4. The Future of the Delta as an Aquatic Ecosystem

"All truth passes through three stages. First, it is ridiculed. Second, it is violently opposed. Third, it is accepted as being self-evident."

Arthur Schopenhauer

As we saw in Chapter 2, environmental and ecosystem concerns have come to dominate Delta policy, management, and operations in recent decades. This change has come from increased social and political attention to the environment since the 1970s, and it has taken stark legal reality with the listing of several native species as threatened or endangered under the state and federal Endangered Species Acts (Table 2.2). Other federal and state water quality laws (such as the federal Clean Water Act) also influence management of the Delta and estuary. Many aspects of Delta water and land management, from export operations to levee maintenance, are significantly affected by these legal and political concerns. However, these issues are not the only reason for examining the Delta's ecosystem; significant biological issues are also of concern. Invasive species have come to pose expensive challenges to many of the services provided by the Delta. Problems include the collapse of levees from burrowing animals, the clogging of water diversions with alien aquatic weeds, and concerns about the cost and health implications of the physical and chemical means used to control alien species. In addition, recent sharp declines in native species, particularly the delta smelt, indicate the need for attention to biological issues. At the same time, our understanding of the Delta's ecosystem and many of its key species has improved considerably over the last 10 to 20 years, allowing for a more complete analysis of ecosystem problems. This chapter provides an overview of our thinking about the Delta in environmental and ecological terms.

From an aquatic ecosystem perspective, a fundamental conflict exists between two Deltas, namely, the strongly tidal estuarine Delta, which supports a complex ecosystem with a diverse biota, and the agricultural Delta, made up of islands (many subsided) surrounded by high levees. The estuarine Delta naturally fluctuates, both within and across years, between brackish and fresh water. The agricultural Delta created by humans is largely managed as a freshwater system, which provides water for farming and urban areas. Any time that the Delta moves from being a predictable freshwater system toward being a more saline system, major efforts are made to shift it back, by repairing levees, releasing water from reservoirs, reducing water exports, and other actions. As discussed in Chapter 3, it is increasingly evident that a Delta that fluctuates between these states will ultimately win this conflict, as a result of the combined effects of sea level rise, land subsidence, climate change, and levee failures.

The question for this chapter is, "What is likely to happen to the Delta ecosystem as it shifts toward being a more estuarine system in which salinities fluctuate with tides, season, and climate?" Subsidiary questions are: (1) "What habitats need to be abundant in the Delta to favor desirable organisms?" and (2) "What can we do to direct this shift to create an ecosystem that supports desirable organisms?" It is now possible to provide reasonable answers to these questions because of our improved understanding of the ecology of the Delta and the San Francisco Estuary.

Improved Understanding of the Delta Ecosystem

Several basic assumptions on how the estuary operates have proven to be incorrect or only partially correct. Our current understanding of the estuary is based on a series of recent "paradigm shifts" (summarized in Table 4.1 and Appendix A) that should lead to more workable solutions to problems in the Delta. At the same time, it must be recognized that the estuary will continue to change in ways that are difficult to predict, especially as the result of climate change and invasions of alien species. For example, if water temperatures become too warm during the narrow windows of time when delta smelt (*Hypomesus transpacificus*) spawn, their ability to reproduce may be reduced or eliminated (Bennett, 2005).

The present ecosystem is clearly not working well to support desirable organisms, as indicated by the continuing decline of delta smelt, striped bass, and other fish. Because the Delta is always going to have an ecosystem dominated by the combined results of human actions, invasive species, the amount and timing of freshwater inflow, land subsidence, and infusions of toxic materials, the easiest way to assess the nature of desired ecosystem states in the future is to examine how various manipulations will favor key desirable and undesirable species (Table 4.2). Essentially, identifying the species we want in an ecosystem can drive the creation of the most desirable future states of that ecosystem. Throughout this chapter, we focus mainly on the aquatic system but provide some discussion of the terrestrial systems, recognizing that any configuration of the Delta in the future will have to include habitat for key terrestrial species as well, especially overwintering migratory birds (such as waterfowl), neotropical migrants (such as various warblers and thrushes), and sandhill cranes (Table 4.3).

Which Habitats Favor Desirable Organisms?

Views on which organisms are perceived as desirable have changed through the years, but today they include largely (1) native species, especially endemic species (i.e., those native only within a particular area), (2) species harvested for food and sport, including alien species, and (3) species that support the organisms in the first two categories, usually as food, such as copepods and mysid shrimp (Table 4.2). To maintain the Delta as a region that supports these desirable species, especially native aquatic species, there must be habitats with: (1) abundant zooplankton and mysid shrimp, (2) less intrusion of invasive clams, (3) low densities of freshwater aquatic plants, and (4) physical habitat that is diverse in structure and function. To provide these conditions, six basic habitats in the Delta need to be enhanced or maintained: (1) productive, brackish, open-water habitat, (2) brackish tidal marsh, (3) seasonal floodplain, (4) freshwater wetlands, (5) upland terrestrial habitat, and (6) open river channels. These habitats once dominated the San Francisco Estuary. Remnants of these habitats remain and their characteristics can guide restoration efforts, albeit cautiously (Lucas et al., 2002). Overall, a Delta that presents a mosaic of habitats is likely to be the most hospitable to desirable organisms and the most likely to resist invasions by additional alien species. A key to developing such a mosaic is that it would not be stable in either space or time; conditions in each area would change with season and year. Descriptions of the six basic Delta habitats are provided below. Figure 4.1 shows the current locations of these habitats.

Table 4.1

New Understanding of the Delta Ecosystem

New Paradigm	Old Paradigm
1. **Uniqueness of the San Francisco Estuary**	
The San Francisco Estuary has complex tidal hydrodynamics and hydrology. Daily tidal mixing has more influence on the ecology of the estuary than riverine outflows, especially in the western and central Delta. Conditions that benefit striped bass (an East Coast species) do not necessarily benefit native organisms.	The San Francisco Estuary works on the predictable model of East Coast estuaries with gradients of temperature and salinity controlled by outflow. Freshwater outflow is the most important hydrodynamic force. If the estuary is managed for striped bass, all other organisms, and especially other fish, will benefit.
2. **Invasive Species**	
Alien species are a major and growing problem that significantly inhibits our ability to manage in support of desirable species.	Alien (nonnative) species are a minor problem or provide more benefits than problems.
3. **Interdependence**	
Changes in management of one part of the system affect other parts. All are part of the estuary and can change states in response to outflow and climatic conditions. Floodplains are of major ecological importance and affect estuarine function. Suisun Marsh is an integral part of the estuary ecosystem and its future is closely tied to that of the Delta.	The major parts of San Francisco Estuary can be managed independently of one another. The Delta is a freshwater system, Suisun Bay and Marsh are a brackish water system, and San Francisco Bay is a marine system. Floodplains such as the Yolo Bypass have little ecological importance. Suisun Marsh is independent of the rest of the estuary.
4. **Stability**	
The Delta will undergo dramatic changes in the next 50 years as its levees fail because of natural and human-caused forces such as sea level rise, flooding, climate, and subsidence. A Delta ecosystem will still exist, with some changes benefiting native species. Agriculture is unsustainable in some parts of the Delta.	The Delta is a stable geographic entity in its present configuration. Levees can maintain the Delta as it is. Any change in the Delta will destroy its ecosystem. Agriculture is the best use for most Delta lands.

Table 4.1 (continued)

New Paradigm	Old Paradigm
5. **Effects of Human Activities**	
Pumping in the Delta is an important source of fish mortality but only one of several causes of fish declines. Entrainment of fish at the power plants is potentially a major source of mortality. Changes in ocean conditions (El Niño events, Pacific Decadal Oscillation, ocean fishing, etc.) have major effects on the Delta. Hatcheries harm wild salmon and steelhead. Chronic toxicants continue to be a problem, and episodic toxic events from urban and agricultural applications are also a major problem.	Pumping in the southern Delta is the biggest cause of fish declines in the estuary. Fish entrainment at power plants is a minor problem. Changes in ocean conditions have no effect on the Delta. Hatcheries have a positive or no effect on wild populations of salmon and steelhead. Chronic toxicants (e.g., heavy metals, persistent pesticides) are the major problems with toxic compounds in the estuary.

Table 4.2

Important Aquatic Species and Habitat Conditions That Improve Their Abundance

Species	Desirability	Description	Salinity	Temperature (°C)	Flow	Rearing Habitat
Delta smelt	+++	Threatened species, endemic	Fluctuating[a]	< 20°	Tidal	Open water, pelagic, brackish
Longfin smelt	+	Declining species	Fresh-marine	< 16°	Tidal	Open water, pelagic, marine
Splittail	+	Endemic	Brackish-fresh	< 24°	Tidal	Brackish tidal marsh
Tule perch	+	Native, declining	Fresh-brackish	< 22°	Tidal, river	Tidal marsh, river edge
Striped bass	++	Sport fish, declining	Fluctuating	< 25°	Tidal	Open water, pelagic, brackish
White sturgeon	+	Sport fish, declining	Brackish-marine	< 20°	Any	Bottom, open bay
Green sturgeon	++	Threatened species	Fresh-marine	< 20°	High river for spawning	River, then marine
Chinook salmon[b]	+++	Endangered to commercially fished	Fresh-marine	< 20°	Tidal, river currents	Shallow edge and flooded
Large estuarine copepods	+++	Important in food webs	Fluctuating	Depends on species	Tidal	Open water, pelagic
Mysid shrimp	+	Important in food webs	Fluctuating	< 20° ?	Tidal	Open water, pelagic
Diatoms	++	Basis for food webs	Various	Various	Tidal	Open water
Largemouth bass	–	Alien predator, game fish, indicator	Fresh	< 30°	None, low	Backwaters, sloughs
Asiatic clam	–	Alien filter-feeder	Fresh	< 35°	River, tidal	River channels, flooded islands
Overbite clam	– – –	Alien filter feeder	Brackish	< 23°	Tidal	Suisun, San Francisco Bays

Table 4.2 (continued)

Species	Desirability	Description	Salinity	Temperature (ºC)	Flow	Rearing Habitat
Brazilian waterweed	– – –	Alien plant pest	Fresh	< 35º	None-low	Delta sloughs
Water hyacinth	–	Alien plant pest	Fresh	< 35º	None	Delta sloughs

NOTES: +/– indicates desirability of species to humans as seen by how likely the species are to influence management decisions (+ positive, – negative, with the strength of the desirability indicated by the number of + and – signs). All + species are declining, and all – species are abundant or increasing. Temperature, salinity, and flow represent preferred conditions.

[a] Fluctuating salinities means that the salinities will change enough on an annual and interannual basis to discourage undesirable nonnative species.

[b] There are four runs of salmon (winter, late fall, fall, and spring) with different status and habitat requirements.

Table 4.3

Selected Important Terrestrial/Upland Species for Which Changes in the Delta, Suisun Marsh, and Surrounding Areas Will Cause Changes in Abundance

Species	Desirability	Importance	Delta	Suisun	Upland/ Agricultural Areas	Riparian Areas	Notes
Wintering waterfowl	+++	S, R, D, B	xxx	xxx	xx	xx	50+ species
Neotropical migrant birds	++	R, D, B	xx	xx	xxx	xxx	Many species, including three species listed under CESA
Swainson's hawk	++	E, S, R	xx		xxx	xx	
Sandhill crane	+++	E, S, R	xxx		xxx	x	Major wintering population
California clapper rail	++	E, R		xx			Requires tidal marshes
Black rail	+	E, R	x	x			
Yellowbilled magpie	+	S, D, R	xx	x	xxx	xx	Decline from West Nile virus
Salt marsh harvest mouse	++	E		xxx			
Beaver	–	N, R	xx	x		xx	Burrows into levees
Muskrat	– –	N, I	xx	x	x	xx	Burrows into levees
River otter	+	S, R	xx	xxx		xx	Major population
Mexican freetail bat	+	S, R, B	xx	x	xx	xx	Large population, eats pest insects
Giant garter snake	+	E	xx		x	xx	Listed
Fairy shrimp	+	E	x		xxx		Four listed species under ESA and CESA; in vernal pools (special habitat)
Valley elderberry longhorn beetle	++	E	xx	x	x	xxx	*De facto* protection for elderberry bushes; may be delisted

Table 4.3 (continued)

Species	Desirability	Importance	Delta	Suisun	Upland/ Agricultural Areas	Riparian Areas	Notes
Mosquitoes	– – –	N	xxx	xxx	xxx	xxx	Several species; spread West Nile and other diseases
Tules	++	S, B	xxx	xxx	x	xx	*Scirpus* species; habitat, bank protection, etc.
Fremont cottonwood	+	S, B	xx		x	xxx	Major riparian tree, important for birds, etc.
Local endemic plants	+	E, D	xx	xxx	xxx	xx	Highly localized with special requirements
Perennial pepperweed	– –	N, I	xx	xx	xx	xx	Representative of invasive alien plants

NOTES: +/– indicates desirability of species to humans as seen by how likely the species are to influence management decisions (+ positive, – negative, with the strength of the desirability indicated by the number of + and – signs). Importance: E (listed as threatened/endangered by state or federal agencies), D (declining), S (symbolic, charismatic, and emblematic of region), R (recreation, hunting, birdwatching, etc.), N (nuisance species), I (introduced species), B (ecologically beneficial species). The number of xx's in major habitat area indicates importance of the habitat to the organism.

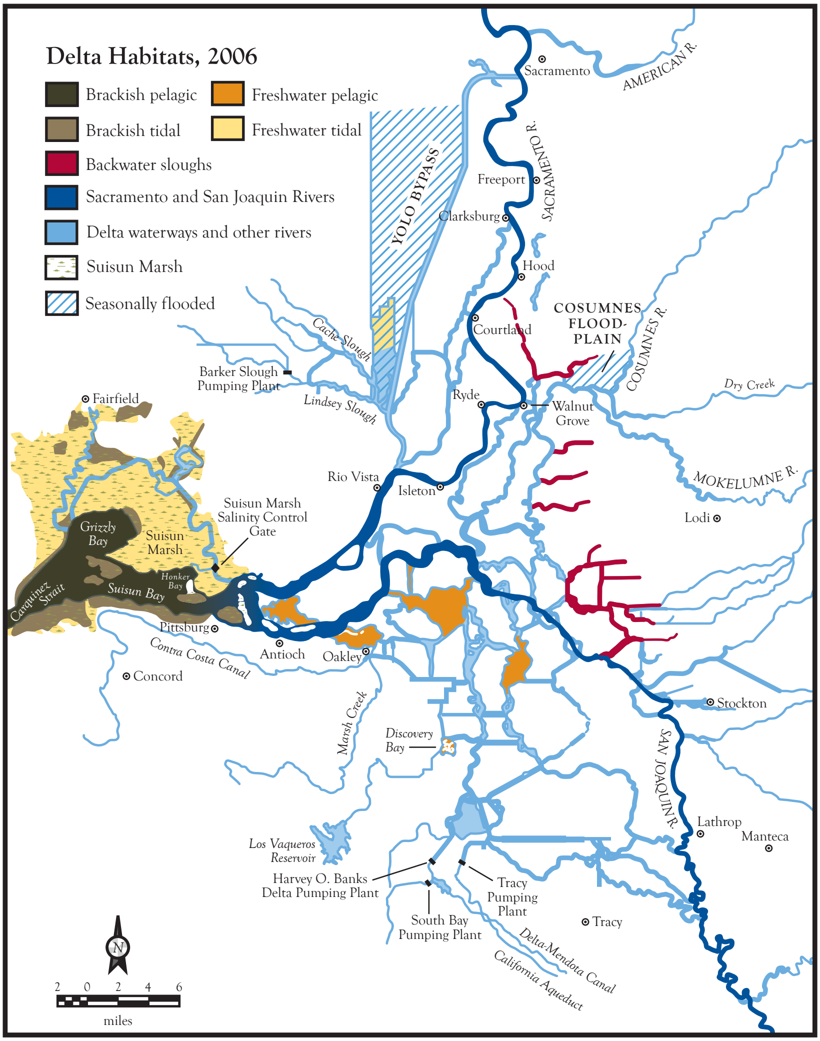

Figure 4.1—Delta Habitats, 2006

Productive Brackish Open-Water Habitat

For the past 20 to 25 years, the greatest concern over declining numbers of fish that depend on the Delta has been for open-water (pelagic), plankton-feeding fish, mainly delta smelt, longfin smelt, and striped bass. Their long-term decline has apparently accelerated since 2001, increasing concern for the viability of their populations and those of other pelagic fish.[1] This decline is tied in part (but by no means entirely) to the shift in the food web of Suisun Bay and the Delta. Previously, most energy and carbon flowed through pelagic zooplankton and fish; currently, most energy and carbon instead flow through the alien overbite clam (*Corbula amurensis*), which became established in the region in 1986 (Carlton et al., 1990).

Historically, Suisun Bay was the principal brackish water region where most open-water habitat existed. It was without abundant clams (except in dry years when marine clams invaded) and therefore supported abundant diatoms (a type of algae or phytoplankton), which were fed on by zooplankton (mainly *Eurytemora affinis*, a copepod), which in turn were fed on by both small plankton-feeding fish (e.g., delta smelt) and mysid shrimp (mainly *Neomysis mercedis*). The mysid shrimp then became a major item in the diets of larger planktivores, especially longfin smelt and juvenile striped bass. But with the invasion of the brackish water tolerant overbite clam, these food organisms became greatly depleted, presumably reducing the growth and survival of the planktivores. Thus, open-water habitat still exists, but its productivity is funneled more into clams than into desirable fish.

As productive open-water habitat has diminished in brackish water areas, other areas favorable to pelagic organisms have been reduced as well. This loss is mainly the result of the Brazilian waterweed (*Egeria densa*) and other submerged aquatic vegetation, which have invaded freshwater sloughs, channels, and flooded islands of the Delta (Brown, 2003). Waterweed grows in dense mats in shallow water (< 3 m) along the channel edges and can completely choke shallow quiet water habitats during the warmer months. These plants slow the flow of water and retain sediments, nutrients, and other materials from the water column; consequently, the water tends to be clearer. These more transparent waters support populations of alien invertebrates and fish, including centrarchids, mainly largemouth bass, bluegill, and redear sunfish. In contrast, the more open, less transparent habitats in the Delta are more likely to support populations

[1] http://science.calwater.ca.gov/pdf/worksho ps/POD/IEP_POD_Panel_Review_Final_010606_v2.pdf. For a graph showing trends in abundance indices of key pelagic species, see Figure 1.3.

of striped bass, delta smelt, Chinook salmon, and splittail (Nobriga et al., 2005).

Generally, where Brazilian waterweed is abundant, open-water habitat is reduced and alien fish and invertebrates dominate, conditions mostly undesirable from an ecosystem perspective (Brown, 2003; Nobriga et al., 2005). The bass (and other warm-water fish) support fisheries, but these fisheries do not depend on the estuary for their existence (as do fisheries for striped bass, salmon, and splittail). Where currents are too strong for Brazilian waterweed to become established, freshwater channels may support dense populations of the Asiatic clam (*Corbicula fluminea*) which can strip the water column of plankton, reducing food supplies for pelagic fish. This is especially true today in the southern Delta, where the Asiatic clam is abundant in the San Joaquin River channel.

These changes mean that estuarine-dependent pelagic organisms, such as striped bass, have seen a loss of habitat in both freshwater and brackish water. The key to restoring the desirable pelagic species is to recreate habitats that have a high variability in nonbiological (or "abiotic") factors such as salinity, channel flows, depth, and water clarity (Nobriga et al., 2005; Lopez et al., 2006). This is the kind of estuarine habitat that once dominated many Delta channels and Suisun Bay: open-water areas that varied sufficiently in salinity from fresh to moderately salty (roughly 8–10 parts per thousand (ppt)) seasonally or across years and often had strong tidal currents and low water clarity.[2]

In areas where such conditions return, it is unlikely that the overbite clam, Brazilian waterweed, or the Asiatic clam will be able to persist. It appears that moderate salinities during the summer growing season will exclude Brazilian waterweed. The Asiatic clam may require salinities exceeding 13 ppt for complete exclusion but the species is rarely abundant where salinities exceed 5–6 ppt for extended periods of time (Morton and Tong, 1985). Unfortunately, the biggest problem species in brackish water, the overbite clam, can live and reproduce in water ranging from fresh to 28 ppt, at temperatures of 6°C to 23°C (Parchaso and Thompson, 2002). Like many clams, its growth and reproduction are limited by food supply,

[2]As a rough guide, seawater is 35 ppt and fresh water is less than 3 ppt. Drinking water is less than 1 ppt.

but this clam is large enough and lives long enough (two to three years) so that it can survive many weeks with limited food (Parchaso and Thompson, 2002).[3] Nevertheless, the overbite clam is highly stressed when exposed to fresh water (Werner, 2004) and has not colonized areas in the estuary that are fresh for extended periods of time, despite being physically able to do so. This suggests that annual exposure to fresh water for three to six months may limit its ability to invade some areas.

Today, the best example of habitat with low numbers of these alien species is Suisun Marsh, especially in Nurse Slough (R. E. Schroeter, UC Davis, personal communication, 2006). This turbid habitat, with few clams, contains abundant phytoplankton and zooplankton and thus is favorable for rearing small estuarine fishes such as delta smelt and juvenile striped bass. Essentially, this habitat has enough variability in abiotic conditions, especially salinity, that undesirable populations of both freshwater and brackish water organisms are inhibited.[4] The most likely location of restored habitat of this nature would be on flooded islands close to sources of both salt water and fresh water (e.g., Sherman Island, Twitchell Island). Alternatively, undesirable alien species could be excluded by keeping islands completely enclosed by levees but adding gates that would allow free access to tidal flows in most years. If gated, these pelagic habitat islands could be drained and dried as a control measure for invasive species when necessary (Table 4.4).

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[3]Overbite clams can persist in fresh water because they can burrow into sediments, which can retain salts for long periods of time, and then clamp their valves together until good conditions return. "So a Corbula living in the sand can simply burrow down, crack its valves for a little freshening periodically and live as long as the water doesn't drop below its oxygen limit or until it runs out of energy stores" (J. Thompson, U.S. Geological Survey (USGS), personal communication, May 2006). Nevertheless, most overbite clams residing in lower Suisun Slough were killed during the winter of 2005–2006, presumably because of continuous freshwater flows from Cordelia Slough, which receives water from nearby creeks. Clams survived, however, in the reach of Suisun Slough immediately above the mouth of Cordelia Slough, which lacked the heavy freshwater influx (R. E. Schroeter, UC Davis, personal communication, 2006).

[4]What may be as important as variability per se is the suddenness of change; conditions, especially salinity, that change abruptly (over a few days) may eliminate undesirable organisms more effectively than more gradual change.

Table 4.4

Likely Responses of Populations of Common Delta Fish and Shrimp to Increases in Three Salinity Regimes in a Large Open-Water Environment

Species	Fresh	Brackish	Fluctuating
Delta smelt	– –	–	+
Longfin smelt	–	–	+
Striped bass[a]	–	–	++
Splittail	0	+	++
Tule perch	+/–	?	+
Prickly sculpin	–	0	+
Hitch	+?	0	0
Blackfish	+	0	0
Fall-run Chinook	+/–	+/–	+/–
Spring-run Chinook	+	+	+
Winter-run Chinook	+	+	+
Steelhead	0	0	0
White sturgeon	0	+	0
Largemouth bass[a]	++	0	–
Lepomis spp[a]	++	0	–
Inland silverside[a]	++	+	+
American shad[a]	0	0	0
Threadfin shad[a]	+	0	+
Shimofuri goby[a]	0	+	+
Yellowfin goby[a]	0	+	+
Golden shiner[a]	++	–	–
Mosquitofish[a]	++	+	0
Siberian prawn[a]	–	+	++
Mysid shrimp	0	+	+

NOTES: For definitions of symbols, see Table 4.2. Salinity in this case is the indicator of the changed environment; changes in water clarity, temperature, and depth would also influence fish populations. A freshwater habitat would essentially resemble present-day Franks Tract and Mildred Island. A brackish water habitat would be like present-day Suisun Bay. A fluctuating salinity environment would be most like portions of Suisun Marsh.

[a]Indicates non-native species. 0 = no change.

Brackish Tidal Marsh

Brackish tidal marsh is the main habitat along the sloughs of Suisun Marsh, in the unleveed portions of Suisun Marsh, and in marshes along the edge of Suisin Bay. This ecosystem was once much more extensive in Suisin

Marsh, Suisun Bay, and the lower Delta. Brackish tidal marsh is typically shallow (< 2 m at high tide), cool (< 20°C), turbid (transparency < 35 cm), and complex in structure, with a strong tidal influence (Matern, Moyle, and Pierce, 2002; Brown, 2003). Such habitat is important for rearing desirable fish, especially splittail, juvenile striped bass, and perhaps juvenile Chinook salmon. Not only are fish in general more abundant in the unleveed sloughs, but the proportion of native fish also tends to be high (R. E. Schroeter, personal communication, 2006). Such areas also are presumed to be an important source of nutrients for adjacent channels and bays. Areas inundated by tidal water for only short periods support vegetation important for such threatened species as salt marsh harvest mouse, black rail, and clapper rail.

With sea level rise, this habitat will expand in Suisun Marsh, as levees eventually overtop and breach. The depth of the habitat will depend on how much subsidence occurs before the inevitable flooding takes place and on how much the growth of submerged vegetation keeps up with sea level rise. Ideally, some shallow channels in the marsh will continue to have characteristics that exclude the overbite clam and favor native fish, through the input of fresh water from the Sacramento River, local runoff, and, perhaps, tertiary treated sewage from the Suisun-Fairfield urban area. If we recognize the inevitability of sea level rise, it should be possible to maximize its benefits or control its effects, by planning for a "new" brackish Suisun Marsh.

Seasonal Floodplain

Recent studies show that seasonally flooded habitat in and just above the Delta (i.e., Yolo Bypass, Cosumnes Preserve) is important for spawning splittail and for rearing juvenile salmon and other fish (Sommer et al., 2001a; Crain, Whitener, and Moyle, 2004; Moyle et al., 2004; Moyle, Crain, and Whitener, in press). The Yolo Bypass is unique as a "flow through" system, in which water has a limited "residence time" (i.e., it moves through the bypass relatively quickly). As a result, it floods on an irregular basis (when water spills over the Fremont Weir) and drains quickly. Much of the invertebrate biomass is chironomid midges, which can persist (as eggs) in dry soil.

The most productive floodplain habitat for fish outside the Yolo Bypass is covered with annual vegetation and is flooded with river water from roughly early February through April. In contrast to the Yolo Bypass, the water in these areas often drains slowly, so has a high residence time, allowing it to develop dense populations of zooplankton. The best places to create and maintain such habitat (e.g., expanded Cosumnes Preserve, Cache Slough region, lower San Joaquin River) need to be actively managed to maintain a habitat mosaic and to make sure that flooding occurs on at least part of the available habitat each year. These areas can also be important foraging and roosting areas for migratory waterfowl.

Freshwater Wetlands

Much of Suisun Marsh and parts of the Delta (e.g., Cache Slough region) are managed directly or by default as freshwater marshes. Such marshes are important for an array of plants and animals, especially waterfowl and shorebirds. There are several types of these wetlands, with distinctive characteristics, that presumably all need to be maintained. As the area of freshwater wetland shrinks in Suisun Marsh, more freshwater wetlands may have to be created on Delta islands currently devoted to agriculture, especially if waterfowl habitat (and hunting) is to be supported at present levels. These islands could follow the models proposed by Delta Wetlands Corporation, which have wide levees that slope toward the interior, supporting riparian vegetation and interior water levels that are managed for waterfowl (or water storage).[5]

Upland Terrestrial Habitat

Agricultural areas, especially those islands on which corn and rice are grown, can be important foraging areas in winter for sandhill cranes, migratory waterfowl, and raptors such as Swainson's hawk. Presumably such areas will continue to exist in parts of the Delta that lie at or above sea level. However, this habitat is prone to urban development. To maintain adequate

[5]The Delta Wetlands project is a proposal to use two islands in the central Delta (Bacon and Webb) as freshwater storage facilities and two others as waterfowl habitat. It is one of five surface storage projects identified in the CALFED Programmatic Record of Decision (CALFED, 2000a).

areas of this habitat, substantial tracts (e.g., Staten Island) will have to be managed, often behind levees, with wildlife as the highest priority.

Open River Channels

Delta channels, especially those leading to flowing rivers, must be maintained as migratory corridors for salmon, steelhead, lamprey, splittail, delta smelt, and other fish. Ideally, fish migration corridors should also minimize the risk of entrainment in the pumps in the southern Delta. These channels also need to provide juvenile rearing habitat along their edges and offer connectivity between spawning and rearing areas (e.g., for splittail, between floodplain spawning habitat and brackish tidal marsh rearing habitat). The present configuration of the Delta, especially the southern Delta, results in complex flow patterns through the channels that presumably confuse migratory fish going both upstream and downstream. Channel configurations need to be reconstructed in ways that resemble historical conditions—that is, with more natural spatial patterns with fewer straight lines and more dendritic, or branchlike, patterns (J. Burau, USGS, personal communication). These channels also need to be managed in ways that discourage alien species.

How Can We Create a Delta That Supports Desirable Organisms?

The crisis brought on by the continuing pelagic organism decline, especially delta smelt, has led to the realization that the Delta ecosystem is not providing for the needs of key organisms. The growing recognition that major changes to the Delta will occur as the result of the factors discussed in Chapter 3 is also forcing a reexamination of the future of the Delta ecosystem. In addition, we now know that many of our basic assumptions about how the Delta operated as an ecosystem that were used in planning in the past were wrong or misguided (Table 4.1 and Appendix A). Taken together, these realizations provide both the motivation and the opportunity to rethink how we might manage the Delta's ecosystem, using guidelines that follow.

Given the inevitable changes that will occur to the Delta ecosystem, our choice is either to respond to each change as a disaster or to plan for it as an opportunity to create more predictable and productive environments for fish and wildlife. Some key features of a carefully planned effort at controlling change to favor desired organisms include (1) tying the Delta to adjacent ecologically important areas, (2) creating island and channel habitat diversity by reengineering Delta planforms to enhance dendritic channel patterns that support various habitats (particularly in terms of salinity and water residence time), (3) preventing the "hardening" of secondary Delta lands by urban development, and (4) improving connectivity between rivers and parts of the Delta.

Tie the Delta to Adjacent Areas

Much of the discussion of the Delta ecosystem focuses on the central and southern Delta because these areas have significant subsidence problems and major, immediate connections to the SWP and CVP pumps. From an ecological point of view, it is unclear what can or will actually be done to islands in these areas to benefit the species of concern, given the high likelihood of uncontrolled flooding (discussed in Chapter 3). We need therefore to look to areas adjacent to the Delta to provide most of the desired ecological functions. It is also quite likely that money invested in these adjacent areas will produce a bigger return in ecological value on a per dollar basis than money spent on interior Delta projects. Some key areas include:

1. **Cache Slough region.** This area, to the north, adjacent to the Yolo Bypass, is within the legal boundaries of the Delta but is rarely discussed in a Delta context, in part because what happens there has little effect on the delivery of fresh water via the pumps of the southern Delta. Yet it has large tidal excursions (much of the tidal water moving up the Sacramento River channel winds up there), a complex, branching channel pattern, and is a known spawning and rearing area for delta smelt and probably for other native fish as well. It is the outlet for water draining from the Yolo Bypass, with potential major interactions ranging from exporting nutrients to rearing juvenile salmon (Sommer et al., 2001a and 2001b). Arguably, this region is most like the historical Delta, although many of its channels have been leveed or otherwise altered. A "natural" levee failure experiment exists there now (Liberty Island, which flooded in 1998) and much of the

land is in private ownership. It also has the intake for the North Bay Aqueduct (in Barker Slough), which may constrain some uses.

2. **Yolo Bypass.** The Delta doubles in size when the Yolo Bypass is flooded. The problem is that the bypass floods only erratically and not always at times optimal for fish and birds. The bypass presents some major opportunities for ecosystem manipulation (e.g., by gating the Fremont Weir), which are currently under discussion (Department of Fish and Game, 2006). It is also a major spawning and rearing area for splittail and other native fish, a rearing area for juvenile salmon, and a potential source of nutrients for Delta food webs (Sommer et al., 2001a and 2001b). This region could act as a major interface with the Delta ecosystem, especially in the Cache Slough region, a role that will likely grow in importance, both through deliberate manipulations and through the increased frequency of flooding as a result of climate change.
3. **Van Sickle Island/Southern Suisun Marsh.** Van Sickle Island is a major marshy island that borders the west side of upper Montezuma Slough (by the tidal gates) and the south side of Suisun Bay, where the Sacramento River enters. Its levees failed in several places during the winters of 1997–1998 and 2005–2006, but they were fixed by DWR to protect infrastructure around the Roaring River that helps to keep salt water at bay.[6] This infrastructure is the water delivery system that maintains the interior marshes as freshwater systems for duck hunting clubs. One potential negative effect of allowing Van Sickle Island to flood is that this may increase the likelihood of highly saline water arriving at the pumps of the southern Delta. Nevertheless, Van Sickle Island has high potential as a place to create a large expanse of brackish tidal marsh, a desirable feature that may be inevitable as sea level rises. The potential negative effect on water delivery might be lessened if the island were breached on the Montezuma Slough side, with south-side levees being maintained, before the system was inundated naturally.

[6]DWR took this step even though these are private levees, not "project" levees under state and federal responsibility.

4. **Cosumnes/Mokelumne River confluence area.** The Cosumnes River preserve is a floodplain demonstration area, relatively small, but important for fish spawning and rearing (Moyle, Crain, and Whitener, in press). There are opportunities both within the preserve area and nearby for expanding the floodable lands and creating more upland habitat useful for sandhill cranes, waterfowl, and other species of interest.
5. **Upland agricultural areas.** Sandhill cranes and waterfowl need these farmland areas, preferably planted in corn, for winter foraging. Much of this habitat is on islands that could or will flood (e.g., Staten Island). However, upland areas around the Delta are increasingly turning into housing tracts and vineyards. This trend needs to end if habitat for cranes and waterfowl is to be maintained. This is especially important as heavily subsided islands become submerged or converted to other uses.

Create Island and Channel Habitat Diversity

If we want habitat heterogeneity, then we should consciously choose the types of island and channel habitats we want and figure out how to achieve the right balance among them. This process would involve managing island levees and land uses, as well as reengineering some Delta channels to create a more naturally diverse dendritic channel structure, which would allow for greater variability in salinity, residence time, and flow velocities across the Delta (J. Burau, personal communication, 2006). Of course, the possibilities for restructuring the system will depend on the nature of the cross-Delta water delivery system. Here are some possible alternatives for island and channel management:

1. **Natural pelagic habitat.** This would consist of islands or sections of islands in the western Delta (i.e., Sherman, Twitchell, Bradford, Jersey) in which strategic levee breaches could cause strong tidal excursions, allowing salinity fluctuations that inhibit overbite clam, Asiatic clam, Brazilian waterweed, and other undesirable species. Basic island configuration could be maintained by specially designed levees, if desired, but it might be possible to just let one or two islands revert to open water without levees. Without significant effort, however, many

subsided islands will become warm-water fish habitat like Franks Tract or Mildred Island, described below.

2. **Controlled pelagic habitat.** These areas would be modeled on the proposed Delta wetlands project and would feature sloping interior levees supporting riparian forest and tule beds.[7] They would have gates in several places to regulate inflow and outflow. An ideal feature would be the ability to dry them completely when undesirable invasive species become too abundant. If strategically placed, islands with sufficient area and depth might be used to regulate salinity or outflow in extreme situations (e.g., levee failures on other islands). One advantage of this kind of management is that options for various ecological and water supply uses would be kept open.
3. **Wildlife habitat.** These islands could also be maintained for ducks and other waterfowl, as in the Delta Wetlands model. They would be flooded only enough to produce duck habitat, which includes some wildlife-friendly farming, and would presumably be dry in summer, except for recreational ponds. Waterfowl production and hunting opportunities are likely to decrease in Suisun Marsh, as a result of flooding by salt water from sea level rise and deliberate manipulations. Hunting could shift from Suisun Marsh to some Delta islands, where new hunting clubs could be established. This shift would allow for opportunities to create more tidal habitat in Suisun Marsh. This option assumes, of course, that subsided islands with large, inward-sloping levees would be able to resist flooding from sea level rise and that a source of fresh water would be available for wildlife habitat. Much would depend on the amount and rapidity of sea level rise and on the design and operation of the interior Delta.
4. **Warm-water fish habitat.** Franks Tract and Mildred Island are examples of warm-water fish habitats and originated as subsided islands that have been "let go." They have become heavily invaded by alien species from plants to invertebrates to fish, but they do have such recreational benefits as boating and fishing. The location and size of

[7] Here, we suggest an alternative use of flooded islands—for habitat instead of freshwater storage—using the same basic technology of sloped and rocked interior levees.

such open-water areas in the Delta could make a big difference both in Delta tidal circulation and in the timing and frequency of saltwater fluctuations.

5. **Agricultural islands.** Some of the least subsided islands could be maintained indefinitely for wildlife and Delta-friendly agriculture. A key would be to promote agricultural practices that discourage urbanization and prevent—or even reverse—further subsidence. One focus for the development of such islands could be sandhill crane and Swainson's hawk foraging areas.

Prevent Hardening of Adjacent Upland Areas

When upland areas around the Delta become urbanized, are turned into vineyards, or become devoted to other uses that greatly increase land values, land use choices diminish. "Hardened" areas are also likely to have increased human use, and this change may have significant consequences for wildlife. For example, if Staten Island and other Delta islands that are used by sandhill cranes for foraging become submerged, the cranes will need similar agricultural land elsewhere—and hardened areas will be unable to provide it.

This is largely a planning issue, and big development forces are arrayed against the maintenance of low-value farm crops (see Chapters 3 and 5). But the value of these upland areas to wildlife, including endangered species, should be emphasized. Rather than an area of urban development, the Delta could be considered open space and a benefit to citizens of nearby urban areas, from Sacramento to Stockton to San Francisco.

Improve Connectivity

In any proposed changes, the importance of Delta channels for upstream and downstream migrating fish has to be kept in mind. Clear migration routes to the Sacramento and San Joaquin Rivers, as well as to the Mokelumne and Cosumnes Rivers, must be maintained and enhanced. Potentially, a redesigned Delta could improve connectivity in a number of ways: by reducing exposure of fish to entrainment in the pumps in the southern Delta and other agricultural, urban, and power plant diversions; by better management of barriers and gates on Delta channels; by rebuilding key channels to improve passage and water movement; and by providing rearing habitat for juvenile fish. Improving connectivity is clearly not an easy task in the effort to balance water supply and ecological needs in a changing Delta. For example, in the present Delta, the delta smelt and Chinook salmon have different, and at times opposing, needs.

Research Needs and Potential Experiments

Management of the Delta as an ecosystem should be driven by the best scientific information available. Despite considerable new information, a great deal of uncertainty remains about the effects of various management actions. Nevertheless, there is a growing consensus that major change is going to happen, whether we like it or not. Because there is never enough information to make decisions with absolute certainty, a synthesis of existing information is needed to reduce decisional paralysis. Here are some suggestions.

1. **Commission an overview.** Given the great increase in knowledge of the system in the past 15 years, it would be useful to have a new, overarching study of the ecology of the estuary, along the lines of Herbold and Moyle (1989) and Herbold, Jassby, and Moyle (1992), beyond just the open-water system (Kimmerer, 2004).
2. **Examine invasive species.** A recently compiled database on invasive species in the Delta (Light, Grosholz, and Moyle, 2005) begs for analysis of species interactions, potential problem species in response to Delta changes, and predictions of the nature of potential future invaders.
3. **Develop predictive models.** The interactive effects of changing salinity, temperature, depth, water clarity, and flow on key alien species such as Brazilian waterweed, overbite clam, Siberian prawn, and Asiatic clam in particular should be studied.
4. **Pursue synthetic studies.** These studies should focus especially on how to manage the Cache Slough region and Suisun Marsh for desirable species, as sea level rises and climate changes. The Cache Slough region also needs basic ecological studies.
5. **Perform hydraulic modeling.** Analyze whether it is possible to manage selected islands as open-water systems to favor desirable pelagic organisms (delta smelt, striped bass, etc.)—and if so, how.

6. **Develop experimental islands.** A factor that inhibits taking action to convert Delta islands to different uses is uncertainty: What happens in reality when we breach levees or allow an island to be flooded? One way to reduce uncertainty is to develop experimental islands. This is being done today at Dutch Slough on the southwestern edge of the Delta, although funding limitations are reducing options and monitoring (B. Herbold, U.S. EPA, personal communication, 2006). Sherman Island also has potential for experimentation, because of its shallowness and key location near the lower apex of the Delta. It could be segmented into smaller "islands" with different experimental flooding regimes (J. Cain, Natural Heritage Institute, personal communication, 2006).

Some of this research might be accomplished by traditional agency and academic efforts. However, there will be an increasing need to integrate research efforts to make faster improvements in our understanding and to focus additional research efforts more intently on remaining uncertainties. The efforts of the CALFED science program in this area remain embryonic and are not particularly integrated. Greater funding and much greater scientific leadership will be needed if we are to take an aggressively adaptive approach to management.

Conclusions

The Delta ecosystem has been changing rapidly and often unpredictably for the past 150 years, a trend that is likely to accelerate unless we take action to control the change as much as we can. Ultimately, the rate of change may slow down even if we do nothing but respond to emergencies. However, the resulting Delta system is likely to have many undesirable features and species and to be missing many of the species we regard as important today. Such an outcome is not inevitable, though. There are reasonable steps that can be taken to restore Delta habitats to more desirable, variable conditions in terms of flow and water quality, conditions that would better support desirable species and disrupt the establishment of invasive species.

The approach outlined here represents a new and different scientific understanding of how the Delta and its ecosystem function. As will be seen in later chapters, our improved understanding of the Delta's ecosystem leads to the consideration of very different land and water management alternatives and to new conclusions for Delta policy and management. New and more promising alternatives can be designed to take advantage of this improved understanding.

Before exploring these alternatives, we provide some background on recent Delta policymaking (Chapter 5) and then assess the ability of water users and the larger water supply system to adjust to changes in Delta water management policies (Chapter 6). In the end, it is desirable to have solution alternatives that support as many as possible of the Delta's current services.