. 2002). However, low growth rate of diatoms (a kind of phytoplankton important in aquatic food webs) has been linked to high concentrations of ammonium, a form of nitrogen released by sewage treatment plants (Dugdale et al. 2007). Additionally, a decline in chlorophyll concentration in the Delta in the early 1990s was associated with a decline in phosphorus inputs from sewage treatment plants and in total phosphorus in the Delta (Van Nieuwenhuyse 2007), suggesting that nutrient concentrations do influence phytoplankton growth. These results appear to conflict with a moderate increase in phytoplankton production (as measured by chlorophyll) in the Delta in the last decade (see Figure 4.4; Jassby 2008). Thus, the ecosystem-level effects of variation in nutrient concentrations are unclear. In the particular case of ammonium, an improvement in sewage treatment would reduce the rate of input, but at this stage the response of phytoplankton would be difficult to predict, and potential effects on fish are unknown.

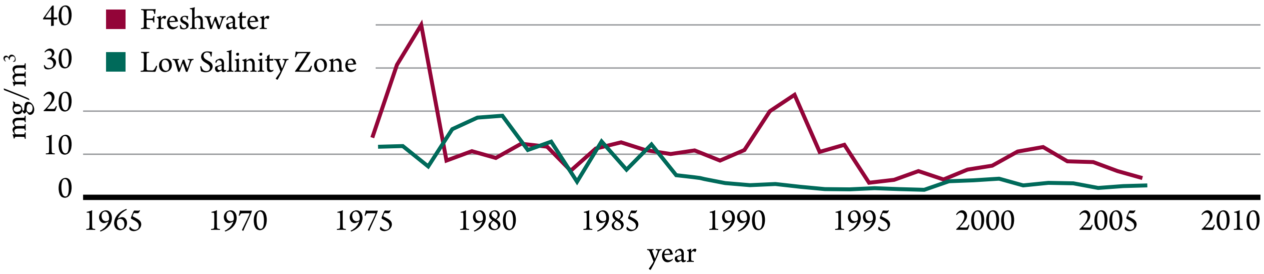
Phytoplankton production in the Delta declined 43 percent between 1975 and 1995 (Jassby et al. 2002) to about 35 percent of the median production among the world's estuaries, although it has since increased (Jassby 2008). The first stage of the decline occurred in the 1970s due to unknown causes, and the second occurred in 1987 in the western Delta and Suisun Bay and was associated with the introduction of the overbite clam (*Corbula amurensis*) (see "The Benthic Pathway" below). Most of the phytoplankton input to the Delta is from local production; of the total, about 68 percent was buried or consumed within the Delta each day and another 23 percent was removed by in-Delta agricultural and export diversions, based on data from 1975 through 1993 (Jassby et al. 2002).

Microcystis aeruginosa is a colonial cyanobacteria (formerly called "blue-green algae") that forms intense blooms in the Delta. These blooms can produce toxins, and may be interfering with feeding by zooplankton (Lehman et al. 2005). The more or less simultaneous increase in *Microcystis* blooms with the decrease in pelagic fish may be coincidental, but the link is being investigated.

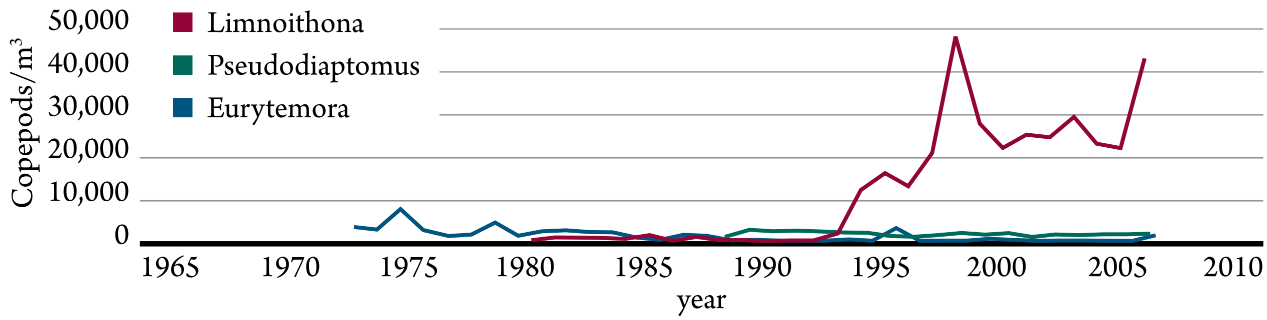
The Zooplankton Pathway

Phytoplankton production supplies energy and nutrients to small organisms including bacteria and zooplankton. Bacteria, which consume dissolved organic matter, are key elements of all aquatic food webs, but in the Bay-Delta they have been studied only in the low salinity zone. Bacteria are small but so abundant in the low salinity zone that their total mass in the estuary is about ten-fold higher than that of fish. Bacteria there consume more organic carbon than is produced locally by phytoplankton (Murrell et al. 1999), implying an organic carbon subsidy from another part of the system. Bacteria can be consumed by small single-celled organisms such as ciliate protists, and by the overbite clam (Werner and Hollibaugh 1993). Research is ongoing on the importance of bacteria and ciliates in the food web.

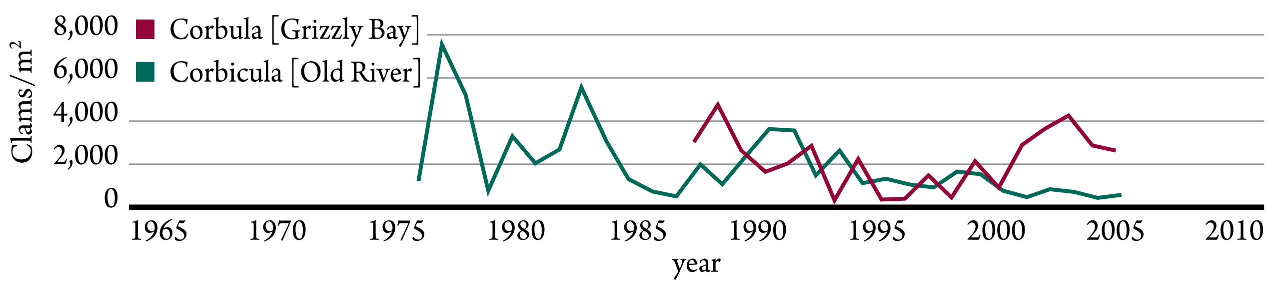
Zooplankton comprise a very broad assemblage of animals ranging from microscopic to a few millimeters in size. Nearly all of the fish species of the estuary have a larval stage that is both part of and a predator on the zooplankton, particularly on copepods. Many fish continue to eat zooplankton as juveniles or adults. As in other estuaries, most of the zooplankton of the San Francisco Estuary are small (less than one half millimeter long) including rotifers and the nauplius larvae of copepods (Orsi and Mecum 1986). Larger zooplankton (approximately one to twenty millimeters long) include cladocerans in freshwater, and copepods, mysid shrimp and the larval forms of benthic invertebrates and fish throughout the estuary. Predatory gelatinous plankton such as jellyfish are common in harbors and channels (Rees and Gershwin 2000), but are not common in the open waters of the estuary, although they have become seasonally abundant in Suisun Marsh in recent years.



a. Changes in chlorophyll concentrations in the Delta and Suisun Bay over time. Chlorophyll, measured in milligrams per cubic meter (mg/m3), is the mean value from March through October for each year in each region. (Source: IEP Environmental Monitoring Program 2008)



b. Changes in the abundance (copepods per cubic meter) of three copepods—*Eurytemora*, *Pseudodiaptomus*, and *Limnoithona*—over time in the low salinity zone of the Delta. *Eurytemora* abundance is the mean value from March through May for each year. *Pseudodiaptomus* abundance is the mean value from June through October for each year. *Limnoithona* abundance is the mean value from March through October for each year. The low salinity zone is the region of the Delta with a mean salinity of 0.5 to 6 practical salinity units, excluding the South Delta. (Source: IEP Environmental Monitoring Program 2008)



c. Abundance of overbite clam (*Corbula amurensis*) in Grizzly Bay and the Asian clam (*Corbicula fluminea*) in Old River over time. Overbite clam and Asian clam abundance (clams per square meter) is the mean value from March through October for each year in each region. (Source: IEP Environmental Monitoring Program 2008)

Figure 4.4. Changes in chlorophyll concentrations, copepod abundance and clam abundance in the estuarine ecosystem over time.

Rotifers and larger zooplankton have declined in abundance in parallel with the phytoplankton (compare chlorophyll and copepod panels, Figure 4.4). Zooplankton are generally considered consumers of estuarine phytoplankton, particularly diatoms in the freshwater regions of the Delta (Müller-Solger et al. 2002). However, in both brackish (Bouley and Kimmerer 2006; Gifford et al. 2007) and saline (Rollwagen Bollens and Penry 2003) regions of the estuary, several zooplankton species feed heavily on ciliate protists, implying a more complex and less efficient food web than previously believed. Every quantitative study of reproduction or feeding by zooplankton in the estuary has demonstrated food limitation (Müller-Solger et al. 2002; Kimmerer et al. 2005).

The species composition of the zooplankton has changed over the thirty-five years of monitoring, particularly in the low salinity zone. Before 1987, the mysid shrimp *Neomysis mercedis* was the most abundant large zooplankton in the upper estuary and an important food item for young fish such as striped bass. After the overbite clam was introduced, the abundance of *N. mercedis* declined sharply, presumably because the overbite clam competes with *N. mercedis* for food. Other mysid shrimp species that have been introduced to the Bay-Delta are smaller and less abundant than *N. mercedis* was, and therefore provide less food to fish (Feyrer et al. 2003). Introduced amphipod crustaceans are an alternative prey for fish that formerly consumed mysids (Feyrer et al. 2003; Toft et al. 2003). The abundance of amphipods is not monitored effectively, however, which represents a significant gap in our understanding of the estuarine food web.

Copepod species composition has changed radically through declines in the abundance of some species and introductions of new species largely from turbid estuaries of mainland Asia (Kimmerer and Orsi 1996; Orsi and Ohtsuka 1999). The tiny, introduced copepod *Limnoithona tetraspina* is now the most abundant copepod in the upper estuary (see Figure 4.4; Bouley and Kimmerer 2006). These copepods feed only on moving cells (not diatoms), and are small and sedentary so they are not important food for many fish species.

The Benthic Pathway

Bottom-dwelling (benthic) organisms differ fundamentally from those that live in the overlying water in that they have limited ability to move. Most of them have planktonic larvae, but once these larvae settle to the bottom they do not move far if at all. This means that their response to changes in salinity is qualitatively different from that of the plankton. Organisms that live in the water column (such as the plankton) can move with the water and are not subjected to rapid changes in salinity. In contrast, benthic organisms can be bathed in water of very different salinity at each end of the tidal cycle, and long-term exposure to unfavorable salinity can interfere with feeding or be lethal. Distributions of benthic organisms change in response to seasonal and interannual changes in salinity mainly through die-back and recolonization.

Most of the energy produced by phytoplankton is consumed by benthic organisms, principally by two species of clam (see Figure 4.4). The overbite clam, first reported in the estuary in 1986, is the most abundant bivalve in brackish water. The Asian clam *Corbicula fluminea*, first reported in 1945, is the most abundant in freshwater. Although other benthic species can be important at some locations and seasons, these clams are overall the most important in consuming plankton and in the transfer of contaminants through the food web. Their distributions overlap at very low salinity, and the zone of overlap moves as salinity moves landward in the dry season and seaward in the wet season.

The overbite clam lives within the top few centimeters in all sediment types and all water depths in the estuary. It ranges from above the San Joaquin-Sacramento River confluence in dry years (Hymanson 1991) through Central and South San Francisco

Bay. Abundance can exceed 10,000 per square meter and usually peaks in summer or fall (Hymanson et al. 1994). Abundance in the shoals of San Pablo Bay declines during extended periods of high freshwater flow, and drops to zero in the winter due to predation by migratory ducks (Poulton et al. 2004). A similar seasonal pattern has been observed in Grizzly Bay (Thompson 2005). White sturgeon *(Acipenser transmontanus),* Sacramento splittail *(Pogonichthys macrolepidotus)* and Dungeness crab *(Cancer magister)* also eat overbite clams (Stewart et al. 2004).

Overbite clams reproduce in spring or fall when food is sufficient (Parchaso and Thompson 2002), and larvae stay in the plankton about two to three weeks, dispersing throughout the estuary (Nicolini and Penry 2000). The overbite clam can consume phytoplankton, bacteria and copepod larvae (Werner and Hollibaugh 1993; Kimmerer et al. 1994). The co-occurrence of the decline in phytoplankton (see Figure 4.4) with the invasion of the overbite clam suggests that the clam is over-grazing the system; grazing rates in Grizzly Bay are often at least as fast as phytoplankton growth rate (Thompson 2005; Cloern and Nichols 1985).

The Asian clam is ubiquitous in the Delta and in Suisun and San Pablo Bays during wet years (Hymanson et al. 1994). Abundance of young clams can exceed 200,000 per square meter during high settlement periods in Franks Tract, a submerged island (Lucas et al. 2002). Asian clams are most abundant in the Central Delta; they limit phytoplankton biomass in Franks Tract (Lucas et al. 2002), whereas low abundance of clams on Mildred Island allows it to be a phytoplankton Source for the surrounding channels (Lopez et al. 2006).

Taken together, these clams exert strong control over the phytoplankton and possibly zooplankton and other small organisms throughout the northern estuary from the Delta to Suisun and possibly San Pablo Bays. Because of their overlapping range, there are few places without clams, and many places where phytoplankton cannot accumulate because of clam grazing. Thus, together they limit the capacity of the ecosystem to produce food for fish and other organisms.

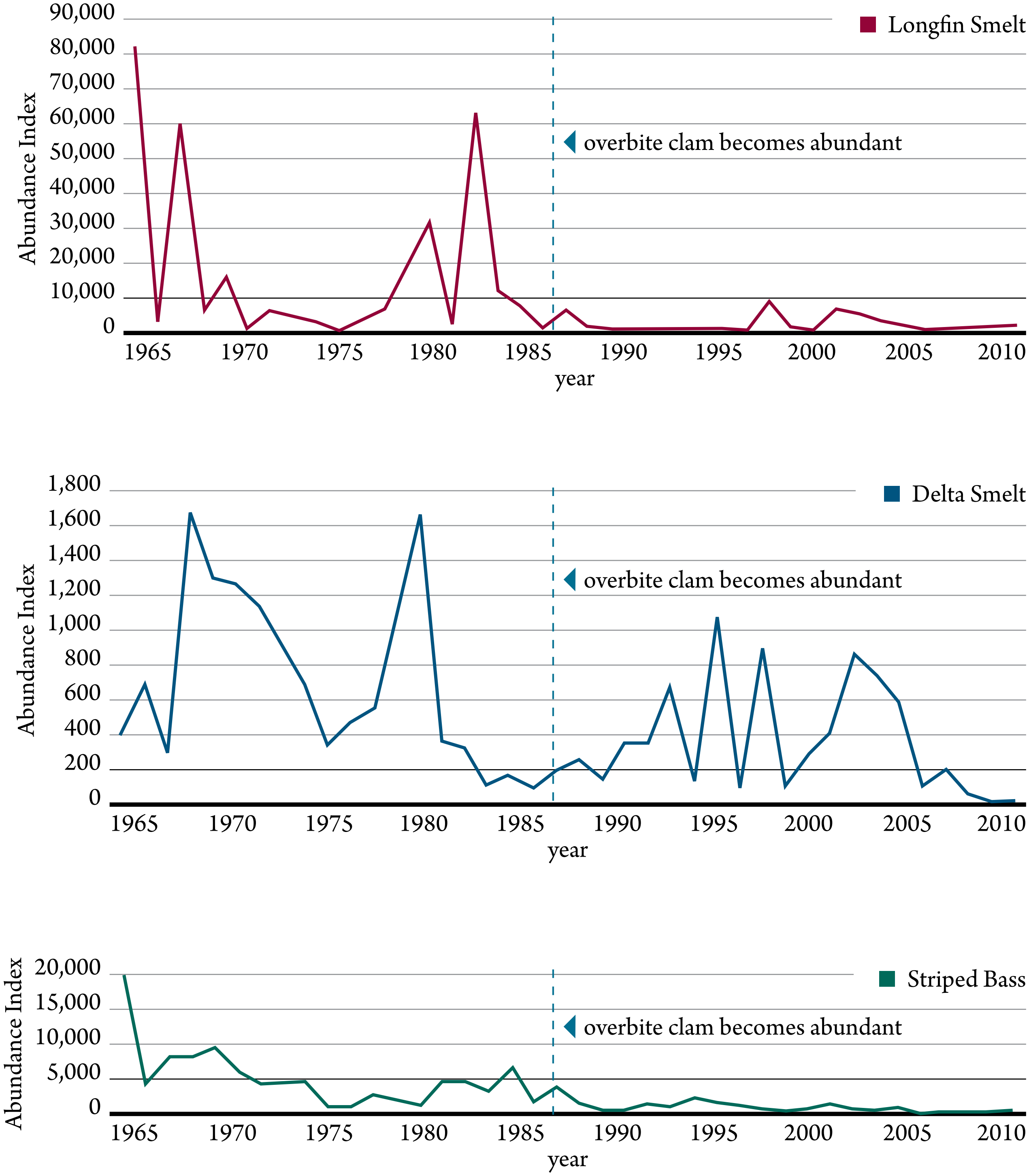
Apart from their roles as consumers of phytoplankton, overbite clams play a key role in the cycling and bioaccumulation of contaminants in the food web. Overbite clams accumulate selenium from their food to concentrations sufficient to affect reproductive success in their predators (Stewart et al. 2004).[2] Overbite clams are important food for diving ducks; they are easier to forage upon and more nutritious than other prey bivalves, but their thicker shell reduces digestibility (Richman and Lovvorn 2004). This, together with depletion of clams during summer (Poulton et al. 2002), may result in food limitation for migratory ducks.

Fish

Many of the Estuary's fish are introduced species (Dill and Cordone 1997), particularly in fresh to low salinity habitats (Moyle 2002; Brown and Michniuk 2007), and less so in the marine environment. Many estuary-dependent fish species have declined in abundance during the approximately three to four decades of monitoring (see Figure 4.5). Although these declines could be seen as continuous, many consist of short periods of rapid decline, and some show periods of increase. For example, abundance of young striped bass declined steeply around 1977, probably because of an increase in mortality of older adults due to changes in ocean conditions (Kimmerer et al. 2001). Delta smelt abundance declined in the 1980s but was back up in the mid-1990s, both for unknown reasons.

Many of the estuarine-dependent fish species respond positively to freshwater flow. Numerous reasons for the relationships between fish abundance and freshwater flow have been discussed. The rea-

2 Discussed in greater detail in Chapter 3



4.5. Changes in abundance indices for longfin smelt, Delta smelt, and striped bass over time in the Delta. (Source: Fall Midwater Trawl Survey 2008) son probably is not due to an increase in food supply, since the zooplankton that most young fish feed on do not increase in abundance with flow (Kimmerer 2002). This suggests that aspects of physical habitat may be more important in determining the response of fish to flow, including habitat quantity (as seen for splittail feeding on floodplains, Feyrer et al. 2007) and estuarine circulation patterns.

Some species of estuarine-dependent fish declined in abundance around the time the overbite clam became abundant (see Figure 4.5; Kimmerer 2002). The impact of the overbite clam on estuary-dependent fishes may have been muted because the northern anchovy *(Engraulis mordax)* became less abundant in low salinity waters, presumably because of the decline in food there (Kimmerer 2006). Because anchovies can filter-feed, they are capable of consuming small organisms more efficiently than most other fish, which pick out prey individually. The departure of anchovies may have reduced predation on zooplankton and therefore competition with other plankton-feeding fish, and also allowed the small copepod *Limnoithona* to thrive (Kimmerer 2006; Bouley and Kimmerer 2006). This sequence of events would not have been predictable in advance, and provides a cautionary tale for predicting the outcomes of future introductions.

Since around 2001 attention has focused on the decline of several open-water fishes (Delta smelt, longfin smelt *(Spirinchus thaleichthys)*, juvenile striped bass, and threadfin shad *(Dorosoma pretense)*, (see Figure 4.5) and some prey species. This decline was labeled the POD (Sommer et al. 2007). The causes of the POD remain uncertain, although potential contributing factors are the changed estuarine food web, export pumping, declining habitat quality, and toxic effects (Baxter et al. 2008). All of these are subject to ongoing research coordinated by the POD Management Team. As with the longer-term downward trends of fishes (see Figure 4.5), the POD is very likely due to more than one cause.

Of the POD species, the Delta smelt is arguably the most imperiled estuarine fish in the United States, and knowledge of its biology has been increasing rapidly (Bennett 2005). The areal extent of its spawning habitat and the geographic distribution of larvae and juveniles depend on freshwater inflow (Dege and Brown 2004; Hobbs et al. 2007), although the fall index of smelt abundance is unrelated to flow (Jassby et al. 1995; Kimmerer 2002). In drier years, when Delta smelt are distributed eastward into the Delta, entrainment losses at the export pumps may be high (Kimmerer 2008). Preliminary results of the POD investigations suggest high entrainment during winter may have an especially damaging effect on the Delta smelt population (Baxter et al. 2008). Furthermore, habitat suitability for Delta smelt has declined because of increasing water clarity (smelt are most common in turbid water), high temperature in summer, and salinity intrusion in fall (Feyrer et al. 2007; Nobriga et al. 2008). This change in habitat suitability is correlated with the number of juveniles produced per adult fish, but only since the overbite clam invasion occurred (Feyrer et al. 2007).

In addition to the POD species, a great deal of effort has been expended to understand and minimize the impacts of poor conditions in the Delta on Chinook salmon *(Oncorhynchus tshawytscha)* and Central Valley steelhead *(Oncorhynchus mykiss)*. Many young salmon enter the Delta as fry and rear there instead of in the streams, yet little is known about the contribution of these fish to the population. Salmon that migrate through the Delta encounter a risky habitat with large numbers of predators and presumably a confusing directional signal, made unnatural by the general southward flow of water toward the export pumps (Brandes and McLain 2001). Some of these fish are lost to the export pumps (Kimmerer 2008), but there has been no comprehensive attempt to estimate overall losses through the Delta and how they vary with flows, export flows, and barrier placement. Studies conducted to date (Newman and Rice 2002; Brandes and McLain 2001) have focused only on subsets of this problem. Particle tracking models show that most particles, which simulate salmon, that are released in the San Joaquin River under most flow conditions are lost to entrainment into the export pumps (Kimmerer and Nobriga 2008). Survival indices for salmon smolts released at various sites on the San Joaquin River have been low and not very responsive to flow, also suggesting poor survival under most conditions (SJRGA 2006).

Marshes and Shorelines

The Delta was once mainly tidal marsh, and the entire estuary was bordered by tidal marshes including the extensive Suisun Marsh. These former marshes doubtless were an important component of the Delta ecosystem. Although only about 5 percent of the original marsh remains estuary-wide, some remnants exist in the Delta and more in Suisun Marsh and farther seaward (Atwater et al. 1979).

Most of the research on marshes in the Bay-Delta is on salt marshes of the lower estuary, with particular recent emphasis on the effects of introduced cordgrass on marsh function (Callaway and Josselyn 1992). Within the Delta, research has emphasized extant or restored marshes as fish habitat (Brown 2003a) or their effects on water quality.[3] This emphasis arose because of plans by CALFED to expand the extent of tidal marshes in the hope of increasing organic matter supply to the estuarine food web and providing habitat for fish. However, the organic matter produced in marshes can also contribute to the production of methylmercury and can impair drinking water quality (Davis et al. 2003; Brown 2003b).[4] Furthermore, many of the fish species of greatest concern are open-water species unlikely to use these habitats to any great extent (Brown 2003a).

Shorelines and shallow regions in the Delta have become heavily overgrown with the invasive Brazilian waterweed *Egeria densa*, whose extent has been increasing (Brown and Michniuk 2007). Waterweed beds support large populations of invertebrates that comprise a fairly self-contained food web distinct from that of neighboring open water (Grimaldo 2004). Waterweed beds appear to provide conditions suitable for spawning and rearing of introduced predatory fish such as black bass (Grimaldo et al. 2004; Brown and Michniuk 2007). These introduced predatory fish are capable of consuming larvae, juveniles and adults of smaller species of native fishes and probably minimize any benefit waterweed beds might have for native fish populations (Brown 2003a; Nobriga and Feyrer 2007). Native fish larvae are rare along the edges of waterweed beds (Grimaldo et al. 2004). These beds of waterweed are major impediments to restoration of the Delta and make it difficult to predict how the system may respond to future management actions.

The principal exception to the rather pessimistic findings above is floodplains such as the Yolo Bypass and the Cosumnes River, which are inundated only during winter floods. These areas provide important feeding habitat for Chinook salmon and splittail (Sommer et al. 2001; Feyrer et al. 2006). They are less subject to invasion by non-natives than permanently flooded areas (Moyle et al. 2007), presumably because the limited duration of inundation does not overlap with the higher spawning temperatures needed by most non-native fishes. These findings suggest that seasonally inundated areas may be more valuable for restoration than shallow areas that are permanently underwater (Feyrer et al. 2006; Moyle et al. 2007). However, seasonal flooding and drying of aquatic habitats may increase production of methylmercury. [5]

Much of Suisun Marsh consists of private lands managed to support waterfowl for hunting. The long history of research in Suisun Marsh has fo-

3 Discussed in greater detail in Chapter 3

4 Discussed in greater detail in Chapter 3

5 Discussed in greater detail in Chapter 3

cused predominantly on marsh channels as habitat for estuarine fishes (Moyle et al. 1986). Very few published studies have focused on the function of the marsh itself (Culberson et al. 2004), although research is underway on aspects of marsh function and the influence of invasive plants.

Freshwater Flow and Tide

Freshwater flow into the estuary is a key driver of ecosystem response, and arguably the most important process for resource management in the state. Manipulating freshwater flow is one of the few management tools available in the system. Variability in freshwater flow (see Figure 4.1) affects the tidal freshwater reaches of the Delta through its effects on inputs of sediment and related substances and on water residence time, which regulates accumulation of phytoplankton biomass. In addition, increasing freshwater flow increases the area and volume of freshwater habitat by moving the salt field seaward. Movement of the salt field, in turn, affects processes in brackish to saline regions of the estuary out into the Gulf of the Farallones (Walters et al. 1985). This movement is indexed by a variable called "X2", the distance (in kilometers) up the axis of the estuary from the Golden Gate to where the tidally-averaged bottom salinity is two practical salinity units (psu) (Jassby et al. 1995). X2 is used in managing flow into the estuary, and is considered a measure of the physical response of the estuary to changes in freshwater flow (Kimmerer 2002). It is related to abundance of several populations of estuarine-dependent species (lower abundance occurs at low flow and high values of X2; Jassby et al. 1995), although those relationships changed after both the decline attributed to the overbite clam (Kimmerer 2002) and the more recent POD (Sommer et al. 2007); now few of the species that spawn in freshwater show relationships with X2.

The effects of freshwater flow within the estuary are modified by tidal flows (see Figure 4.6). Tides mix and transport salt, other substances and organisms within the estuary. The tides do not merely slosh back and forth; tidal flows in the branching channels of the Delta are quite complex and can result in considerable mixing. For example, scientists are investigating the role of tidal flows in Franks Tract, which may act as a kind of tidal pump that transports ocean salt into the Delta. In brackish parts of the estuary, salt is transported upstream by asymmetrical flow patterns arising from interactions between the net seaward flow due to the rivers and tidal flows and influenced by the complex channel–shoal structure of the estuary. Organisms such as larval fish may use the tidal flows to maintain position within the estuary by moving up and down in the water column (Bennett et al. 2002).

Roles of Diversions

Water diversions in the Delta range from small pumps and siphons that serve individual farms to the massive state and federal facilities in the southern Delta (Figure 4.1 shows export volumes). There is little evidence that the small diversions in the Delta have any effect on fish populations, in spite of the expenditures made to install or upgrade fish screens on these diversions (Moyle and Israel 2005). The South Delta export facilities entrain so many fish that it is often assumed that export pumping has massive effects on fish populations within the Delta. Losses of Delta smelt and Sacramento basin Chinook salmon ranged from zero up to 20 percent to 30 percent, depending on flow conditions and assumptions about pre-salvage mortality (Kimmerer 2008). Export pumping has been blamed in part for declines of species such as striped bass (Stevens et al. 1985), Chinook salmon (Kjelson and Brandes 1989), and Delta smelt (Bennett 2005). However, no quantitative estimates have been made of the population-level consequences of the losses of fish caused by export pumping. It is difficult to know the impact of these losses in the context of much

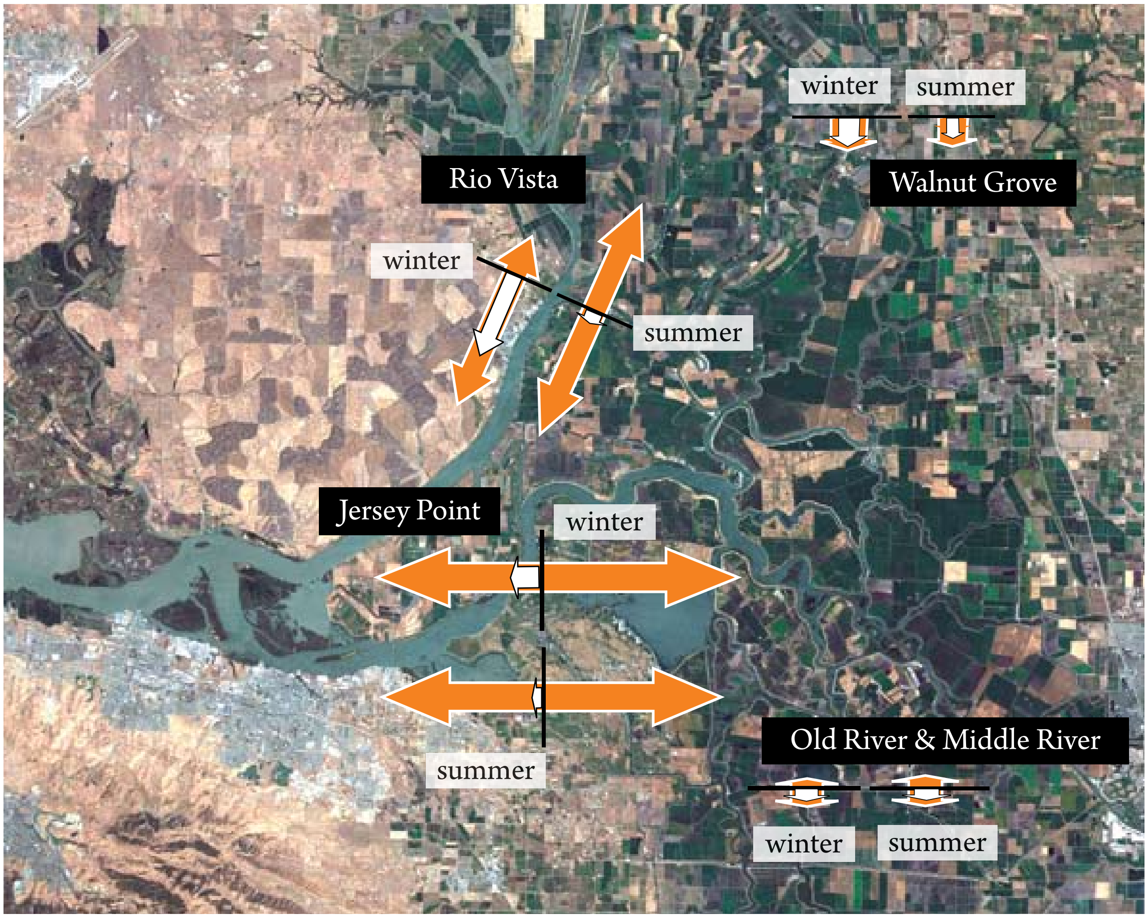


Figure 4.6. Tidal and net flows in different regions of the Delta in winter and summer. Orange arrows show tidal flow (with the exception of Old and Middle Rivers, upstream tidal flows are upward or to the right, downstream flows are downward or to the left; Old and Middle Rivers flow north, so upstream flow is downward and downstream flow is upward). White arrows show the net flow (net flow is the average movement of water in the channel). Tidal flows dominate through most of the Delta and are particularly high in the West Delta. Net flows are greatest where the rivers enter the Delta. Net flows are upstream (going south) in the South Delta because of export pumping. (Source: Satellite image courtesy of NASA Landsat Program, http://landsat.gsfc.nasa.gov/. Monitoring data depicted was provided by the United States Geological Survey. The sizes of the arrows are for illustration purposes only.)

larger variability in survival and reproduction of these species. Export pumping also alters flows in Delta channels, which may have indirect effects on fish, and removes phytoplankton and zooplankton from the Delta. These losses can be substantial, but their effects on the ecosystem are unknown.

Water Residence Time and Connectivity

Aquatic habitats vary in their degree of hydrologic isolation, which can be described in terms of residence time of the water. Long residence time corresponds to isolated habitats in which local conditions control variability in water chemistry and biological activity. When residence times are short, habitats are well connected and variability is controlled by the movement of water. Estuarine scientists generally believe that spatial variability in conditions is favorable for long-term persistence of the ecosystem. Cloern (2007) used a simple model to explore exchange between a productive donor region and a recipient region of net consumption and found that overall production was maximum at intermediate levels of hydrodynamic connectivity. This concept of donor and recipient habitats is probably important throughout the system. For example, the low salinity zone, usually in Suisun Bay, receives dissolved organic matter, phytoplankton, and zooplankton from the Delta, and the Delta receives large inputs of dissolved organic matter, phytoplankton and zooplankton when the Yolo Bypass floods.

Connectivity also arises through movement of organisms, from the small-scale feeding excursions of resident fish predators in waterweed beds, to the large-scale upstream and downstream migrations of anadromous fish, and even the 4,000-kilometer seasonal migrations of waterfowl. Long-distance migrations link the estuary to distant regions responding to different environmental factors. For example, salmon and striped bass can be affected by ocean conditions that have no discernible direct effect on the estuary. An extreme example of biological connectivity is that between the export pumping plants in the Delta and upstream reservoirs, which are linked by operator requests for changes in river flow to support changes in pumping rate.[6]

Connectivity between estuarine channels through marshes to terrestrial environments was largely cut off by levee construction many decades ago. The consequences of this early change in the Delta can only be guessed at. Research is ongoing on the potential functions of these linkages throughout the estuary.

6 Discussed in greater detail in Chapters 2, 5, and 6

Persistent Problems for Management

Several problems that have persisted for decades continue to impede effective management and restoration of the Bay-Delta system. Although these have been mentioned in previous sections, we raise them here by way of emphasis. We do not offer solutions, but suggest that these problems must be considered as constraints on future management decisions.

Export Pumps and Fish

There is a common perception that the effects of the export pumps in the southern Delta on fish populations are substantial. There are several good reasons for such a perception. First, large numbers of fish are collected at the fish facilities (Brown et al. 1996) and large numbers of them very likely die during the entrainment and salvage process (Gingras 1997). Second, endangered species legislation focuses on protecting individuals as a means of protecting populations. Third, some calculations have shown proportional losses of listed species to be rather high (Kimmerer 2008), although the capacity of these species to overcome such losses is unknown. Fourth, amounts of water exported have increased steadily since the 1960s, while species have declined. Nevertheless, there is no conclusive evidence that export pumping has caused population declines. The lack of unequivocal evidence of large effects of pumping on fish populations does not rule out such effects and, for rare species such as Delta smelt, caution dictates that potential effects should not be ignored.

Another reason for the focus on pumping effects is that controls on export pumping provide the principal tools for managing most species in the Delta, particularly pelagic species. Freshwater outflow is another potential tool that has been applied in the form of the X2 standards, but the efficacy of that control has been weak for some species since about 2000, and nonexistent for Delta smelt (Sommer et al. 2007).

Toxic Effects

Toxic effects of contaminants, including heavy metals and organic compounds, present a very difficult problem. Hundreds of contaminants of many different chemical forms are present in the system (Hinton 1998). Analysis and detection are expensive, and in some cases methods are insufficiently sensitive to detect toxic levels (Oros et al. 2003). Monitoring is incomplete because of the expense and difficulty of some analyses, and because no monitoring program could provide enough spatial and temporal coverage to ensure reliable detection of all toxic chemicals. Several persistent contaminants such as mercury and selenium are abundant in the watershed or in Delta sediments, can accumulate in food webs, and can impair human health.[7] Many of the organic contaminants are present only sporadically, making their effects even more difficult to detect. Bioassays have revealed evidence of toxic effects on invertebrates and fish in the Delta (Kuivila and Foe 1995; Whitehead et al. 2004), but the cause of the toxicity is unknown.

The sporadic and unpredictable occurrence of toxic "hits" is worrisome in that damage to biological populations can arise without any detectable signal of a toxic event. In addition, such events can confound any analysis of population dynamics or experimental work on Delta species. Examples include the low growth rate of phytoplankton in water collected from Suisun Bay (Dugdale et al. 2007), and occasionally poor survival of zooplankton collected for experiments (Kimmerer et al. 2005), both of which could be due to toxic effects.

Clam Effects

The Asian and overbite clams exert a dominant influence on the food web of the Delta. Although there may be a period of a month or two, depending on the season, with low clam abundance near the low salinity zone, that seems insufficient to offset the effects of the two clams. Furthermore, tides and river flow transport chlorophyll and planktonic organisms from areas of high concentration without clams to areas of low concentration with clams, thus depleting even areas fairly remote from the direct influence of clams (Kimmerer and Orsi 1996; Jassby et al. 2002).

The presence of these clams and their rapid colonization of newly available habitat severely limit opportunities to improve conditions in the Delta for fish and other species of concern. Their high filtration rates ensure that, wherever clams are abundant, phytoplankton concentrations will remain low, limiting the growth of consumer organisms. The direct effects of the overbite clam on zooplankton (effects of the Asian clam have not been examined) also reduce the food available to higher trophic levels. The bioconcentration by clams of contaminants such as selenium adds an additional difficulty to this problem. Control of clam populations does not seem feasible, so these problems will persist.

When zebra mussels and quagga mussels enter the estuary, more change will ensue. There is no reason to expect this change to be beneficial, and it will likely result in a further decline in the availability of phytoplankton to support the desired Delta food web.

Waterweed Effects

Many waterways of the Delta are choked with Brazilian waterweed, impeding boat traffic but also trapping sediments, forming habitat for a host of mainly introduced species, slowing water circula-

7 Discussed in greater detail in Chapter 3

tion and increasing local water temperature. The sediment trapping increases water clarity, which reduces the suitability of the habitat for native species, particularly Delta smelt (Feyrer et al. 2007). The non-native fish species form the basis for an important recreational fishery, but they also prey upon native fishes (Nobriga and Feyrer 2007). A major thrust of restoration in the Delta has been developing shallow habitat suitable for native fish. If such habitat is taken over by waterweed, any benefit is eliminated. At present there is no known method for getting rid of waterweed other than through mechanical removal and poisoning, both of which present other problems.

Introduced Species

Apart from the specific examples above, the general topic of introduced species is important for understanding changes in the estuary and watershed, and for management. Species are introduced when an initial group of individuals is transported to the Bay-Delta, in the ballast water of a cargo ship or in a shipment of bait from another estuary, for example. If the initial density of the organisms and local conditions are favorable, the new species can begin to increase in abundance. Disturbed physical habitat can be conducive to successful colonization, although that seems less obvious in open-water environments. Introduced species often go through a period of "overshoot," in which abundance climbs very high and then settles down to some lower level. For example, the Chinese mitten crab *(Eriocheir sinensis)* was first detected in 1992, peaked in abundance in 1998, and then declined to less than 1 percent of its peak population (Rudnick et al. 2003).

In examining the effects of introduced species on the ecosystem, it is helpful to distinguish between introduction events and the ongoing presence of species that were introduced some time ago. Introductions or range extensions can result in sudden and permanent rearrangement of the ecosystem. In the case of "ecosystem engineers" such as the Brazilian waterweed, this rearrangement includes a change in physical habitat. However, once a species has become established, it is part of the ecosystem, and its effect on other species is qualitatively similar to other interactions between species. Following an introduction, the rearranged system may have less capacity to support native species or other species of concern to people. However, if the ecosystem undergoes change well after a non-native species has become established, it makes little sense to attribute that change to the introduced species unless it can be shown how the introduced species could have caused the change. Thus, explaining the POD as an effect of introduced species raises the question of how the introduced species could have caused the POD. This is a basic question about the ecology of the rearranged system.

Threatened and Endangered Species

The status of threatened and endangered species is often a driver for concerted management action. Several dozen native species are listed or have been proposed for listing in the Central Valley, including nine species of fish.[8] Endangered species legislation prescribes a rather narrow approach to species conservation focused on protecting individual organisms and critical habitat. In contrast, ecosystem-based management starts from the assumption that declining species are a symptom of ecosystem-level problems that, if reversed, could reverse declines in individual species. This is difficult to test, and difficult to implement when legal requirements dictate a species-specific approach.

Impending changes in the Delta will likely place additional stresses on listed species. Human actions, such as a change in the way water is moved through the Delta, may have positive or negative effects that are difficult to predict. Catastrophic events, such as levee failures (Mount and Twiss 2005), would likely have negative effects through direct mortality and

8 Discussed in greater detail in Chapter 1

changes in habitat configurations. Climate change has the potential to make the Delta uninhabitable for some species, including Delta smelt and San Joaquin salmon.

Reversing declines for species such as Delta smelt is particularly difficult. Delta smelt is unresponsive to freshwater flow, and few of the likely contributing factors (for example, low food supply, declining turbidity, abundant predatory fish) are very responsive to human control. Export pumping, although blamed for many of the Delta's ills, is only one of several potentially harmful factors.

New tools are being developed by ecologists and conservation biologists that could be used to enhance species preservation in the face of climate change. For example, captive broodstocks of Sacramento winter-run Chinook salmon and Delta smelt have been established as a hedge against catastrophe (Arkush and Siri 2001). Other tools include assisting species range extensions so that they can keep ahead of changing global climate, seed-banking and cryopreservation of genetic material and genetic manipulation to improve resistance to new environmental conditions. Most of these tools are "last-ditch" measures of untested utility.

Forecasting the Future

Change is the one certainty for the Delta. Ongoing climate change with resultant sea-level rise, increasing human population, new invasive species, and the effects of expected but sporadic events such as floods and earthquakes will combine to ensure the Delta of the future will be very different from that of today. Partly in response to these expected changes and partly to solve current problems, intentional changes to the Delta's configuration, such as an alternative means of moving water around the Delta, are likely.

The scientific community will be called upon to forecast what these changes will mean for the ecosystem. This forecast will be difficult for several reasons. The first is the inadequate coverage by our monitoring programs of the ecosystem processes that underlie much of the variability we see in the system. The second is the extreme complexity of the ecosystem, with its layers of spatial, temporal and biological variability. The third is the high uncertainty about future species introductions which, as we have seen, can radically alter the system's response to management and natural inputs. Finally, the extent of the future changes in the physical configuration of the Delta are uncertain.

To begin this essential forecasting process will require a concerted effort by the scientific community. Any anticipated changes in Delta configuration must be identified and examined for their likely consequences. Key uncertainties must be identified and research undertaken to reduce them. To accomplish all this will require mobilization of new resources, additional talent and newly developed methods.

Conclusions

The principal challenge facing managers of the estuary is how to maintain ecosystem services, given the obvious conflicts among them and the long-term changes likely for the ecosystem. Although much of the management focus so far has been on conflicts related to water diversions, in the long term additional human activities are likely to conflict even more with desired ecological services, such as the maintenance of rare or endangered species. Without substantial action, the ecosystem is likely to diverge further from what society would prefer. It will certainly change substantially within the next fifty years or so, as a consequence of the interactions among climate change (increased floods and longer droughts), sea-level rise, land subsidence, levee failure, invasions of new species and changes in land and water management.

Although scientific information is essential for management decisions, we are well aware of the limits of science. For example, the information available a few years ago to assess the causes behind the POD consisted mainly of data on distribution and abundance of the fish species and their presumed food. The acceleration of research into the likely mechanisms for the decline illustrates that monitoring alone is insufficient to develop an understanding of the processes by which species' populations change.

Some previous management decisions made with little or no scientific involvement have not been effective (Lund et al. 2007). Prime examples are the assumptions by CALFED that physical habitat could be constructed as an alternative to freshwater flow, and that the existing ecosystem could be maintained in its present configuration. Thus, we think it is important to keep science integrated into planning processes. Yet inherent mismatches exist between the information needs and time pressures of managers and the ability of the scientific community to provide the necessary information. When such a mismatch exists, it may be wise to be guided by the precautionary principle of taking actions that do the least harm to desirable organisms. On the other hand, the time for taking tentative, timid actions has passed. The most desirable future state of the Bay-Delta's ecosystem is likely to come about only through large-scale actions that are guided by the most current understanding of system processes, while acknowledging inherent uncertainties.

Although it is tempting to call yet again for adaptive management, previous such calls have not been very successful. Instead, we recommend that scientific investigations and ways of thinking be incorporated further into the management process. At the same time, the scientific community should continue its quest for new ways of approaching problems, testing new ideas, developing new tools (for example, molecular methods, new sensors and modeling approaches) and focusing on what we need to know to provide the forecasts that are so clearly in demand.

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