Delta Vision

Context Memorandum: Delta Ecosystem

This context memorandum provides critical information about the Delta ecosystem to support policy making. As they are developed, the context memos will create a common understanding and language about the critical factors in establishing a Delta Vision.

This is an iterative process and this document represents the beginning of a dialogue with you about how best to understand these lessons and to inform recommendations by the Delta Vision Blue Ribbon Task Force. You have two weeks to submit comments that may be incorporated into the next iteration.

You may submit your comments in two ways: either online at dv_context@calwater.ca.gov or by mail. If you are using mail, please send your comments to: Delta Vision Context Memo: Delta Ecosystem, 650 Capitol Mall, 5th Floor, Sacramento, CA 95814.

Your attributed comment will be posted on the Delta Vision web site (http:www.deltavision.ca.gov). Please cite page and line number with specific comments; general comments may be keyed to sections.

Your participation in this iterative process is valuable and important and is greatly appreciated. Thank you for your comments.

Context Memorandum: Delta Ecosystem

Iteration 1: August 13, 2007

Executive Summary

The Sacramento-San Joaquin Delta and the Suisun Marsh are important components of the San Francisco Estuary, which is the largest estuary on the Pacific coast and one of the largest in the United States. The Delta is formed by the convergence of the Sacramento, San Joaquin, Calaveras, Cosumnes, and Mokelumne rivers, which drain over 40% of the State's land area and convey 47% of the State's annual runoff. The Delta is a critical hub in California's statewide system of water management and redistribution, providing drinking water to 23 million Californians and irrigating billions of dollars in crops. Cities and towns around the margin of the Delta are among the fastest growing urban regions in California and many of these cities and towns get their water from the Delta. The Delta is also an important recreation area for this growing population and for millions of visitors. Besides food, water and a place to play, the Delta provides an array of ecological services to the people of the region and of California as a whole including waste disposal, detoxification and recycling, transportation corridors, recreational and commercial fishing/hunting.

The ecological services of the Delta, which are critical to human health and wellbeing, and the unique ecosystems and species of the Delta are threatened by unsustainable use. New, more holistic approaches to the human/environment relationship in the Delta are needed if the loss of services and species is to be halted and reversed. Our concept of the Delta also needs to change from one that views the Delta as a stable and relatively uniform system to one that views it as a diverse and variable system. This memo describes the ecological foundation for such a new conceptualization. The memo is built around twelve key ecological principles, which are summarized below together with their main policy implications.

Principle 1: The physical environment (hydrology, climate, chemistry, landforms) of the Delta and associated lands establishes the template within which the ecosystem mosaic of the Delta is formed.

Main Policy Implication: Desired species and ecosystems in the Delta cannot be sustained without ensuring that the necessary physical structures and processes are in place to accommodate them.

Principle 2: The natural environment of delta/estuaries is dynamic and variable and the organisms that live there are adapted to that variability.

Main Policy Implication: Management of the Delta/estuary needs to incorporate enough of the natural variability of estuaries to provide the necessary physical environmental template for native species. Human uses of large parts of the Delta/estuary may have to be changed to accommodate the necessary variability.

Principle 3: Climate and weather are primary drivers of the physical environment of the Delta/estuary. Due to accumulating greenhouse gases in the atmosphere, global and local climates are changing. California is likely to be warmer and dryer in the future, precipitation in the mountains will shift from snow to rain, storms are expected to be more frequent and more severe, and sea level will rise. These changes in climate and weather will have dramatic effects on the physical template of the Delta/estuary.

Main Policy Implication: Management of the Delta/estuary will need to be robust to change and uncertainty and designed to respond to conditions that may change rapidly. Management tools, such as adaptive management, that recognize uncertainty and use management as a means to learn about the system as well as to influence it need to become standard procedure.

Principle 4: Individual species have particular tolerances for habitat variables like temperature, dissolved oxygen, and toxic substances. These variables have changed in the past (naturally and by human activity) and will continue to change in the future (by climate change, population growth, changing industrial/agricultural practice). Species seasonal cycles (e.g., reproduction, migration) may also be cued by different environmental variables (e.g., day length, temperature, flow, soil moisture). These variables will change in different ways as global climate change proceeds (e.g., temperature and flow patterns will change a lot, day length will not change). The future environment of the Delta/estuary may exceed the tolerance limits of some species or important processes that were cued by different signals (e.g., spring plant growth and the arrival of migratory species) may become uncoupled.

Main Policy Implication: Loss of some species from the ecosystem may be inevitable. However, this should not be an excuse for abandoning policies to conserve native biodiversity. Rather it implies a need for more creative forms of biodiversity conservation, such as establishment of refuge populations where conditions remain suitable.

Principle 5: Humans and human created landscape units are integral to the ecosystem mosaic of the Delta and have profound influence on the overall ecosystem dynamics.

Main Policy Implication: Management of human activity and uses of the landscape and water is integral to successful management and conservation of desired species, ecosystem types and biodiversity in the Delta/estuary.

Principle 6: Primary production (the generation of new carbon compounds through photosynthesis) is the foundation of ecological production and food webs supporting fish and birds in the Delta. Sources of carbon compounds include local production as well as carbon transported into the ecosystem from upstream and from the ocean. Aquatic primary production in the estuary is unusually low for a delta/estuary ecosystem but appears to be a critical source of carbon supporting valued aquatic species.

Main Policy Implication: Existing levels of aquatic primary production in the Delta/estuary must be maintained and increased if possible.

Principle 7: The potential energy established by primary production can follow a number of pathways in the ecosystem. It can be exported from the system or buried in sediments and effectively lost from the ecosystem. It can be consumed by primary consumers or cycled through microbial decomposition. The primary consumer path provides the most direct route to organisms higher in the food web, such as fish or birds. The microbial decomposition path is a longer, more indirect route in which most of the energy is dissipated through respiration before reaching larger organisms. In the aquatic communities of the Delta, a high proportion of primary production is cycled through the less efficient microbial pathway.

Main Policy Implication: Management and restoration for natural communities should emphasize ways to enhance the direct pathway (from phytoplankton to zooplankton to fish) for energy transfer in the aquatic community.

Principle 8: Competition and predation are fundamental processes structuring the biological community. The effects of these processes tend to cascade down through the food web so that some species near the top of the food web can have a large influence on the structure and dynamics of the community as a whole (keystone species). Humans can act as a top predator (keystone species) when they exploit commercially or recreationally valuable species in an ecosystem and can disrupt system dynamics and structure by changing landforms and hydrology or introducing non-native species that play a keystone role.

Main Policy Implication: Human actions in an ecosystem always have multiple consequences. Exploiting some species and/or introducing others have far reaching implications for the ecosystem. Constructing roadways, dredging channels or diverting water have impacts far beyond the local area. Management policies need to be framed in the context of their consequences for the ecosystem as a whole not just in terms of their effects on an immediate perceived problem.

Principle 9: The dynamics of a species is determined by the balance between births and deaths within the population. Populations may decline if birth rates fall or if death rates rise. Birth rates can be influenced by many factors including past levels of nutrition (affecting growth rates and development of reproductive organs), current levels of nutrition (affecting number and quality of offspring that can be produced) and past or present exposure to toxic substances/endocrine disruptors/mimics (affecting both the ability to reproduce and/or the viability of offspring). Quality of the breeding environment (e.g., presence of appropriate cues to stimulate breeding behaviour, such as nest building in birds) and, if populations are small, the ability to find a mate can also influence birth rates. Death rates can be increased by exposure to toxic substances (both acute and chronic toxicity), extremes of environmental variables to which the organism is sensitive (e.g., temperature, salinity), being transported to an unsuitable environment (e.g., the export pumps), poor feeding conditions, increased exposure to predators or efficient competitors, and an outbreak of disease. Disentangling the multiple potential causes of a decline (or increase) in abundance of any species is very complex and can be virtually impossible in some circumstances.

Main Policy Implication: Multi-factorial, ecosystem based approaches to species conservation are more likely to be successful than approaches that address single high profile "causes". Maintaining ecosystem structure and function appropriate for the species of interest is essential.

Principle 10: The Delta/estuary is a mosaic of terrestrial and aquatic ecosystems that interact in important ways (e.g., they exchange materials, energy and organisms). The size, shape, arrangement, and connections among ecosystem patches is critical to the way the Delta/estuary functions. The Delta/estuary itself is an ecosystem patch within the larger ecosystem mosaic of the Central Valley, Sierra and Coastal mountains and the coastal ocean. This concept of ecosystems as a mosaic of patches nested within larger patches has important implications for the way humans manage and interact with the landscape. Human activity changes patch character (marshes are converted to farm land, farm land to urban land), patch size (small farm patches are combined to form large farm patches, urban lands expand, roads and other transportation corridors fragment large patches into smaller patches, etc.), patch connectivity (formerly contiguous patches are separated by a new patch type, formerly isolated patches are connected, etc.) and physical and chemical dynamics within and between patches (discharge of contaminants, organic and inorganic nutrients, etc.).

Main Policy Implication: Management plans and decisions need to be informed by a landscape perspective that recognizes the interrelationship among patterns of land and water use, patch size, location and connectivity, and species success. The landscape perspective needs to be developed at several physical and temporal scales (e.g., patches within the delta, delta within the valley and temporal scales of patch dynamics and evolution). Achieving a sustainable balance of ecosystem services and biodiversity conservation in the Delta is likely to involve allocating considerably more land and water to support natural and semi-natural systems than is presently the norm.

Principle 11: Invasive species are capable of disrupting ecosystem processes and can have serious negative effects on native species. The Bay-Delta ecosystem is already one of the most invaded ecosystems in the world. The planktonic community of San Francisco Bay has been described as essentially Asian in character with virtually no native species present any more. Particularly damaging invaders in the Bay-Delta (in terms of their effects on the native community) include the overbite clam (*Corbula amurensis*), the Asian clam (*Corbicula fulminea*), Brazilian water weed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), perennial pepperweed (*Lepidium latifolium*), and the giant reed (*Arundo donax*). A recent arrival that is likely to become a problem is the

New Zealand mud snail (*Potamopyrgus antipodarum*) and waiting in the wings are zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena bugensis*). Invasive species represent one of the most serious obstacles to preservation and restoration of listed native species.

Main Policy Implication: An aggressive approach is needed to address the serious and growing problem of invasive species in the ecosystem. As recommended under the United Nations Convention on Biodiversity, a multibarrier approach should be adopted including effective regulation and monitoring to prevent new introductions, an aggressive program of eradication for newly arrived invaders, and development of efficient control programs for established invaders.

Principle 12: Ecosystems are complex, dynamic, and self-organizing. The Bay-Delta ecosystem is human dominated and any sustainable vision for the Bay-Delta needs to incorporate both the human and the non-human dimensions of the ecosystem. Traditional attempts to manage non-human sub-systems independent of the human sub-system in a sectoral, isolated and incremental manner have inevitably led to a downward spiral of ecosystem services and loss of valued ecosystem components. The current undesirable condition of the Bay-Delta ecosystem is a graphic illustration of this outcome. More holistic approaches to ecosystem management that acknowledge the need to allocate substantial resources to maintain ecosystem integrity and ecosystem services are necessary. This should not be seen as a restatement of the meaningless “jobs vs the environment” cliché. Rather, it is a recasting of the original CALFED vision that we will all get better together. In this case, however, getting better does not mean giving everyone more of what they already have. Instead, it means establishing a sustainable balance of ecosystem services and human demands from which everyone will benefit.

Main Policy Implication: Governance for the Bay-Delta should be based on the concept of ecosystem-based management (EBM), a concept that integrates society, economy and the environment. The core elements of this approach were worked out some time ago (see, e.g., Ecological Society of America, 1995, “The scientific basis of ecosystem management”, Washington, DC). EBM was adopted as the guiding philosophy of CALFED but implementation has been weak. A more aggressive and committed implementation process is needed in the future.

Context Memorandum: Delta Ecosystem

Iteration 1: August 13, 2007

Section 1. Introduction

The Sacramento-San Joaquin Delta and the Suisun Marsh are important components of the San Francisco Estuary, which is the largest estuary on the Pacific coast and one of the largest in the United States. The Delta is formed by the convergence of the Sacramento, San Joaquin, Calaveras, Cosumnes, and Mokelumne rivers, which drain over 40% of the State's land area and convey 47% of the State's annual runoff (DWR, 2005, Figure 1). The Delta is also a critical hub in California's statewide system of water management and redistribution. Water pumped from the Delta by the State Water Project and Central Valley Project provides irrigation water for a significant portion of California's multi-billion dollar agricultural industry, for industry, and a portion of the drinking water for more than 23 million Californians. The Delta itself is an important agricultural region. Cities and towns around the margin of the Delta are among the fastest growing urban regions in California and many of these cities and towns get their water from the Delta. The Delta is also an important recreation area for this growing population and for millions of visitors. Besides food, water and a place to play, the Delta provides an array of environmental services to the people of the region and of California as a whole including waste disposal, detoxification and recycling, transportation corridors, recreational and commercial fishing/hunting.

The Delta is also home and critical habitat to myriad species besides humans including both resident and migratory species. For example, the Delta and upper San Francisco Bay is the only home to the endemic Delta smelt (*Hypomesus transpacificus*), which is at threatened species. Smelt numbers have fallen so low that extraordinary measures are being taken to protect it, including turning off the pumps that export water out of the Delta. The marshes and woodlands of the Delta are critical feeding, resting and breeding habitat for numerous migratory bird species that are managed and protected under international agreements including the greater sandhill crane (*Grus canadensis tabida*), ducks, and many other species. Balancing human uses of the Delta and adjacent lands, particularly water resources, with the obligation to manage and conserve Delta biodiversity, represents a significant challenge for which California has yet to find a sustainable solution.

The purpose of this context memo is twofold. First, it will describe the ecological structure and dynamics of the Sacramento/San Joaquin estuary and upper San Francisco Bay. Although the Bay-Delta is unique in many ways it also has many similarities to other river delta/estuaries. The scientific understanding of other delta/estuaries helps us to understand the functioning of the Sacramento/San Joaquin Delta/estuary and is the critical foundation of ecological principles that will support solutions to the problems of the Delta. In describing the Delta ecosystem the memo will take the position that humans and human activities are an integral part of the dynamics of the system. This is consistent with the current thinking that environment, economy, and society are interlinked and interdependent subsystems that cannot be managed independently. These interrelationships are at the core of both the concept of sustainability and the concept of ecosystem based management. Ecosystem based management will provide the framework within which to suggest policy solutions.

The Delta of today is very different ecologically from the Delta of 200 years ago. Prior to European colonization, the Delta was a vast Tule (*Scirpus* spp.) marsh that flooded during spring freshet and dried up during low flows. The boundaries between water and land were not fixed but shifted seasonally and annually so that in wet years and wet seasons the Delta was more like a giant shallow lake and in dry seasons and dry years a giant prairie cut through by narrow river channels. Over the past 150 years, levee building and human occupation of the land have transformed the Delta into a highly dissected landscape of trapezoidal channels and agricultural fields with dense urban development around the margins. Annual freshets have also been truncated by upstream storage. Less than 10% of the formerly seasonally and tidally flooded wetlands remain. In addition, introductions of non-native species have greatly altered the biological community of the Delta. Neither the historic species composition nor the historic patterns of flooding and desiccation can be reestablished. However, these were the conditions under which species native to the Delta evolved and they now must cope with the current geometry and hydrology of the Delta. Any sustainable vision for the Delta that includes conservation of native species like Delta smelt or California clapper rail (*Rallus longirostris obsolitus*) will probably need to incorporate those features of the historic Delta condition that are critical to their ways of living.

Our second purpose is to suggest actions that will contribute to the long term sustainability of the Bay-Delta ecosystem. In keeping with the ecosystem based approach, these will go beyond the traditional, usually highly localized recommendations for habitat protection and restoration to include broader issues of land and water use. This may seem radical. However, the incremental remedial approach to environmental management in the Delta has proven to be inadequate to the challenge of achieving sustainability. It is time to consider more inclusive policies and to envision new and more enduring relationships between environment, economy and society. Despite the tremendous changes that have been imposed over the past 150 years, the Bay-Delta remains rich in ecological promise and potential. The policy suggestions in this document are directed at realizing more of that potential in the future.

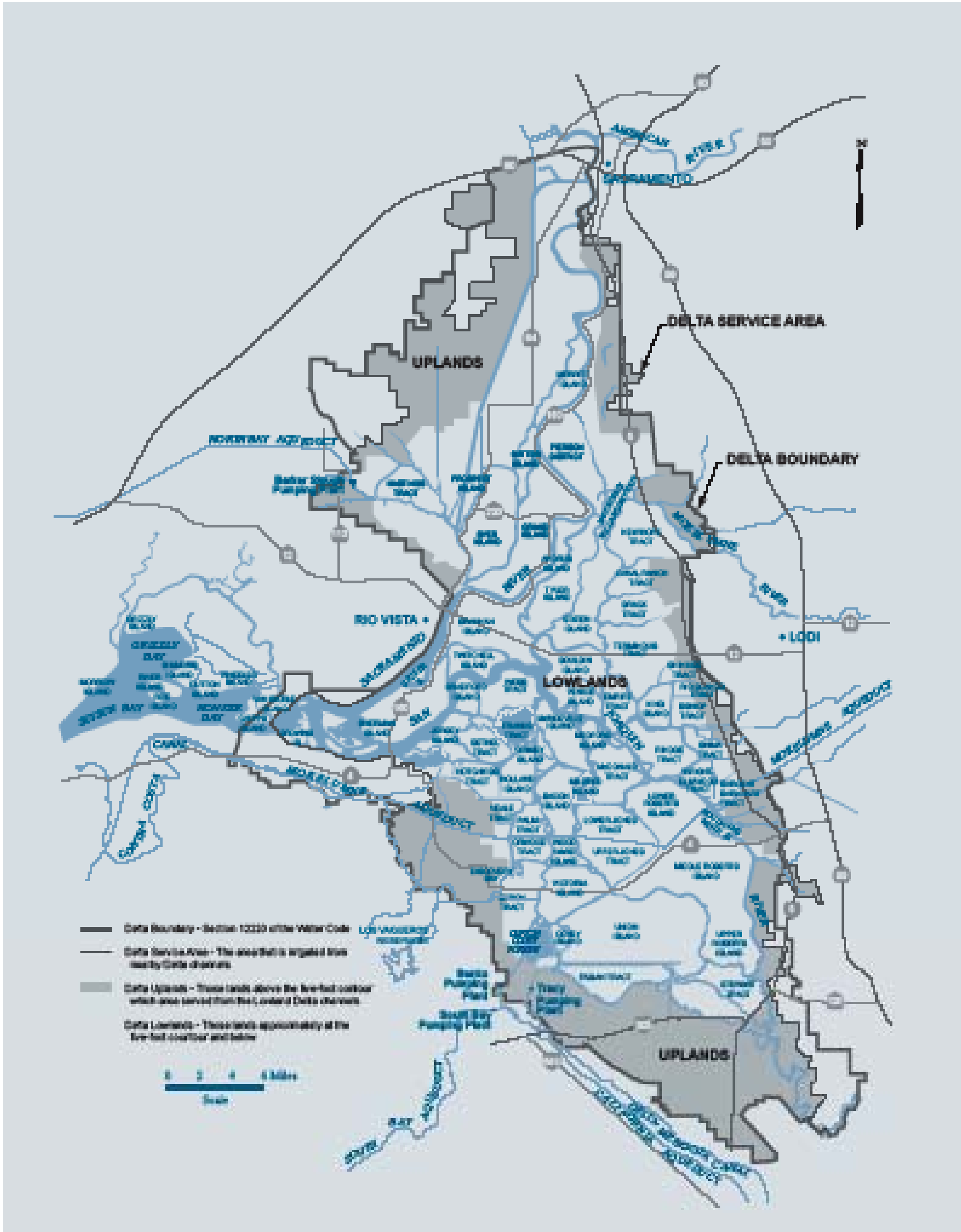

Figure 1. Map of the Legal Delta and Suisun Marsh (from DWR 2007)

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Section 2. The Dynamic Nature of Delta/Estuary Ecosystems

Delta/estuary ecosystems are by nature physically and biologically dynamic and comprised of a complex mosaic of interacting ecosystem types. The biological dynamics of the Delta are driven primarily by the physical dynamics. When the Delta and the rivers upstream were undeveloped, seasonal variations in freshwater inflow to the Delta were very large. During high flows the rivers flowed out across the Delta islands and adjacent lands creating a shallow freshwater lake and pushing marine influences seaward. During low flows the rivers retreated into defined channels and salt water penetrated into the Delta (Lund et al. 2007). In the western Delta and Suisun Bay, because the land is flat, tidal excursions across mudflats and marshes were large. Sediment carried downstream by freshet was deposited in slack water areas, only to be resuspended by the next freshet, or by wind and waves, and redeposited elsewhere, so that the geometry of the estuary was constantly changing. During winter and spring most of the Delta was wet and cool. During the summer and autumn it was dry and hot. For the organisms that lived in the Delta, this dynamic physical environment presented both problems and opportunities. Mobile organisms could move to take advantage of new habitats and new feeding opportunities as floodwaters advanced and receded or as tides moved in and out. Sedentary organisms had to be able to tolerate being wet or dry, hot or cold, salty or fresh. Organisms with different preferences or tolerances for physical variables like salinity or wetness occupied different zones or bands within the estuary, creating a complex mosaic of different communities and ecosystems, typically grading from salty to fresh and wet to dry. Some organisms, like the Tules (*Scirpus* spp.) were very successful in the Delta environment and established extensive and almost impenetrable stands. Many sessile organisms were opportunistic, flourishing when conditions were favourable and persisting in a resting stage when conditions were bad. Aquatic organisms often timed their reproduction in relation to spring freshet when inundation of islands and floodplain maximized available habitat and feeding opportunities for their young. For many terrestrial organisms living in areas of higher elevation, water was a precious resource and reproduction was timed to coincide with the brief spring abundance of water. Vernal pool ecosystems illustrate this dependence very well; bursting with inflorescence, the breeding stages of insects, and mating frogs in the brief wet season; dry, brown and silent for most of the year.

Human development of the estuary and the river systems upstream has been directed at constraining or eliminating certain aspects of this natural variation. Levees were built to prevent seasonal flooding of islands and floodplains so that the land could be farmed or cities and towns could be built. Dendritic drainage channels were straightened, protected by levees and then deepened and extended to create navigable access channels and new islands. Freshwater inflows to the Delta were managed to prevent salt intrusions from contaminating water withdrawn for irrigation and domestic use (DWR 2007). Woodlands and Tules were cleared to create pasture or cropland or for urban development. The landscape of the Delta was changed and simplified.

Coincidentally, human activity in the Delta and watershed introduced new factors into the Delta ecosystem. Hydraulic mining in the watershed swept millions of cubic meters of sediments and mercury into the Delta and upper San Francisco Bay. Return flow from agriculture and discharge from urban and industrial development introduced other toxic substances (metals, pesticides, hydrocarbons) and nutrients into the Bay-Delta. Toxic substances can accumulate in sediments to be released during flooding or erosional events and low concentrations in water or sediments can be concentrated through the food chain to cause toxic response in predators (and sometimes humans). Non-native species were introduced intentionally (e.g., striped bass, *Morone saxatilis*) or incidentally (e.g., water hyacinth, *Eichhornia crasippes*, Asian clam, *Corbicula fluminia*) and expanded to become significant (and sometimes troublesome) components of the Bay-Delta ecosystem. In fact, the Bay-Delta is described as one of the most invaded ecosystems in the world (Cohen and Carlton 1998). Most recently, the potential impacts of global climate change have been recognized. Among other effects, climate change will alter the amounts and seasonal timing of freshwater entering the Delta and sea level will rise causing salt to penetrate deeper into the Delta. In an analysis of past climates of the Delta, Malamud-Roam et al. (2007) suggest that climate for the past 150 years has been unusually stable and that the Bay-Delta is likely facing much greater climate variation in the future.

Native species have had to accommodate to the new geography, hydrology, chemistry, and biology of the Bay-Delta. Many were probably unable to do so and have disappeared from the ecosystem. Only a few of these losses have been recorded; no one was paying much attention through the 19th and most of the 20th century as the ecosystem was reconfigured. Now, however, species and biodiversity conservation are a high priority nationally and for California. Concern for species conservation has been driving many recent decisions about water and environmental management. Ecosystem science and conservation science are struggling to understand and advise decision-makers about how to sustain declining species in this new ecosystem.

The Bay-Delta and its watersheds have a long history of ecological research, beginning with some of the first research on Pacific salmon in the Pacific region (Rutter 1904) and progressing to more broadly based studies of San Francisco Bay and the Delta as concern for other species and environmental conservation developed (e.g., Skinner 1962). The Interagency Ecological Program (IEP) was established more than 30 years ago to coordinate research and monitoring among various government agencies. As a result of IEP and other research efforts the Bay-Delta ecosystem is well studied. Research activity has intensified since the establishment of the CALFED Bay-Delta Program and in particular since the rapid decline in abundance of several pelagic fish species (The Pelagic Organism Decline, url: http://science.calwater.ca.gov/pod/pod_index.shtml). Recent ecological analyses building on the long time series of observations under IEP and new studies conducted during the past decade have led to significant rethinking of the way the Bay-Delta ecosystem functions. These changes were presented as "paradigm shifts" in Lund et al. (2007) (Box 1). Although this new understanding is of tremendous value in designing new and more sustainable policies and management approaches, the level of uncertainty about how the Delta functions and how it will respond to management interventions is still very high.

Box 1. **Paradigm Shifts** as adapted from Dr. Peter Moyle's Appendix A "Paradigm Shifts in Our Understanding of the San Francisco Estuary as an Ecosystem" in *Envisioning Futures for the Sacramento-San Joaquin Delta* (Lund et al, 2007).

New Paradigm	Old Paradigm
Uniqueness of the San Francisco Estuary	
The San Francisco Estuary is unique in many attributes, especially its complex tidal hydrodynamics and hydrology.	The San Francisco Estuary works on the simple predictable model of East Coast estuaries with *linear* gradients of temperature and salinity controlled by outflow with edging marshes, both salt and fresh water , supporting biotic productivity and diversity.
Invasive Species	
Alien species are a major and growing problem that significantly inhibits our ability to manage for desirable species.	Alien (nonnative) species are a minor problem or provide more benefits than problems.
Interdependence	
Changes in the management of one part of the entire estuary system affect other parts.	The major parts of San Francisco Estuary can be managed independently.
Stability	
Delta landscapes will undergo dramatic changes as the result of natural and human-caused forces such as sea level rise, flooding, climate, and subsidence.	The Delta is a stable geographic entity in its present configuration.
Delta Pumping	
The big pumps in the southern Delta are one of several causes of fish declines and their effect depends on species, export volume, and timing of water diversions.	The big SWP and CVP pumps in the southern Delta are the biggest cause of fish declines in the estuary.

Section 3. Physical Habitat as the Template for Ecosystem Structure and Function

The physical structure and dynamics of the Bay-Delta (e.g., hydrology, chemistry) establishes the conditions within which the ecological character of the Bay-Delta is expressed. Topography and landforms dictate the underlying physical structure but this structure has been much altered by human development.

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The Bay-Delta is a narrow portal through which the Pacific Ocean connects with California's Central Valley and the Central Valley connects with the ocean. The Central Valley is remarkably flat and consists largely of material eroded from the Sierra Nevada and Coast Ranges and deposited in low alluvial fans. As well as being a primary source of sediments for the valley floor, the Coast Ranges and particularly the Sierras are the primary source of water for the valley and the Delta. The valley is thought to have originated below sea level as an offshore depression that was later enclosed by the uplift of the Coast Ranges. On multiple occasions in the past, the valley has been filled with water, creating a large lake that left a veneer of muddy deposits. About 650,000 years ago, rising waters of Lake Clyde broke through the Coast Ranges and drained into the Pacific Ocean through the modern San Francisco Bay. Abundant vegetation growth in the developing Delta that alternately flourished and was buried under marine or freshwater sediments created the deep organic soils typical of Delta islands. With the arrival of European colonists, the long term geological evolution of the Bay-Delta was overlain by rapid human driven development as levees were constructed, islands were drained, crops were planted, channels were dredged, forests were cleared and cities and towns constructed. Human alterations to the landscape constitute some of the most dramatic changes in structure and dynamics of the Bay-Delta and so are important drivers of ecological change.

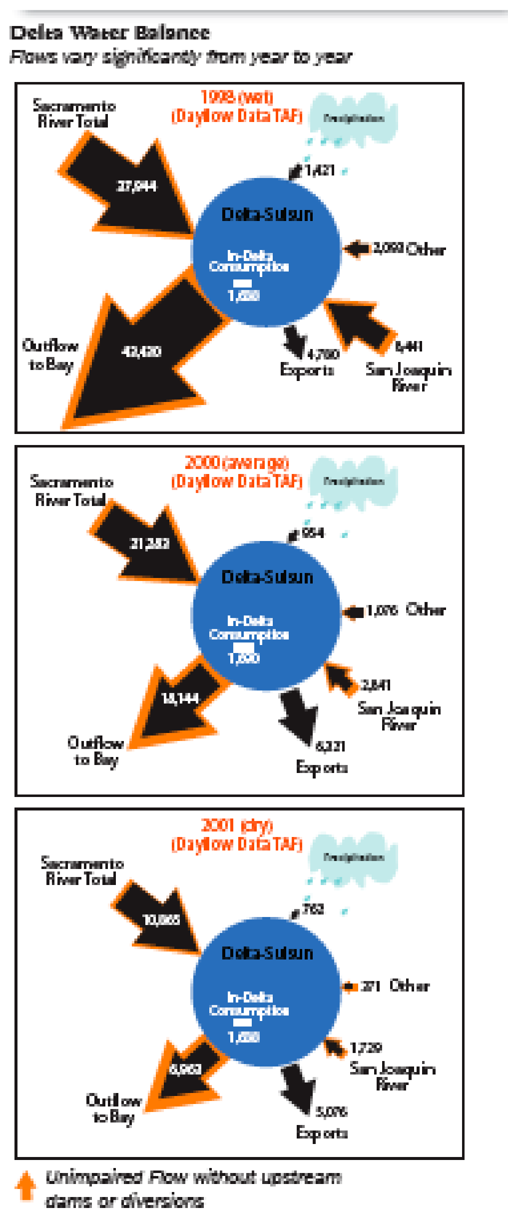

Figure 2. Water balance in the Delta under wet, normal and dry years (from URS 2007)

Hydrodynamics of the Delta/estuary. The movement of water through the Bay-Delta is one of the most important physical processes affecting the ecosystem. Fresh water enters the Delta from upstream, travels through the 700 miles of Delta channels and discharges into Suisun Bay or via the State Water Project and Central Valley Project in the south Delta (water exports). Within the

Delta there are hundreds of small withdrawals for agricultural and industrial use. Contra Costa County also withdraws its drinking water from the central Delta and water is withdrawn from the north Delta to feed the North Bay Aquaduct. In an average water year, about 13,000 cfs of water enter the Delta, about 3000 cfs is exported, about 850 cfs are used within the Delta and about 9000 cfs is discharged to Suisun Bay. These numbers vary with season and water year (Figure 2). Since 1985, 85% of Delta inflow has been from the Sacramento and 11% from the San Joaquin. At high Sacramento River flows, a substantial amount of water is diverted through the Yolo bypass to reduce flood risk. Water enters the bypass above Sacramento and reenters the Delta below Rio Vista.

The seasonal cycle of natural flows into the Delta was characterized by very high flows in the spring when snow was melting in the Sierras and very low flows in the late summer and autumn before the winter rains began. The timing of snowmelt has moved earlier in the year and more precipitation has fallen as rain as climate has warmed over the past century. As a result, the amount of annual flow that occurs after March each year has declined although total annual discharge has stayed about the same (Figure 3). This timing shift is expected to become more pronounced as global warming continues. As reservoir storage has increased in the catchment and water development projects were installed upstream in the major rivers, average inflows to the

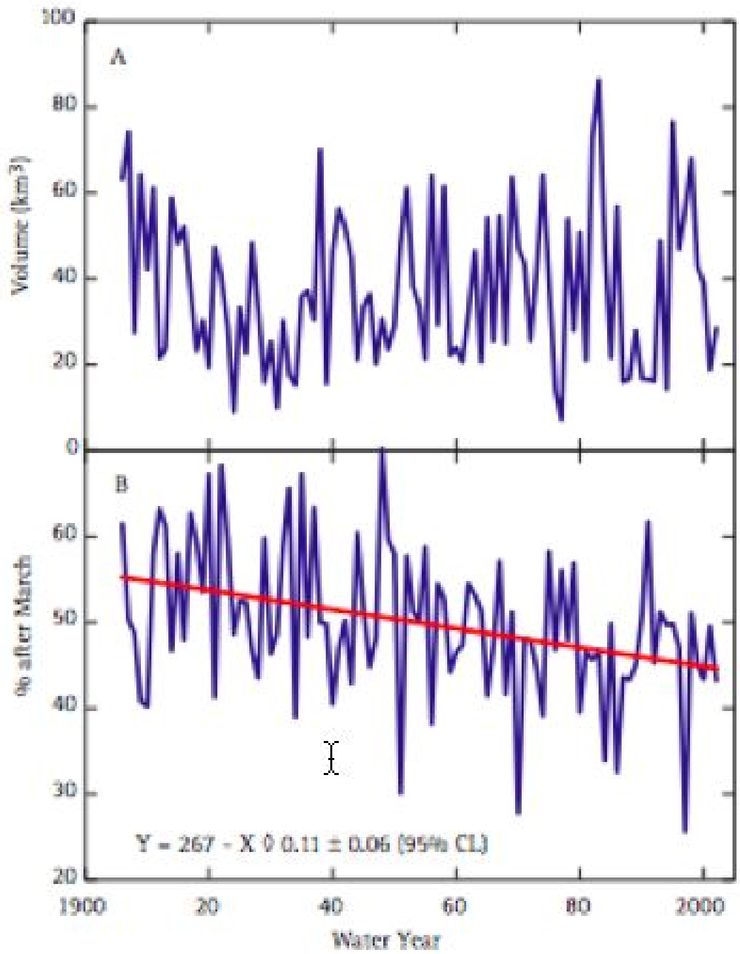

Figure 3. Mean annual volume discharge of rivers into the Delta over the past 100 yr (Panel A) and the percentage of that flow that occurred after March (Panel B). Annual flow is for "water year" which is the 12 month period beginning in October. Red line in Panel B shows the decline in average post March flow. From Kimmerer 2003.

Delta have been reduced. The seasonal pattern of flow into the delta has also been changed to conform with human needs. Spring flows are reduced to control flooding whereas summer and autumn flows are higher to meet the demands of agriculture.

Exports from the Delta through the State Water Project and Central Valley Project constitute a significant removal of water from the Delta. Overall, exports average about 30% of inflows but are frequently more than 50% during summer months. The proportion of inflows that is exported also varies with water year, being higher in dry years (Figure 2). Annual exports have increased steadily since 1950 and, since 2000 have been as high as 8.5 million acre feet (URS 2007). Exports typically peak during late summer (4000-5000 cfs) and are minimal in spring (1500-2500 cfs). In recent years spring exports have been minimized to reduce impacts on migrating juvenile salmon but increased in late summer to make up the total export volume.

The movement of water through the delta is influenced by moveable gates in the Delta Cross Channel (DCC) and by temporary barriers installed seasonally at head of Old River, Grant Line canal and Middle River. DCC is operated in relation to water quality at the export pumps, seasonal fish movements (The gates are closed from February to May to prevent juvenile salmon from entering the central Delta.) and Sacramento River flows (to prevent flooding in the central Delta). Head of Old River barrier is installed during spring to assist salmon movement seaward. Other barriers are put in place to improve water quality to irrigators. The length of time that temporary barriers are in place has been increasing. An additional barrier in Montezuma slough is used to reduce salt intrusion into Suisun Marsh.

Seawater is also a significant component of the water budget of the Delta. Seawater enters the delta via twice daily tides that flow through Carquinez Strait and Suisun Bay and the interaction of tides and freshwater drives much of the mixing and circulation in the Delta. Median tidal range is about 6 ft for San Francisco Bay but is attenuated to less than 3 ft east of Carquinez Strait. Not surprisingly, tidal influence dominates circulation and water elevation on the seaward side of the Delta and fresh water inflows dominate on the landward side. At Chipp's Island, tidal flows typically exceed river flows and tidal flows drive most of the mixing within the Delta. As a result of strong tidal forcing and the networked nature of the Delta channels, the Delta is relatively well mixed and fairly uniform in its water properties (Kimmerer, 2004, Jon Bureau, USGS, Pers. Comm. 2007). The maximum tidal excursion into the Delta varies with freshwater inflow, being greater during low flow periods and smaller during high flows. Prior to the construction of Shasta dam, salinity of 1000 mg Cl/l sometimes reached eastward as far as Stockton and Walnut Grove. Today, freshwater release from Shasta, Folsom and Oroville reservoirs has been used to confine salt intrusion to the western and central Delta (DWR 2007).

X2, the location upstream from Golden Gate to which salinity of 2 parts per thousand penetrates is used as a measure of salt penetration. X2 is a useful ecological indicator as it demarks the division between predominantly freshwater organisms and predominantly marine organisms. The position of X2 is determined by fresh water inflows to the Delta and is lower (i.e., further seaward) during high flows in Feb and March and higher (i.e., further east) during the fall when inflows are low. X2 is most commonly located in Suisun Bay and, in spring, is constrained by regulation to be west of the confluence of the Sacramento and San Joaquin Rivers. In recent years, less fresh water has been moving through the Delta so X2 has been further east on average.

As is evident from the discussion above, water movement through the Delta channels is driven by both freshwater inflows and by tides. Because tidal flows are bidirectional and river flows unidirectional, there is a net movement of water seaward in the Delta. There is also a substantial movement of water toward the export pumps when they are operating at high volume so that net flows in the south Delta may be reversed (i.e, upstream). Two contrasting conceptual models of water movement through the Delta are the “net flow” model and the “tidal flow” model (Kimmerer 2004). The net flow model emphasizes the average direction of water movement (net flow) and generally ignores the shorter term oscillations in flow driven by tides (Figure 4). The net flow model sees the Delta as largely river dominated in terms of its circulation. The tidal flow model, by contrast, sees the Delta as a transition zone between river dominated seaward flows in upstream regions and oscillating tidal flows in downstream regions (Figure 4). The two models lead to different conclusions about how flow will influence movement of juvenile fish in the Delta.

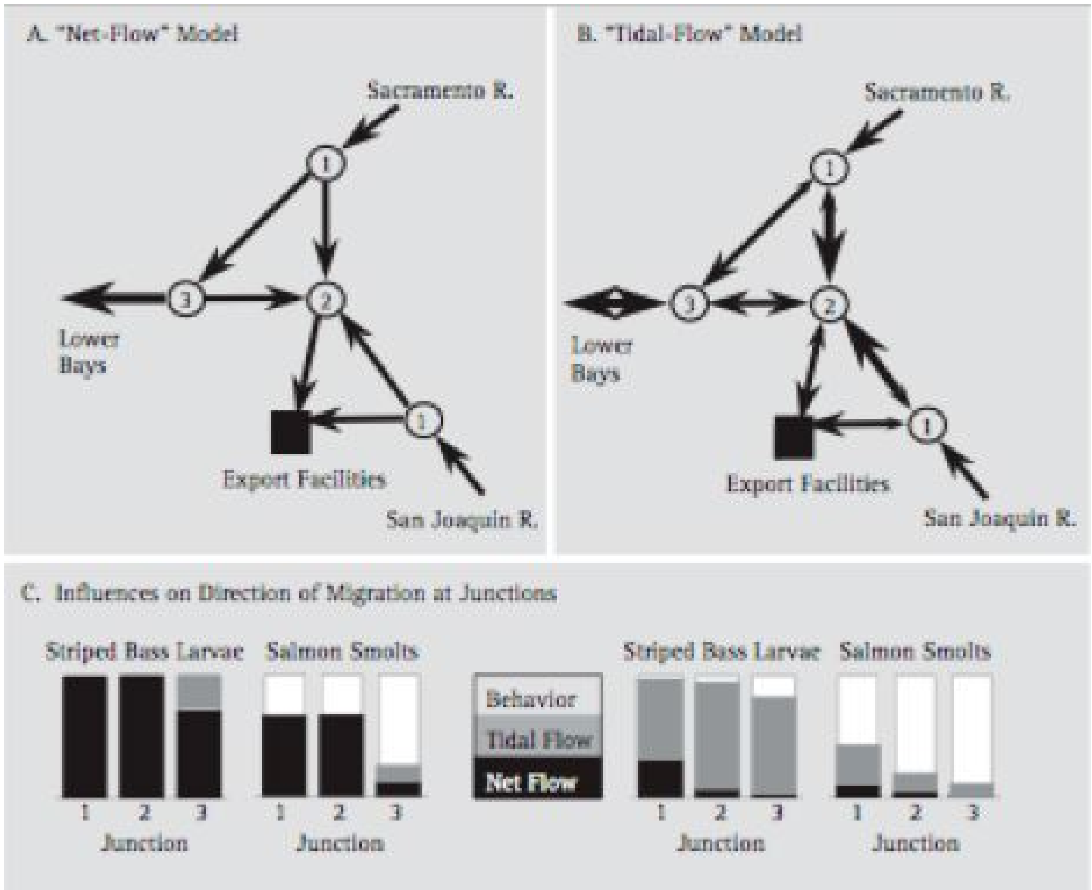

Figure 4. Two different conceptual models of flow through the Delta (from Kimmerer 2004). The net flow model emphasizes net movement of water toward the ocean (or the export pumps) and can be considered a "long term average" kind of model. The tidal model emphasizes the interaction of tidal and riverine forces on water movement with river input dominating in upstream areas and tides dominating in downstream areas of the Delta. The two models lead to different conclusions about the way water movement affects fish movement (panel C, to be discussed in more detail in later sections of this memo).

Temperature. Temperature is a fundamental driver of many biological processes in the Delta. The physiology of most organisms is governed by temperature. Even those organisms that hold their internal temperatures relatively constant (mammals, birds) still respond physiologically to temperature. The timing of transitions between life history stages (e.g., larval metamorphosis, sexual maturation) can also be cued by temperature. Mean monthly air temperature in the Delta region varies from about 8 C in December-January to 22 C in July-August; maximum and minimum average monthly temperatures range from about 6 C to 27 C and the daily variation in temperature is 6 to 10 C (Figure 5). Delta water temperatures track air temperature but have much lower daily variation (Figure 5). Water temperature appears to be little influenced by inflow although high flows in the Sacramento will lower the temperature at Freeport (Kimmerer 2004). Temperature is not constant throughout the Delta, however, but tends to be higher in the south Delta and lower in the north and west Delta (Figure 6).

Climate and Weather.

Climate and associated weather patterns strongly influence the physical template for the ecosystem. Climate also directly affects biological communities through tolerances of individual species to heat or cold, wetness or drought. The terrestrial and aquatic ecosystems of the Delta are very much a reflection of the climate of the region. And climate is changing (IPCC 2007). Although the details of future climate remain uncertain the trend is clear. Atmospheric concentrations of greenhouse gases (mainly Carbon Dioxide), global average temperature and sea level have all risen noticeably over the period of record whereas snow cover in the northern hemisphere has decreased (Figure 7). These trends are expected to continue over the next century and perhaps beyond. Although predicting regional climate change from global models is highly uncertain, current projections suggest that the future climate of California will be warmer and likely dryer (Seager et al. 2007, California Climate Change Center 2006). Depending on how well greenhouse gas emissions are controlled, average temperatures in California will increase between 2.5 and 9 C over the next century (DWR 2006). Since water temperature tends to track air temperature, average water temperatures will increase a similar amount. Changes in precipitation are less certain but recent analyses suggest that southwestern US will experience an overall decline in precipitation (Seager et al. 2007, Figure 8). Higher average temperatures will also shift precipitation from snow to rain, especially in the mountains, and annual snow pack will decrease dramatically. The shift in precipitation from rain to snow will have dramatic effects on hydrology with

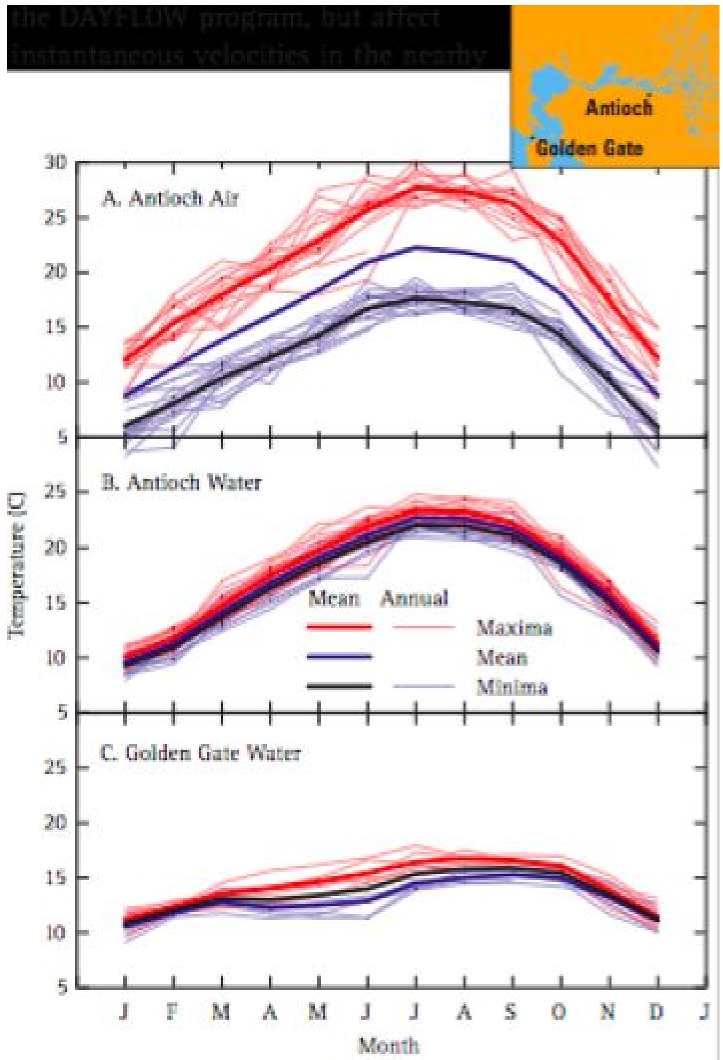

Figure 5. Seasonal and interannual temperature variation in the Delta and San Francisco Bay (from Kimmerer 2004).

increased winter flows and decreased summer flows in most rivers (Snyder and Sloan 2005).

A number of critical, policy relevant, environmental changes will accompany global warming in California. Average temperatures will increase, which will increase demand for water. At the same time, several factors are likely to reduce the amount of water available. As already mentioned, precipitation may decline and evaporative loss will increase. More precipitation will fall as rain rather than snow and winter snow pack will be smaller. Spring freshet will be earlier; more of the annual run off will come down the rivers between October and March and less between April to July. The trend toward earlier run off and lower April to July discharge is already evident in recent data (Stewart et al. 2004, DWR 2006). Winter storm frequency and intensity is likely to be greater. In fact, climate variability as a whole is likely to increase as recent evidence suggests that California has enjoyed a particularly stable climate since European colonization (Malamud-Roam, et al. 2007). Potential flood events will be more frequent in winter and water managers may have to reserve storage space in reservoirs to modulate flooding. This will mean less water for power generation and for irrigation and other uses later in the year (DWR 2006).

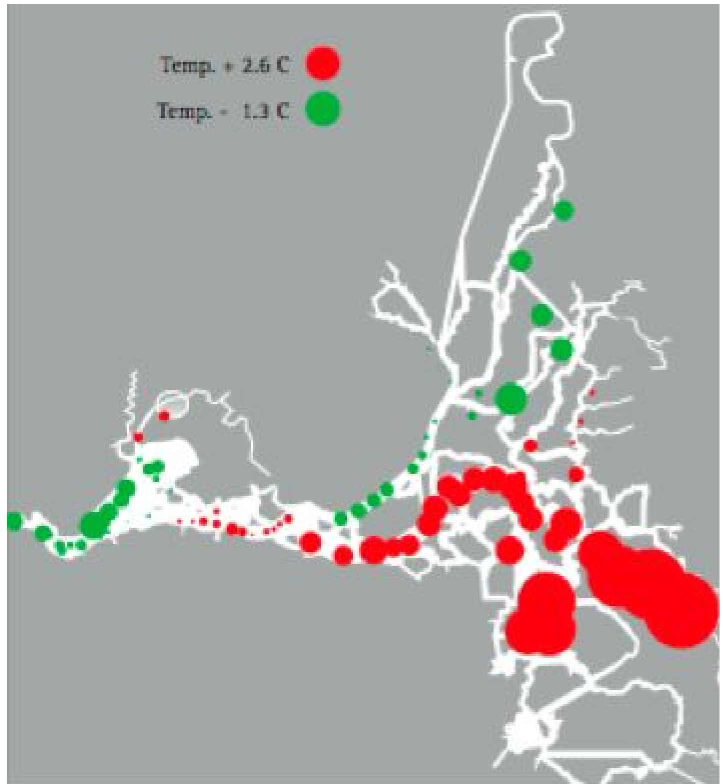

Figure 6. Spatial variation in temperature in the Delta in September (from Kimmerer, 2004).

An important consequence of global warming is sea level rise. Current projections are that sea level will rise about 30 cm over the next century (Figure 9). However, uncertainty in this prediction is wide and sea level increase could be much greater, depending greatly on how fast ice melts in Greenland and the Antarctic shelf. Paleoclimate investigations indicate that about 125,000 years BP, when arctic temperatures were 3 to 5 C higher than at present, sea level was as much as 6 m higher (IPCC 2007). Some experts argue that sea level rise of several meters is sufficiently likely in the next century that policy makers should not ignore the possibility (Hansen

2007). Even a 30 cm rise in sea level would create major changes in water quality and ecological conditions in the Delta and greatly increase flood risk. Increases in sea level of several meters would make many current uses of the Delta virtually impossible.

Water Quality and Contamination.

Environmental water quality, like hydrology and temperature, establishes a template that sets boundaries for species composition and abundance. Key water quality variables in the Delta are salinity, suspended sediment, organic and inorganic nutrients, oxygen, dissolved and particulate organic carbon, trace metals, pesticides, and other contaminants.

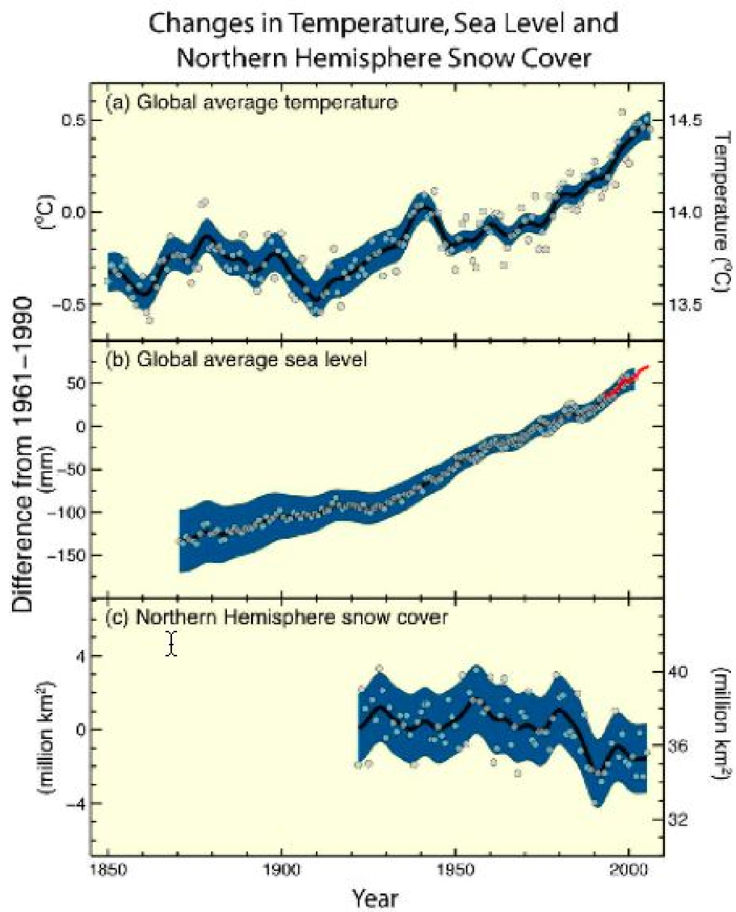

Figure 7. Changes in global temperature, sea level and northern hemisphere snow cover over the past 80-150 years (depending on the availability of records). Changes are shown as deviations from the average for 1961-1990. From IPCC (2007).

The Delta is generally an area of sediment deposition. Because of erosion upstream, estuary/delta waters are turbid with highest turbidity (100 mg/l suspended solids) in Suisun Bay, lower turbidity upstream in the Delta and lowest turbidity in central San Francisco Bay (10 mg/l suspended solids). Suspended solids consist of both organic and inorganic fractions. Organic solids can be a substrate for bacterial growth and, when it settles to the bottom, food for some bottom living invertebrates. Both organic and inorganic particles in the water can combine with certain toxic substances so that the sediment load is an important carrier of toxicity. Upstream dams and the extensive levee system along river channels and around delta islands have cut off important organic and inorganic sediment sources for the Delta so that turbidity has been decreasing over the period of record (1960 to present).

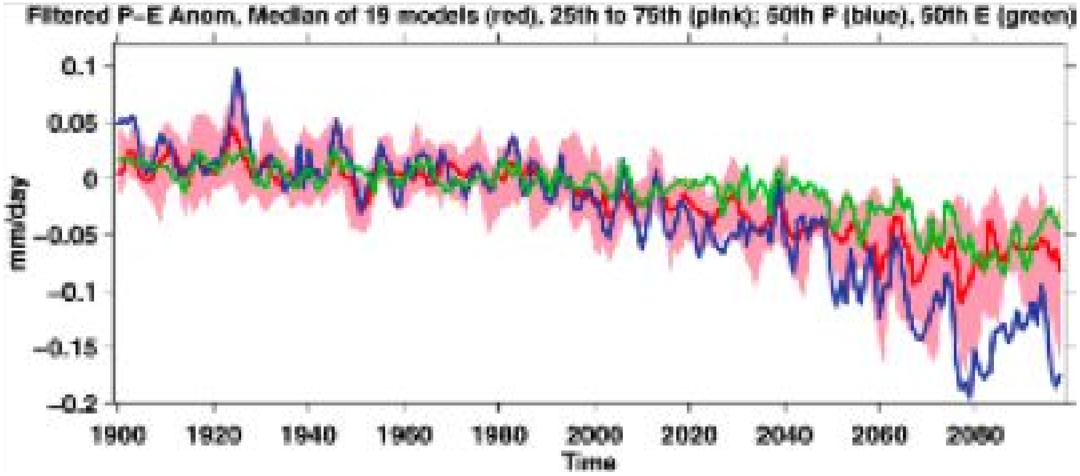

Figure 8. Predicted changes in precipitation, evaporation, and precipitation minus evaporation in southwestern North America based on global climate models. Changes are presented as deviations from the 1900-1950 mean for the climatology of each model. From Seager et al. 2007.

Modeled changes in annual mean precipitation minus evaporation over the American Southwest (125°W to 95°W and 25°N to 40°N, land areas only), averaged over ensemble members for each of the 19 models. The historical period used known and estimated climate forcings, and the projections used the SResA1B emissions scenario. The median (red line) and 25th and 75th percentiles (pink shading) of the P E distribution among the 19 models are shown, as are the ensemble medians of P (blue line) and E (green line) for the period common to all models (1900–2098). Anomalies (Anom) for each model are relative to that model's climatology from 1950–2000. Results have been 6-year low-pass Butterworth-filtered to emphasize low-frequency variability that is of most consequence for water resources. The model ensemble mean P E in this region is around 0.3 mm/day.

Organic and inorganic nutrients (inorganic nitrogen and phosphorus and their organic complexes, silicate, and trace nutrients) provide the raw materials for plant growth. There are many sources of nitrogen and phosphorus to the estuary, including nutrients washed down from upstream, wastewater discharges (sewage, agriculture return flow, industrial effluent), nutrients brought into the delta from the ocean, nutrients regenerated within the estuary by bacterial decomposition of organic material, atmospheric fall-out, and atmospheric nitrogen "fixed" by certain plants. Domestic sewage is often an important source of nutrients and organic material in estuaries (NRC 2000). Prior to passage of the Clean Water Act and associated improvements in sewage treatment, the San Francisco estuary/delta received high inputs of nutrients and organic mater from sewage plants. At this time, estuary waters were often depleted of oxygen resulting from bacterial decomposition of excessive organic material. Sewage treatment plants continue to be a primary source of nutrients to the estuary, with agricultural drainage being less important. Although nutrient discharge to the Bay-Delta has been considerably reduced, the waters are still high in nutrients and aquatic plant growth is mainly limited by low light penetration into the water (because of high turbidity). Concentrations of dissolved oxygen in Delta waters are generally high, although low oxygen concentrations (~ 5 mg/l) are chronic in the Stockton ship canal (Kimmerer 2004) and sometimes in Suisun Marsh.

Dissolved organic carbon (DOC) compounds come from metabolism and decomposition in biological communities. DOC is generally not an issue in terrestrial ecosystems, although soil water is often high in DOC. The majority of DOC is brought into the Delta by rivers, from upstream. Smaller amounts are contributed by fringing marshes and riparian vegetation, by metabolism and decomposition within the Delta and from the ocean.

Thompson et al. (2000) and Leatherbarrow et al. (2005) summarize the data on contamination of San Francisco Bay. Waters and sediments of the Bay (and by extension, the Delta) are broadly contaminated by a range of toxic substances such as trace elements (e.g., mercury, selenium, chromium), pesticides (e.g., DDT, Chlordane, Pyrethroids), and industrial chemicals (e.g., Polycyclic Aromatic Hydrocarbons (PAHs) and Polychlorinated Biphenyls (PCBs)). Concentrations in water and sediment are frequently high enough to be toxic to test organisms (Figure 10). Distribution of all contaminants is patchy with concentrations often highest near known sources and in near

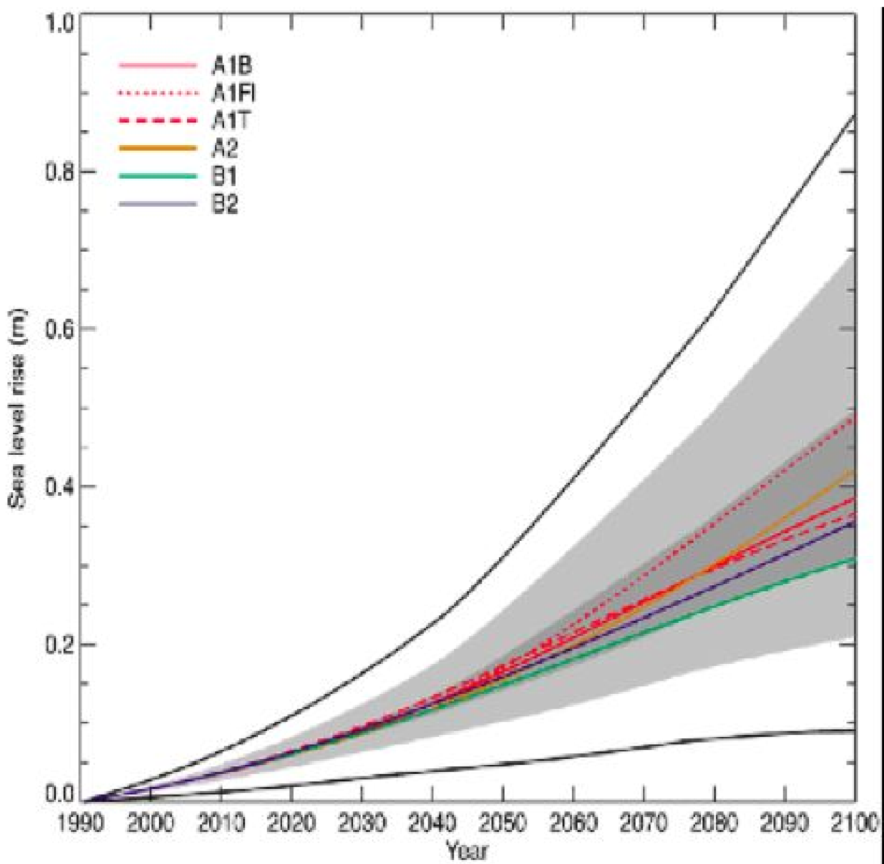

Figure 9. Predicted changes in average sea level from DWR (2006). (Adapted from IPCC, 2001a (http://www.grida.no/climate/ipcc_tar/wg1/fig11-12.htm)
Explanation: Global average sea level rise from 1990 to 2100 for the SRES (Special Report on Emission Scenarios; IPCC 2000) scenarios and seven climate models. The region in dark shading shows the range of the average of models for all 35 SRES scenarios. The region in light shading shows the range of all models for all 35 scenarios. The colored lines in the key and in the graph represent the average of modeling results for six GHG emission scenarios. The region delimited by the outermost black lines shows the range of all models and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. This range does not allow for uncertainty relating to ice-dynamic changes in the West Antarctic ice sheet For additional explanation of this figure see IPCC, 2001a (http://www.grida.no/climate/ipcc_tar/wg1/index.htm).

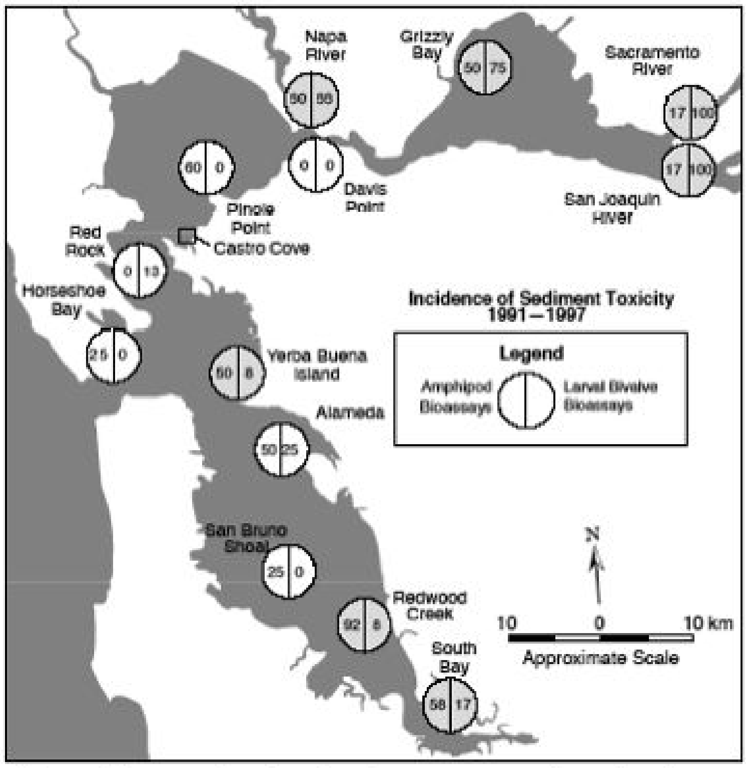

***Figure 4.** RMP sediment bioassay sites showing the percentage of samples that were toxic to amphipods (left hemisphere) and to bivalve embryos (right hemisphere). Shaded circles were sampled 11–12 times between 1991–97, unshaded circles were sampled 5–8 times.*

Figure 10. Distribution of toxicity to amphipods and larval bivalves in San Francisco Bay sediments. Copied from Thompson et al. (2000) [as Figure 4, above.]

shore sediments. Toxicity of water samples is also highest during high flow periods indicating that storm water runoff has high toxicity. Chemical monitoring of fish tissue in the 1990s showed that contaminants (in particular, mercury and PCBs) were high enough to cause concerns for public health (Thompson et al. 2000). A quote from the summary of Thompson et al.'s (2000) paper illustrates the extent of the toxic contamination:

"In 1997, 69% of the water samples exceeded one of the water quality guidelines for trace metals (mostly Cr, Hg, Ni), and 94% of the samples exceeded one of the guidelines for trace organics (mostly PCBs, DDTs, dieldrin); 30% of the aquatic bioassays indicated toxicity. For sediments, 66% of the samples exceeded more than five Effects Range-Low sediment quality guidelines (Long et al. 1995); 6% of the sites exceeded more than two Effects Range-Median guidelines (usually nickel, chlordanes); and 43% of the sediment bioassays indicated toxicity. More than one-half of the fish tissue samples exceeded U.S. EPA screening values for mercury, PCBs, and dioxins." (Thompson et al. 2000, 418).

Context Memorandum: Delta Ecosystem

Iteration 1: August 13, 2007

The contaminant profile of the Bay and Delta is changing constantly as agricultural, contaminants in the Bay-Delta have been well studied for their ecological effects. Two that have been reasonably well studied, however, are mercury and selenium. Both of these trace metals may be having toxic effects on fish and birds in the Delta/estuary. Mercury also poses a human health risk.

Mercury in the Delta/estuary comes primarily from mercury mining in the Coast Ranges and from gold mining in the Sierras. Starting about 1850 and continuing for most of the next century, large amounts of mercury were used during gold mining and an estimated 15 million pounds of mercury were discharged into the watershed. Much of this mercury has found its way downstream into the Delta so that Delta sediments are laced with mercury. However, rivers flowing into the Delta continue to deliver substantial amounts of mercury each year. The dangerous form of mercury is methyl-mercury, an organic complex of mercury created by bacterial metabolism, which is easily absorbed by living organisms. About 5.8 kg of methyl-mercury enter the Delta each year (3.6 kg carried downstream by rivers and 2.2 kg from Delta sediments) and 2.2 kg are exported (1.8 kg to San Francisco Bay and 0.4 kg in export water). The difference (3.6 kg/y) remains in the Delta, making the Delta a sink for methyl-mercury. Within the Delta/estuary, marshes appear to be prime sites for creation of methyl-mercury from elemental mercury, as are intermittently flooded areas like Yolo bypass. The overall dynamics of mercury inputs and outputs from the Delta are very complicated, however, so that it is not yet possible to predict when and where methylation hot spots will occur. Mercury is a toxic substance that concentrates as it moves through the food web. As a consequence, larger, predatory organisms in the ecosystem tend to have mercury concentrations in their tissues much greater than the concentration in water or sediments. In the Delta/estuary, fish eating birds, like tern species (*Sterna* spp.), as well as birds that live and feed in the marshy margins of the Bay where mercury concentrations are high, like rails (*Rallus* spp.) and plovers, have high tissue concentrations of mercury. Many of the sport fishes of the Delta/estuary (such as striped bass (*Morone saxatilis*), white croaker (*Genyonemus lineatus*), largemouth bass (*Micropterus salmoides*)) also have tissue concentrations of mercury sufficiently high that consumption warnings have been issued.

Selenium in the Bay-Delta comes primarily from two sources, as a byproduct of petroleum refining and as a naturally occurring element in Central Valley soils that is mobilized by irrigation agriculture. Low concentrations occur in San Joaquin River water and in San Francisco Bay, however, high concentrations are found in some predatory fishes (e.g., white sturgeon, *Acipenser transmontanus*) and birds (e.g., surf scoter, *Melanitta perspicillata*). Like mercury, selenium is concentrated through the food chain so that low concentrations in water and sediment can translate into high concentrations in predators. In the case of selenium, however, there is considerable variation in selenium concentration among types of predators. Those feeding on the invasive overbite clam, *Corbula amurensis*, have high concentrations of selenium while those feeding on crustacea or fishes not connected to the clam have much lower concentrations. It appears that the overbite clam itself accumulates very high concentrations of selenium that it passes on to its predators. Concentrations of selenium in white sturgeon and surf scoters are in the range known to cause deformities of developing embryos or reproductive failure in those species.

Drivers of Change. The Delta/estuary is one of the most physically and chemically altered estuaries in the United States (Nichols et al. 1986). Change in the physical and chemical character of the estuary continues at a substantial rate. Key drivers of change include: changing land use (e.g., substitution of urban for agricultural land, water based urban development, ecosystem restoration); changing agricultural, industrial, and other chemical based processes that alter the types and amounts of chemical discharges; changing climate (e.g., shifting precipitation patterns, frequency and severity of storms, sea level rise); changing water use patterns and priorities (e.g., growing urban demand, greater allocation for environmental purposes), and the potential for levee failure due to earthquake or severe flood.

Policy Implications. Sustaining the ecosystem function of the Delta cannot be accomplished without also sustaining the physical and chemical foundation of those services. The geometry, hydrology and chemistry of the Delta have all been changed dramatically by past human development of the Bay-Delta and of water supply and distribution systems for California as a whole. Also dramatically altered have been the dynamics of short and long term cyclical change in physical conditions in the Delta. Several species are now finding it difficult to cope with the extent of change. Further dramatic changes, many of which are outside the control of policy makers in the short term, are on the horizon. Management policies need to recognize the importance of the physical template and cyclical variation in the template in establishing the essential conditions for survival of native species. Sustainable policies also need to be robust to substantial impending changes associated with rapid population growth, climate change and sea level rise. Human uses of substantial parts of the Delta may have to be changed to accommodate the necessary variability in physical template and to respond to changing sea level and flood risk. Management tools, such as adaptive management, that recognize uncertainty and use management as a means to learn about the system as well as to influence it need to become standard procedure.

Section 4. The Ecosystem Mosaic of the Delta-Estuary

The Delta/estuary is a complex mosaic of ecosystem types reflecting the complex physical geometry and dynamics of the estuary. There are various ways of conceptualizing the ecosystem of the Delta/estuary (Table 1). These different conceptualizations are all intended to simplify the very complex multivariate nature of the Delta/estuary into a more comprehensible number of dimensions. Each conceptualization is also designed to emphasize and highlight certain characteristics of the system. I will use several of these conceptualizations in developing a picture of the ecosystem. But it is important to keep in mind that all these conceptualizations are simplifications and none provides more than a very limited view of the real ecosystem.

Table 1. Three approaches to conceiving the Delta/estuary ecosystem (Functional roles are, in part, those defined by de Groot et al. 2002)

As Discrete Patches	As Gradients or Ecotones	In Terms of Functional Roles
• Open Water • Shallow Water • Tidal Marsh (fresh/salt) • Vernal Pool • Grassland/Savannah • Upland Forest • Cropland • Pasture • Urban	• Fresh to Salt • Open Water to Upland Forest • Deep to Shallow • Dynamic to Static	• Regulation Function • Habitat Function • Production Function • Information Function • Source/Sink • Reorganizing/Accumulating/ Sustaining/Collapsing

Using the discrete patches conceptual model as an illustration, it is immediately evident that the ecosystem types listed in Table 1 represent only one way of dividing up the larger ecosystem. Figure 11, a highly aggregated land use map of the Delta, represents another, more simplified, way with only 5 ecosystem patch types. It should also be obvious that the Delta/estuary is not an isolated mosaic but is imbedded in a larger ecosystem mosaic of the Central Valley, Coast Ranges and coastal ocean.

The discrete patches model of the Delta/estuary is convenient because each of the defined ecosystem patches has a different kind of dynamics, particularly in its details but also in certain fundamental features. For example, moisture is unlikely to be an issue for organisms in the open water ecosystem but may be a critical variable in grassland/savannah or vernal pool ecosystems. Tidal excursion may be a critical variable for tidal marshes but is unlikely to be significant for upland forest. Furthermore, the patch types can be defined to reflect specific features of the physical template. The discrete patches model is also useful because key organisms (such as listed species) often use different patches in different ways or during different life stages so that the model can be useful in defining specific conservation needs. Later I will use this model to sketch some of the key ecological processes in the Delta/estuary. However, it is also important to realize that the definition of patches and the boundaries between patches in any classification of this sort are often rather arbitrary and the boundaries in particular are seldom fixed in time or space. Furthermore, the gradients between patches (what ecologists call "ecotones") can be important habitats in their own right and critical for some species.

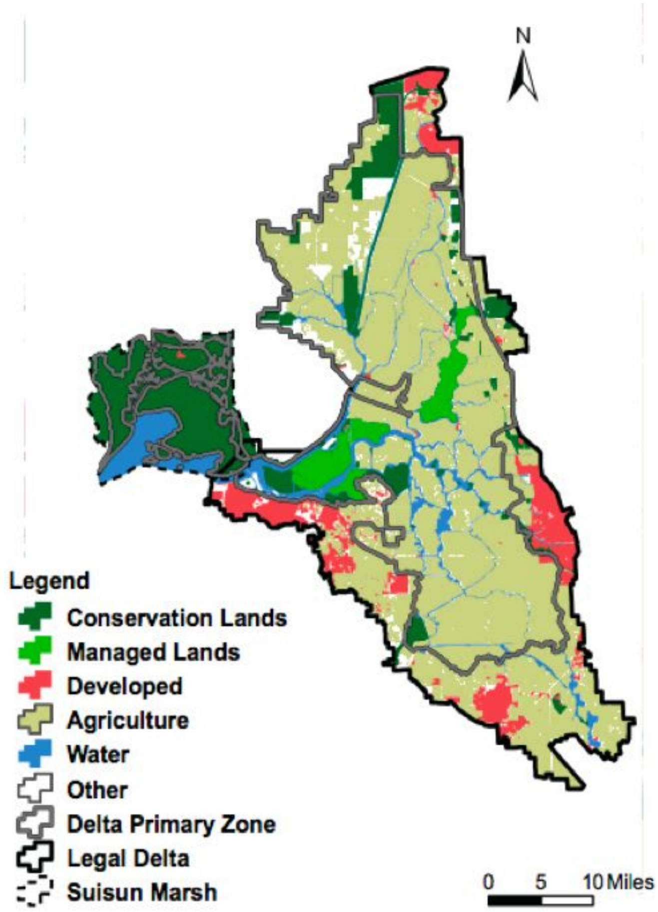

Figure 11. Broad scale Delta land use (From URS 2007).

The discrete patches model is particularly useful in applying the principles of landscape ecology to management of the Delta/estuary. Landscape ecology focuses on the spatial relationships among ecosystem patches in a landscape, the flows of energy and materials among patches, and how patch characteristics contribute to the provision of ecological services. The principles of landscape ecology are playing an increasingly important role in environmental and land use planning (Forman 1995, Ndubisi 2002). The theoretical foundations of landscape ecology also provide an important framework for ecosystem-based management.

A particular problem with the discrete patches model, however, is that it is essentially a static description of the ecosystem mosaic. The physical template and most of the dynamic processes that determine the nature of the patch are invisible. This model must be supplemented with narrative and dynamic process models to reasonably capture the character of each ecosystem patch.

The gradients model of ecosystem structure emphasizes continuity rather than boundaries and highlights exchanges between geographic regions more than the patch model. Since ecosystem patches are never fully isolated, boundaries between patches are simply steep gradients. In the Delta/estuary the gradients vary and the boundaries between patches are more or less distinct. In the aquatic system, which is highly dynamic and the mixing processes are quite strong, a gradients model may be the best representation of the ecosystem (e.g., Kimmerer 2004). In the aquatic system it is very difficult to draw clear boundaries between ecosystem types. This is particularly true in a relatively well-mixed estuary because the degree of isolation between different parts of the system is quite small. And even if discrete water masses can be identified, they are usually not fixed geographically but move and change with tides and discharge. By contrast, however, the boundaries between water and leveed islands in the Delta are quite sharp, so that a patch model is probably more representative of the relationship between these ecosystem types. Boundaries between patch types in the terrestrial part of the Bay-Delta ecosystem are also quite distinct so that the patch model probably works fairly well for terrestrial ecosystems. Like the patch model, the gradients model is a relatively static model and needs further elaboration to bring out the dynamics of local ecosystem function and exchanges.

The functional model of ecosystem structure emphasizes the capacity of the ecosystem to deliver ecological services. In emphasizing function, this model also highlights some of the dynamical processes that characterize different ecosystem types. Using this model, the Bay-Delta system could be characterized in terms of its capacity to deliver services as a whole or it could be subdivided geographically based on dominant services provided by different regions. This model focuses most heavily on the things we want the ecosystem to do for us and so provides an essentially utilitarian perspective on particular ecosystem elements or patches. A graphic illustration of how much human alteration of the Delta has affected overall ecosystem services can be seen in the levels of ecological productivity characteristic of different ecosystem patches. The capacity of an ecosystem to deliver services is, in general, reflected in its overall level of biological productivity. Healey and Richardson (1996) examined changes in productivity in the ecosystem of the lower Fraser River, British Columbia in relation to land use changes. Their estimates provide a good analogy for the Delta/estuary. Prior to European colonization, the lower Fraser ecosystem was dominated by permanent and seasonally flooded fresh and saltwater marsh, coniferous forest, and open water channels unbounded by leevees. Now the built environment of the lower Fraser ecosystem consists primarily of agriculture and urban land use with remnant forest and marsh patches andleveed open water channels. Green plant production (a proxy measure of ecological production) of marshes is typically high, averaging more than 1000 g Carbon per square meter per year (gC/m2/y). Coniferous forest production is lower, averaging about 600 gC/m2/y. Open channel production is very low owing to high turbidity. By comparison with marsh and forest, biological production of agricultural and urban ecosystem patches is much lower, about 500 gC/m2/y and 25 gC/m2/y respectively (Table 2). The transformation of the lower Fraser from forest and marsh to agriculture and urban, therefore, has resulted in a dramatic drop in productivity and capacity to provide ecosystem services, although the direct utility of the new ecosystem patches to humans is much higher than that of the original ecosystem.

Table 2. Representative rates of green plant production (gC/m2/y) in different temperate ecosystem types (compiled from various sources including Vitousek et al. 1986, Pauly and Christensen 1995, Alongi 1998)

Ecosystem Type	Green Plant Production (gC/m2/y)
Natural Ecosystems Upland Forest	680
Bog/Swamp	3300
Grassland/Savanna	300
Fresh Water Marsh	2000
Saltmarsh	1400
Estuary - open water	400
Constructed Ecosystems Cropland	750
Pasture	300
Urban	25

The Delta has experienced a similar degree of ecological transformation as the lower Fraser and change continues daily (Table 3). Agriculture is clearly the dominant land use in the Delta followed by water ("Other Land" includes a number of land uses including protected lands, recreational lands, transportation and service corridors, etc.). Urban and Other Land uses are both growing rapidly while agriculture lands are shrinking.

Table 3. Amount of land in various land use categories in the Delta and changes in acreage over recent years (Copied from land use context memo).

Land Use	Acres 1990	Acres 2004	Percentage of total 2004	Acreage change 1990-2004	Percent change 1990-2004
Urban and Built-up Land	57,351	74,098	9	16,747	29
Agricultural	596,603	557,896	67	-38,707	-6
Other Land	100,090	120,535	14	20,445	20
Water	83,170	85,065	10	1,895	2
Total*	837,214	837,594	100		
*Discrepancy in acreage may be due to refined mapping techniques or changes in land use definition between					
1990 and 2004. Note: the mapping area used in this analysis is about 1 percent larger than the total acreage in the table.					
Based on California Department of Conservation Farmland Mapping and Monitoring Program data.					

In developing a sustainable vision for the Delta/estuary it will be necessary to assign important functions or groups of functions to different regions of the Delta/estuary (For example, waterfowl feeding and breeding, biodiversity protection, food production, water supply, urban growth). This implies a merging of the functional and patch models of the ecosystem. Whatever conceptual model is applied, it seems likely that planning will involve some form of patch designation at least for the terrestrial parts of the system, even if the boundaries are arbitrary in terms of some gradients. Some form of zonal designation is likely also to be needed for the aquatic parts of the ecosystem, even if the boundaries represent administrative convenience rather than any strong ecological separation.

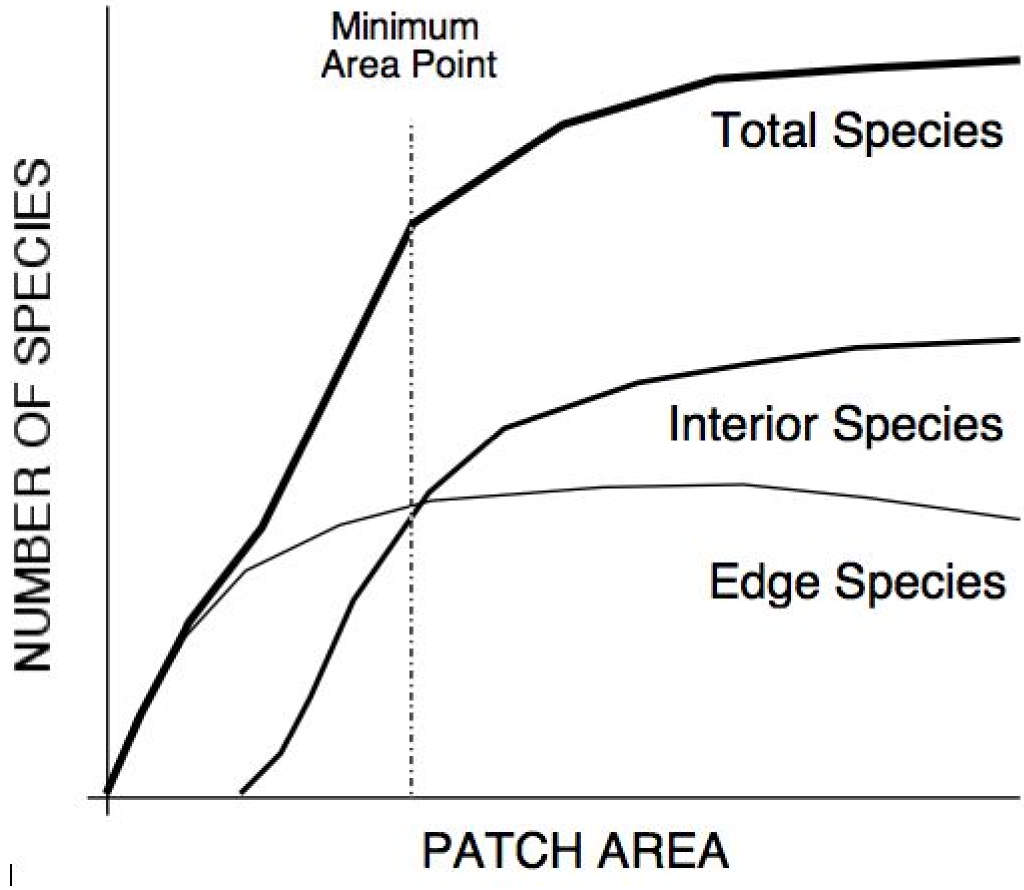

Figure 12. Relationship between the size of a patch of a particular ecosystem type and the number of species found there. Edge species are those that predominantly or exclusively live at the edges of patches or in the interface between patches. Interior species are those that live predominantly or exclusively in the interior of an ecosystem patch, away from the edges. Minimum area point is the patch size at which the number of species begins to drop rapidly.

To be successful, this approach requires an appreciation for the level of service that can be provided by patches of different size and type and how the arrangement and patterns of exchange between patches influence the capacity of a particular patch to provide services (e.g., levees or other barriers that inhibit the exchange of water and sediments between open water and marsh can reduce the capacity of both habitats to generate services). The capacity of different ecosystem patches to provide services is related to productivity, which varies 2 orders of magnitude among ecosystem types (23-3300 gC/m2/y, Table 2). Patch size is also a critical variable. Considerable evidence shows that the number and type of species that can live in a patch is strongly related to patch size. Species found in ecosystem patches can be broadly characterized as living primarily in edge or interior habitats. Edge species are also more likely to be generalists, able to make use of more than one ecosystem patch. Small ecosystem patches are essentially all edge habitat so that only edge species can find a home there. As the patch size increases the ratio of edge to interior habitat decreases so that the ratio of edge to interior species also decreases as patch size increases (Figure 12). Although these general relationships are well documented, defining the appropriate ecosystem patch size to achieve a particular conservation objective remains problematic. Smaller patches distributed around the landscape may conserve more biodiversity in total than a single large patch but may still support fewer interior species. A single large patch may be less vulnerable to small, localized destructive events (such as a small spill of toxic substances) but could be very vulnerable to a large destructive event (such as a major flood or wildfire). On the other hand, smaller patches may individually be more vulnerable to specific destructive events. One of the dilemmas environmental managers face in developing land use policy is whether to argue for a small number of large ecosystem patches or a larger number of small patches. Foreman (1995) argues for an "aggregate plus outliers" rule, in which most habitat is included in a few large patches but a number of small habitat patches provide refuges or stepping stones for species movement between large patches.

Just as important as patch size is patch arrangement. As will be described in more detail later, patches exchange materials and species and these exchanges can be both beneficial and detrimental to the conservation of species and biodiversity. This means it is important what lies at the borders of each ecosystem patch. In some cases, species move from patch to patch to accomplish different life functions (e.g., migrations from feeding to breeding areas and back again). Such species need appropriate corridors to accomplish their migrations. In other cases, a patch type may attract predators that can impose high predation pressure on adjacent patches (e.g., a woodlot that provides nesting sites for raptors can increase predation pressure on adjacent agricultural lands). Urban and agricultural patches may discharge toxic contaminants and organic substances into adjacent ecosystem patches. The current trend to encircle the Delta with urban development, for example, will cut Delta ecosystem patches off from natural or semi-natural upland ecosystems, creating a substantial barrier to exchanges.

Every different composition and distribution of ecosystem patches has different consequences for ecosystem services, for species and biodiversity conservation, and for the capacity of the Delta to maintain its integrity in the face of various stressors. Although there is probably no single optimal ecosystem mosaic, planning for water and environmental management in the Delta must be made in recognition of the importance of these aspects of ecosystem function. Additionally, the connection and exchanges between the Delta/estuary as an ecosystem patch within the large ecosystem of the river catchments and the coastal ocean need to be taken into account. What happens upstream and in the ocean outside San Francisco Bay have important implications for the way the Delta/estuary functions.

Dynamic Processes (Local Food Web Dynamics). Regardless of the model of ecosystem structure one chooses, two general kinds of dynamics need to be considered, local dynamics (localized processes of growth and decay within the ecosystem) and exchange dynamics (processes of exchange between locations, between patches, along gradients, or among functions). Both kinds of dynamics are critical to the overall functioning of the ecosystem although their relative importance may vary. In the well-mixed channels of the Delta, for example, exchange dynamics may be as important, or more important than local dynamics whereas on a leveed island local dynamics may dominate.

Local ecosystem dynamics can be conceptualized and illustrated in terms of food web dynamics. The food web is a diagram or flow chart of who eats whom in the ecosystem. More specifically, it is the network of pathways along which the potential energy of organic carbon compounds (initially generated by photosynthesis) is distributed to all the organisms of the biological community or dissipated through metabolism. Figure 13 is a generalized food web diagram showing movement of energy and material through components of the local ecosystem. Not shown in the diagram are movements of detritus and organisms into and out of the local ecosystem. These movements can have a big impact on local ecosystem dynamics but will be discussed later in terms of exchange dynamics.

The sources and kinds of organic carbon that fuel the local ecosystem are of critical importance. For some ecosystem types (e.g., upland forest), local green plant production dominates and the production and cycling of organic material takes place primarily within the ecosystem. In this case, the whole of the food web is supported by the production of green plants in the local area. By contrast, in the open water ecosystem of the Delta and Suisun Bay, potential sources of organic carbon are more complex and the role of different carbon sources harder to work out. Green plant production (phytoplankton production) in the open water ecosystem is low and has declined dramatically over the period of record from about 100 gC/m2/y in the 1970s to about 25 gC/m2/y presently. Nutrients for plant growth are plentiful in Bay-Delta waters but high turbidity limits light penetration so that light is considered the principal physical factor limiting plankton growth. The dramatic drop in plankton production that began about 1986 is attributed to the invasion of the overbite clam (*Corbula amurensis*), which filters plankton out of the water with high efficiency but other factors have played a role as well, including long term changes in turbidity and flow in the Delta. Yet this source of organic carbon is particularly important to Delta fishes because it passes directly in one or two steps to food organisms on which the fish feed. In the Delta, this local production is supplemented somewhat by plankton production upstream in the San Joaquin River and in fringing marshes like Suisun Marsh as well as the fish food organisms that grow in these connected habitats and are flushed into the Delta. This is an important example of the importance to one Delta ecosystem patch (open water) of exchanges between patches.

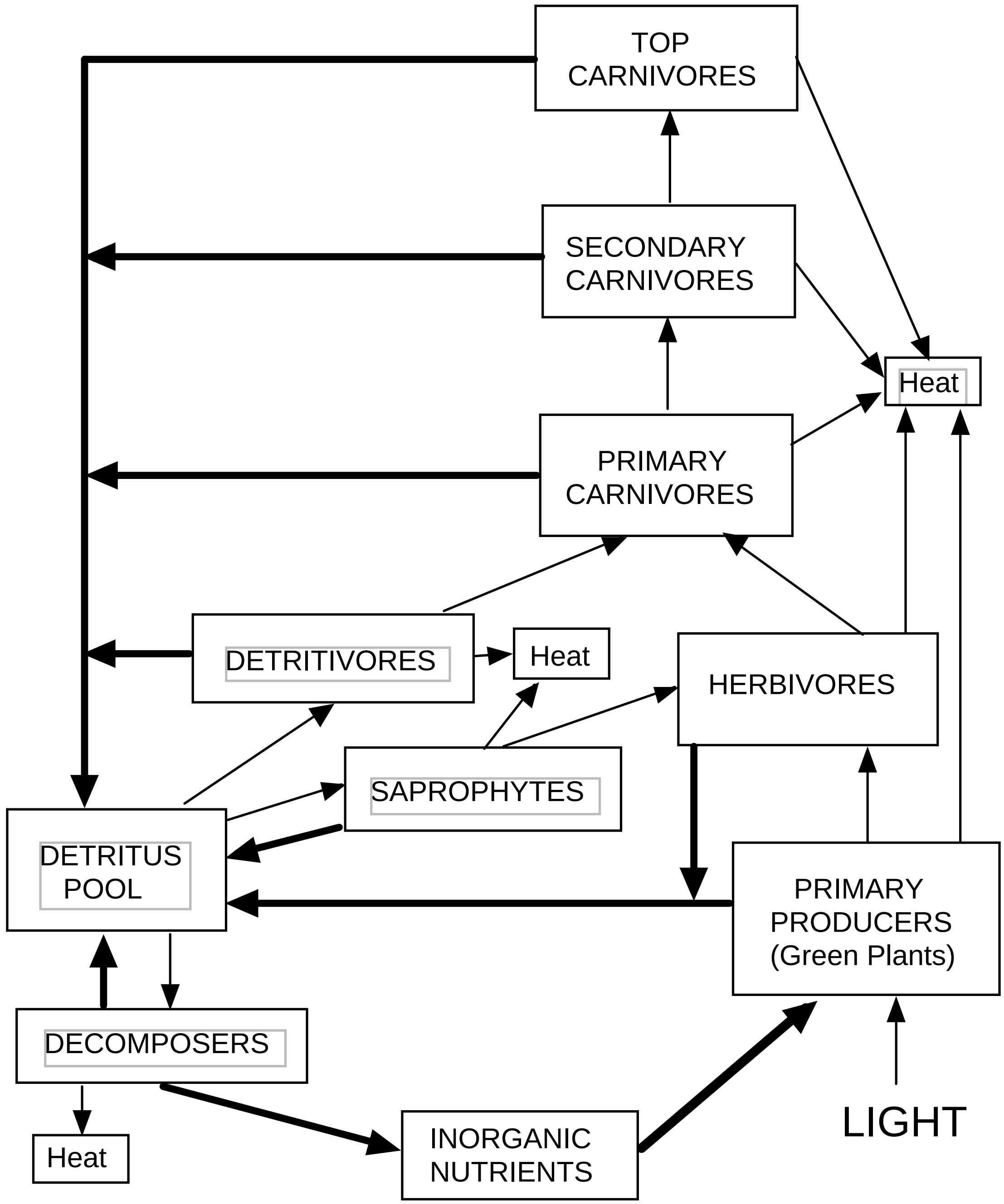

Figure 13. Generalized food web diagram illustrating local ecosystem dynamics. Energy (as organic carbon compounds) fixed by green plants in the ecosystem passes through various consumer levels before being dissipated in metabolism or joining the detrital pool as dead material where it is recycled back into the food web or mineralized to provide new nutrients for plant growth. Detritus or living organisms may enter or leave the local system and affect local food web dynamics through exchange dynamics.

Organic carbon from local plant production in the open water ecosystem of the Delta is supplemented by dead organic carbon (detritus) washed down from upstream, detritus that washes in from adjacent lands, and detritus from the ocean. These other sources of carbon have different values as food for the ecosystem. In general, these outside sources of carbon have lower food value for desired species such as Delta smelt and striped bass for two reasons. The first is that the detritus, particularly much of that from upstream, cannot be directly eaten by organisms that are important food for fish. The material in the detritus pool needs to be transformed first into higher quality food particles by passing through the microbial food web (Figure 13). This passage involves several steps starting with bacteria and then moving to predators of bacteria and predators of the predators, before being incorporated into organisms that are large enough to be fed upon by fish. By this point, most of the potential energy in the detritus has been dissipated in metabolism so that only a tiny fraction of the energy actually reaches the fish. The second reason is that much of this detritus is not easily fed upon by bacteria or other detritivores so that it often passes through the local ecosystem uneaten. Thus, although there is a substantial amount of organic carbon to provide a base for the open water ecosystem, much of it is not a good food source. The food web leading to desired species is, therefore, heavily dependent on local or nearby phytoplankton production (Jassby and Cloern 2000, Sboczak et al. 2002).

As a result of these factors (low inherent productivity, appropriation of much of the production by clams, limited value of detrital carbon), fishes living in the open water ecosystem of the Delta may be food limited. This is less likely to be a problem in other ecosystem patches (except for urban ecosystem patches) and illustrates the fact that different ecosystem patches have different structural and functional properties that are important to environmental management.

The processes of ecological production, consumption, energy flow, and decomposition captured in the food web model may seem somewhat esoteric but they are central to the provision of goods and services from ecosystems to human society. For example, the availability of light and nutrients are important determinants of tree and pasture growth and the model provides a basis for assessing potential fiber production from forest ecosystems and optimal age of harvest (Reiners 1988) as well as estimates of hay production from pasture. Estimates of phytoplankton production and the efficiency of transfer of energy from plankton up the food chain to commercially important fishes provide a basis for assessing potential fishery production (Ryther 1969, Pauly and Christensen 1995). For example, efficiency of energy transfer from one feeding level to the next in the food web averages about 10% so that an organism feeding 4 steps away from green plant production has available only 0.1% of the energy produced by green plants. These same processes help account for poor performance of ecologically important species like Delta smelt, as noted above.

Context Memorandum: Delta Ecosystem

Iteration 1: August 13, 2007

Although the food web (or energy flow) model can be used to describe the dynamics of any local ecosystem, the Delta is made up of both naturally organizing ecosystem patches (e.g., marshes, open water channels) and human constructed ecosystem patches (e.g., urban areas, agricultural fields) that are maintained in an artificial state by human action. Folke et al. (2003) suggest that there are some fundamental differences between naturally organizing and human constructed ecosystems that need to be taken into account in developing and evaluating management policy for sustainability (Table 4). Among other differences is that human constructed systems are sustained only by substantial energy and species subsidies and waste products from human constructed systems are largely transferred to naturally organizing systems for decomposition and decontamination. The variety of subsidies for corn production is illustrated in Figure 14 and amounts to about 11% of total biological production. What is also significant in the agricultural ecosystem, however, is that the vast majority of biological productivity is taken and used in other urban and agroecosystems, not within the production ecosystem. Most human constructed ecosystems are much more dependent on exchange dynamics than the naturally organizing ecosystems they replaced.

Table 4. Fundamental differences between naturally organizing and human constructed ecosystems (adapted from Folke et al. 2003)

Naturally Organizing Ecosystems	Human Constructed Ecosystems
Dependent on solar power as primary energy source.	Dependent on auxiliary energy inputs from human and animal labor, fertilizers, pesticides, irrigation water, machinery as well as solar power
Biotic diversity is high and naturally selected to maximize ecological efficiency and resiliency.	Biotic diversity is low and human selected to maximize economic yields, minimize health problems, or maximize aesthetic values.
All species are under natural selection to maximize their fitness (i.e., genetic contribution to future generations) in the context of the particular ecosystem.	Dominant species are artificially selected or genetically modified by humans to maximize production of goods and services valued by human society.
Temporal change in species abundance and distribution is primarily driven by internal feedback processes.	Temporal change in species abundance and distribution is externally managed by humans to achieve specific social goals.

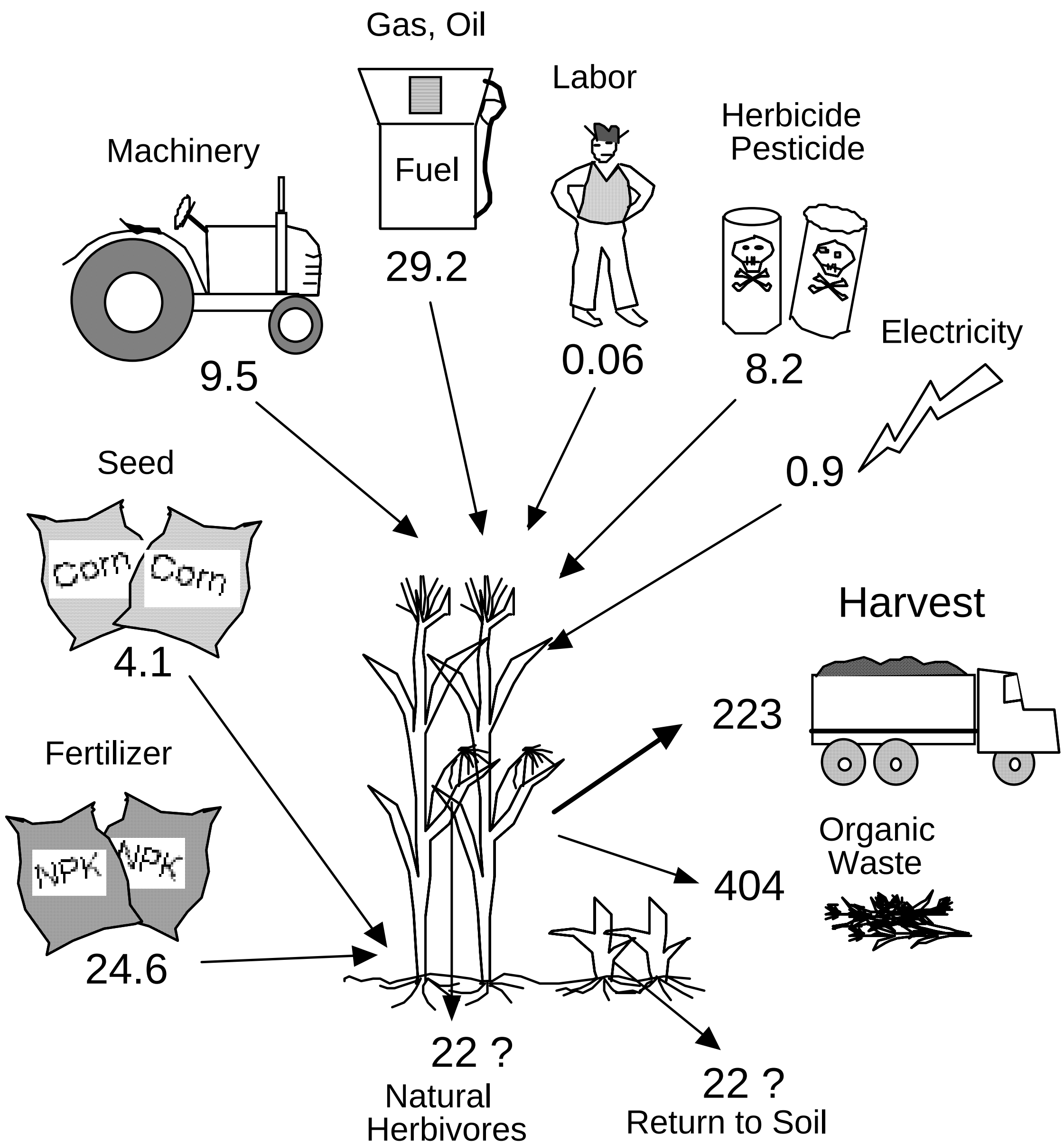

Figure 14. Illustration of the contribution of various sources of energy to corn production and yield. All figures based on papers in Lowrance et al. (1984) with values converted to gC/m2/y equivalents. Total production of the corn plants is about 670 gC/m2/y (corn, organic waste, return to soil and eaten by herbivores) and the human subsidy is equivalent to about 77 gC/m2/y, or 11% of total production

The food web model of local ecosystem dynamics is often described as a "bottom up" model because the processes are driven by green plant production at the base of the food web. An alternative conceptual model is the "top down" or "trophic cascade" model that examines how feeding behaviour and competition among predators at or near the top of the food web influences structure and dynamics throughout the ecosystem. There are two important and interlinked concepts that are central to the top down model, the trophic cascade concept and the keystone species concept. Keystone species play a crucial role in maintaining the organization and diversity of their ecological communities; they are exceptional, relative to the rest of the community, in their importance. Keystone species were first observed and named by Robert Paine (1966, 1969) on a rocky intertidal community in Washington state. Paine removed starfish, a predator at the top of the food web, and observed that the intertidal community changed from one characterized by a patchwork of different species groupings to a community uniformly dominated by mussels. Sea otters have a similar structuring effect on subtidal coastal ecosystems. In the absence of otters, sea urchins often become very abundant, severely grazing all the algae and kelp, producing what has been termed urchin barrens. Where sea otters are present, urchins are kept in check and kelp forests flourish, providing habitat for a diverse assortment of fish and invertebrates (Estes and Palmisano 1974). Although there has been considerable criticism of the keystone species concept there is no doubt that in many communities one or a few species determine the structure of the whole community. It has been suggested that focusing conservation on keystone species could be a means to maintain desired community structure (Rohlf 1991, Woodruff 1989). Although no specific analysis of keystone species has been made in the Delta/estuary, the impact of the overbite clam in appropriating much of the phytoplankton production and channeling energy flow into the microbial pathway suggests it is playing a keystone role. In a less dramatic way, the Brazilian waterweed, Egeria densa, appears to have improved water clarity (by trapping fine sediments) and increased habitat structure in littoral areas, thereby making conditions that favor introduced fishes (Kimmerer 2004, Brown and Michniuk 2007). There is some debate among ecologists as to whether humans should be considered a keystone species (Steneck 1998, Coleman and Williams 2002). However, given humans dramatic alteration of ecological communities through physical restructuring, species exploitation, and species introduction, it seems a reasonable classification.

The trophic cascade concept is one explanation for how species near the top of the food web can have effects that propagate through the community as a whole. The keystone species effects described above for starfish on a rocky shore and sea otters in the subtidal ecosystem are examples of trophic cascades where the effects of the predator near the top of the food web propagate down to the bottom of the food web. In general, predation at the top of the web reduces the abundance of consumers at the next level down, which allows greater abundance of consumers two levels down, and so on. In a three layered food web (consisting of green plants at the lowest level, herbivores in the middle, and predators at the top), therefore, reducing the abundance of predators will allow the herbivores to increase, which will increase grazing and lower the abundance of green plants. These kinds of cascading effects have been observed in many ecosystems and help to explain why seemingly small changes in the abundance of one species can sometimes have dramatic effects on the community as a whole.

Although both the keystone species concept and the trophic cascade concept have had a strong influence on the way ecologists and managers conceptualize the problems of species and environmental conservation, it is usually not possible to identify keystone species or the potential for a dramatic trophic cascade without conducting large scale field experiments. Unfortunately, simply describing the structure and species interactions in a food web does not reveal either keystone species or patterns of cascading effects.

Bottom up and top down processes operate in all communities with different importance at different times so that it can be very difficult to determine details of the forces driving community dynamics. Nevertheless, experience indicates that it is possible to push communities in desired directions by judicious manipulation at either the bottom or the top of the food web. For example, fertilization of unproductive lakes has become a valuable tool in enhancing the production of salmon and trout (Hyatt et al. 2004) and management of top predators offers a means to control excessive phytoplankton production (Carpenter et al. 1995).

Dynamic Processes (Exchange Dynamics). While local food web dynamics is important to sustainability, ecosystem patches within the Delta/estuary also exchange materials and energy in ways that are important to the integrity of the larger system. In the broadest sense, deltas and estuaries are ecotonal systems that connect upland and riverine ecosystems with the oceanic ecosystem. As such, exchange processes are fundamental to their functioning. Rivers flowing into the Delta contribute a broad spectrum of inorganic and organic materials to the Delta/estuary, some of which is trapped or processed there (up to 90% in many estuaries) and some of which moves through to the ocean (Howarth et al. 2000). Tidal forces bring an equally diverse array of organic and inorganic materials into the Delta/estuary that are moved up estuary by advective and dispersive processes. Materials of various sorts (dissolved and particulate organic and inorganic substances) move down slope (carried mainly by water percolating through the soil) from upland to marsh and estuarine ecosystems. Migrating fishes and birds move organic material and nutrients from ocean and marsh to river and upland ecosystems. Anadromous salmon, for example, can be an important source of nutrients for lake, river and floodplain ecosystems (Gende et al. 2002, Lyle and Elliott 1998). There are also important exchanges with the atmosphere, nutrient and contaminant fallout for example, and exchanges of water through evaporation and rainfall (Paerl et al. 2002). Smaller scale exchange processes between different ecosystem patches within the Delta/estuary also affect ecosystem function. These exchange processes affect ecosystem patches within the Delta/estuary in different ways. For some ecosystem patches, exchange processes dominate ecosystem dynamics (e.g., open water system). For others they are less important (e.g., upland forest). In some cases the exchange is primarily in one direction (e.g., atmospheric fallout of nutrients and contaminants). In others the exchange is bi- or multi-directional, among ecosystem patches (e.g., tidal marshes). Understanding these exchange processes and their importance in local ecosystem dynamics is central to effective management of the ecosystem mosaic of the Delta/estuary.

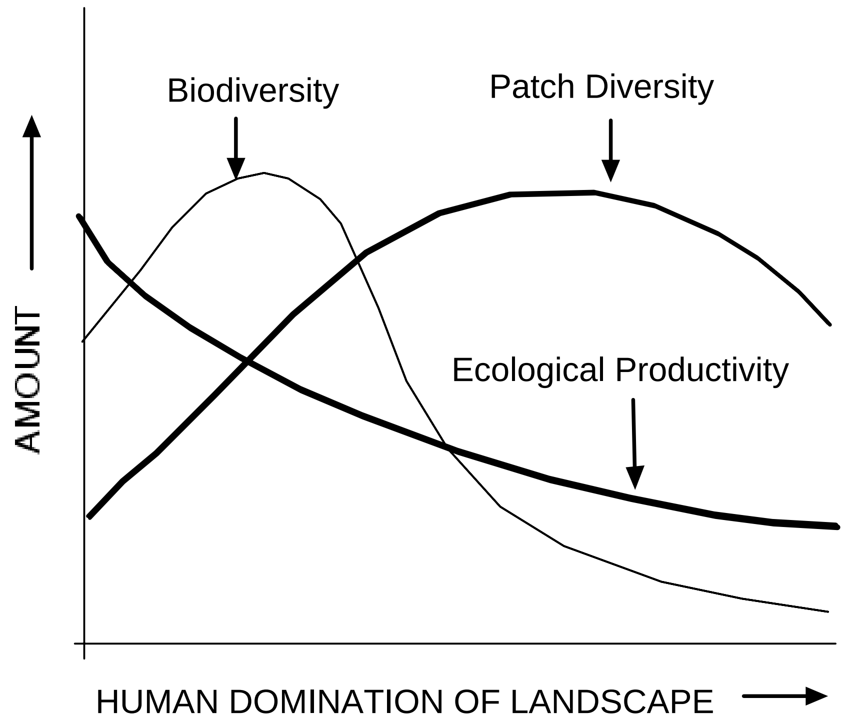

Figure 15. Changes in ecological productivity, biodiversity and patch diversity as human domination of the landscape increases.

Human uses of the landscape affect not only the size and distribution of ecosystem patches, as described in the previous section, but also the exchanges of energy and materials between ecosystem patches. Many of the exchanges of materials and energy among ecosystem patches and the effect of human activity on them are well documented. Removal of vegetation (as in forestry, farming, urban construction and so forth) exposes soil to erosion and increases sediment and nutrient flow into streams. Cultivated lands, for example, release ten times as much nitrogen into stream channels as forested lands. Farming the organic peat soils of Delta islands has led to severe land subsidence. Construction of roads, houses, parking lots, increases the amount of impervious surface on the land and allows storm water to flow more rapidly into streams causing increased flood flows. Storm flows from urban areas typically carry high concentrations of dissolved metal ions into streams that can be toxic to aquatic life. Levees along river banks and around Delta islands disconnect the river from its floodplain and disrupt or eliminate the exchange of sediments and organic material between river and floodplain. Land use and waste discharge practices alter the chemical and sediment characteristics of freshwaters flowing into estuaries while changes in river flows alter the way these materials are distributed in the estuary and the rates of exchange between estuary and marine ecosystem patches. This list, which is only a partial list of the way that water and land use practices propagate through the landscape, shows clearly that the field of effects of any local land use decision is very broad geographically and ecologically.

As human uses occupy more and more of a particular landscape, characteristic changes are seen in three important landscape characteristics: ecological productivity; biodiversity; and patch diversity (a measure of the variation in ecosystem types along a transect through the landscape) (Figure 15). Ecological productivity declines continuously, sharply at first because the most productive landscape patches are usually the first to be converted to lower productivity human uses (e.g., forest and marsh to agriculture and urban). Patch diversity increases at first because human occupation introduces new kinds of ecosystem patches into the landscape and the larger natural ecosystem patches are broken up by human development (e.g., conversion of the extensive Tule marshes of the historic delta into a patchwork of agriculture, urban, marsh). As human domination of the landscape increases, however, patch diversity begins to decline. This is because the landscape changes from one dominated by natural ecosystems with a patchwork of small human constructed ecosystems to one dominated by human constructed ecosystems with a patchwork of small natural ecosystems. Biodiversity increases in the early stages of human occupation because the creation of new ecosystem patches and the initial increase in patch diversity creates opportunities for new species and for species that occupy the edges between ecosystem patches. As human constructed patches occupy more and more of the landscape, however, biodiversity falls rapidly. The early stages of this evolution of the landscape do not violate the principles of sustainability but the latter stages do. The landscape of the Delta/estuary appears to be well into the stage of decline illustrated in Figure 15.

The arrangement of ecosystem patches in the landscape also has important consequences for overall ecosystem function. In a study of the Rhode River and its watershed (a tributary of Chesapeake Bay), Correll et al. (1992) found that riparian forests intercepted more than 80% of nitrate and phosphorus leaching from cropland toward stream channels. Over 90% of suspended sediment was also filtered from surface and groundwater flows by riparian forests before reaching the stream channel. The hardwood forest buffer strips along stream channels in the Rhode River watershed were, therefore, critically important in reducing the flux of nutrients from cropland to the estuary. The same amount of forest might have supported an equivalent assemblage of woodland species if arranged in large stands away from the stream channels. But it would not have performed the critical filtering function in relation to stream nutrients, nor would it have shaded the stream channel and kept the water cool, provided stability and complexity to the channel with its root system, or delivered an organic subsidy to the stream in the form of falling leaves and twigs. The importance of the distribution of the forest in relation to the cropland and stream channel demonstrates very clearly how the arrangement of ecosystem patches in a landscape affects the exchange dynamics of the ecosystem.

The nutrients and sediments entering the stream channel of the Rhode River were ultimately delivered to three different ecosystem patches in its upper estuary, high marsh, low marsh and mudflat. In general, the marshes trapped sediments and nutrients in particulate form but exported dissolved nutrients (Jordan et al. 1983). The high marsh was a sink for phosphorus but exported nitrogen to the estuary, mostly in organic form. The low marsh, by contrast, was a sink for both nitrogen and phosphorus. Surprisingly, the mudflat trapped particulate matter more effectively than the marshes. The mudflat released phosphate but consumed almost all the nitrogen discharged from the Rhode River watershed and possibly some from adjacent Chesapeake Bay as well. The ecosystem patches in the Rhode River estuary were, therefore, critical in trapping nutrients delivered by the Rhode River watershed as well as nutrients from atmospheric deposition. Estuaries, particularly the upper regions of estuaries play an important role in buffering adjacent marine areas from discharges of nutrients and other polluting substances from the land.

If decisions about human uses of the Delta/estuary are to be ecosystem based and sustainable, we need a set of tools to assess the capacity of the landscape to absorb human activity without degrading its capacity for production and regeneration. This is the ecological "resilience" that Holling and his colleagues emphasize (Gunderson et al. 1995). As was shown above, the Delta/estuary is comprised of a mosaic of ecosystem patches each with its own internal dynamics but also exchanging materials, organisms, and energy in such a way that a change in one ecosystem patch propagates through many other patches with potentially far reaching affects. Although the flows of materials and energy are reasonably well understood for many estuarine systems, they have not been well studied in the Bay-Delta. Furthermore, the effects on other patches of a change in one ecosystem patch can seldom be predicted in any detail. As soon as the local change occurs (breaching a levee, for example, or construction of a causeway across a tidal flat), the system begins to respond, shifting and adapting to the changed character of the mosaic with affects on adjacent patches that often feed back into the altered patch to generate further changes. Management of ecosystems, therefore, requires constant attention and adaptation to the changing character of the system. This kind of continual oversight will become increasingly necessary as global climate change begins to impose significant change in the physical template of the Delta/estuary.

Drivers of Change. Just as the physical template of the Delta/estuary has been dramatically altered by human activity, so has the ecosystem responded to become dramatically different than it was in the past. And change continues at a substantial rate today. Key drivers of change include the forces that are changing the physical template (e.g., changing land use; changing agricultural, industrial, and other chemical based processes; changing climate; changing water use patterns and priorities; and the potential for levee failure due to earthquake or severe flood). In addition, species introduction is an important driver of change in the ecological community of the Delta/estuary.

Policy Implications. The Delta/estuary is a complex mosaic of different ecosystem patches, some naturally organizing, some entirely human dominated. Each has its own particular internal dynamics but all are influenced by human activity because of the multiple exchanges between different ecosystem patches. Management of human activity and uses of the landscape and water is integral to successful management and conservation of desired species, ecosystem types and biodiversity in the Delta/estuary. Human actions in an ecosystem always have multiple consequences. Exploiting some species and/or introducing others have far reaching implications for the ecosystem. Constructing roadways or dredging channels have impacts far beyond the local area. Release of the waste products of human social and economic activity into the ecosystem also has important implications for the integrity of the system and its capacity to provide services to society. Management policies need to be framed in the context of their consequences for the ecosystem as a whole not just in terms of their effects on an immediate perceived problem.

Management plans and decisions for the Delta/estuary need to be informed by a landscape perspective that recognizes the interrelationship among patterns of land and water use, patch size, location and connectivity, and species success. The landscape perspective needs to be developed at several physical and temporal scales (e.g., patches within the delta, delta within the valley and temporal scales of patch dynamics and evolution). At present the structure and dynamics of the ecosystem mosaic of the Delta/estuary is not appropriate to support healthy populations of many species, which is leading to their listing under the ESA. Achieving a sustainable balance of ecosystem services and biodiversity conservation in the Delta is likely to involve allocating considerably more land and water to support natural and semi-natural systems than is presently the norm.

Although Delta/estuary systems in general have high biological productivity, the open water system of the Sacramento/San Joaquin Delta/estuary has unusually low productivity. The open water system is also the principal habitat of several important fish species that have declined dramatically in abundance in recent years. These species are supported by a food web pathway that leads directly from green plant production (phytoplankton) in the open water to crustacean food organisms for fish. Unfortunately, energy flow to fish through this pathway has been greatly reduced by invasion of the overbite clam that filters most of the phytoplankton out of the low salinity zone of the estuary where these fishes live. Levels of phytoplankton production in the Delta/estuary must be maintained and increased if possible to improve energy flow to these fishes. Management and restoration for natural communities should also emphasize ways to enhance this food web pathway for energy transfer in the aquatic community.

Section 5. Dynamics of Individual Species

The concept of the Delta/estuary as an ecosystem comprised of a mosaic of smaller ecosystem patches that is itself an ecosystem patch within a larger regional ecosystem is critical to designing management policies that will sustain the most important features and services of the ecosystem mosaic. Nevertheless, the bulk of our management infrastructure and environmental legislation focuses on individual species. This is particularly the case with the Endangered Species Act and many recent management decisions have been dictated by the status of particular species listed under this act. It is important, therefore, to understand the ecological principles that underlie our understanding of increases and decreases in the abundance of individual species. Although these principles are also important to the development of effective management policy it is unfortunate that an emphasis on individual species frequently distracts us from the fact that a healthy species population is an emergent property of appropriate ecosystem structure and function. The bottom line is that we cannot have healthy populations of particular species without the appropriate underlying physical template and its associated ecosystem structure.

It is clear that maintaining healthy populations of native species in the Delta/estuary presents a problem. A total of 31 plants and animals have been listed as threatened or endangered within the Delta (Table 5). Preventing further declines or extinction of any of these species is a high priority objective in Delta water and environmental management. With such a diverse array of listed species as well as many others that depend on the Delta during critical life stages (e.g., migratory shorebirds, ducks) it is not surprising that the needs of individual species play a major role in management decisions.

The abundance and trends in abundance of any species reflects the historic and prevailing balance between births and deaths in the population (The term "births" is not ecologically very precise when referring to plants, which frequently reproduce vegetatively.). Although all populations vary in abundance (some go through extreme cycles in abundance), if there is no long term trend in abundance it means that, on average, births have equaled deaths. In a suitable environment, a species will increase in numbers until it reaches the capacity of the environment to support it (what ecologists call the carrying capacity). When abundance is low relative to the carrying capacity, births greatly outnumber deaths and the population increases quickly. When the population gets close to the carrying capacity, however, competition between individuals searching for food and shelter slows the birth rate and exposes individuals to greater predation risk, raising the death rate. Birth and death rates that change with increasing population density are termed density dependent rates. The concepts of environmental carrying capacity and density dependent birth and death rates are core principles of population ecology. A variety of factors can complicate the interplay of carrying capacity and density dependence to introduce variability into population abundance. If the environment varies, carrying capacity may also vary so that the population never reaches any equilibrium density. Occasional and unpredictable events may kill a lot of individuals (e.g. wildfire in a forest or grassland, disease outbreak, toxic spill) so that the population is almost continually in a growth phase. Population abundance often fluctuates widely in response to these changing forces making it difficult to detect trends and to identify underlying causes of change.

Table 5. Threatened (T) and endangered (E) species in the Sacramento-San Joaquin Delta.

Invertebrates
Apodemia mormo langei - Lange's metalmark butterfly (E)
Branchinecta conservatio - Conservancy fairy shrimp (E)
Branchinecta longiantenna - longhorn fairy shrimp (E)
Branchinecta lynchi - vernal pool fairy shrimp (T)
Desmocerus californicus dimorphus - valley elderberry longhorn beetle (T)
Elaphrus viridis - delta green ground beetle (T)
Lepidurus packardi - vernal pool tadpole shrimp (E)
Fish
Acipenser medirostris - green sturgeon (T)
Hypomesus transpacificus - delta smelt (T)
Oncorhynchus mykiss - Central Valley steelhead (T)
Oncorhynchus tshawytscha - Central Valley spring-run chinook salmon (T)
Oncorhynchus tshawytscha - winter-run chinook salmon, Sacramento River (E)
Amphibians
Ambystoma californiense - California tiger salamander, central population (T)
Rana aurora draytonii - California red-legged frog (T)
Reptiles
Masticophis lateralis euryxanthus - Alameda whipsnake [=striped racer] (T)
Thamnophis gigas - giant garter snake (T)
Birds
Rallus longirostris obsoletus - California clapper rail (E)
Sternula antillarum (=Sterna, =albifrons) browni - California least tern (E)
Mammals
Reithrodontomys raviventris - salt marsh harvest mouse (E)
Sylvilagus bachmani riparius - riparian brush rabbit (E)
Vulpes macrotis mutica - San Joaquin kit fox (E)
Plants
Amsinckia grandiflora - large-flowered fiddleneck (E)
Castilleja campestris ssp. succulenta - succulent (=fleshy) owl's-clover (T)
Cordylanthus mollis ssp. mollis - soft bird's-beak (E)
Erysimum capitatum ssp. angustatum - Contra Costa wallflower (E)
Lasthenia conjugens - Contra Costa goldfields (E)
Neostapfia colusana - Colusa grass (T)
Oenothera deltoides ssp. howellii - Antioch Dunes evening-primrose (E)
Orcuttia tenuis - slender Orcutt grass (T)
Orcuttia viscida - Sacramento Orcutt grass (E)
Tuctoria mucronata - Solano grass (=Crampton's tuctoria) (E)

For a number of native species, however, there have been long term downward trends in abundance, which in some cases have led to the species being listed as threatened or endangered. Unfortunately, for most of these species we do not know if the decline in numbers is a result of fewer births, more deaths, or a combination of the two. A good illustration of the complexities involved in attempting to explain a downward trend in species abundance is the recent pelagic organism decline. Four common resident species in the open water system of the Delta/estuary (delta smelt, *Hypomesus transpacificus*, longfin smelt, *Spirinchus thaleichthys*, striped bass, *Morone saxatilis*, and threadfin shad *Dorosoma petenense*) went into steep decline in numbers about the year 2000 (Figure 16, Sommer et al. 2007). Indices of abundance for two of these species (striped bass and longfin smelt) had been in decline for some time and delta smelt were already sufficiently rare that they had been listed as threatened but the coincidental and sharp decline in all four species was unusual. Two of the species (striped bass and longfin smelt) typically showed increases in abundance during wet years, yet the declines in abundance after 2000 took place during a series of wet years. Abundance indices for longfin smelt and striped bass increased substantially in 2006 but overall

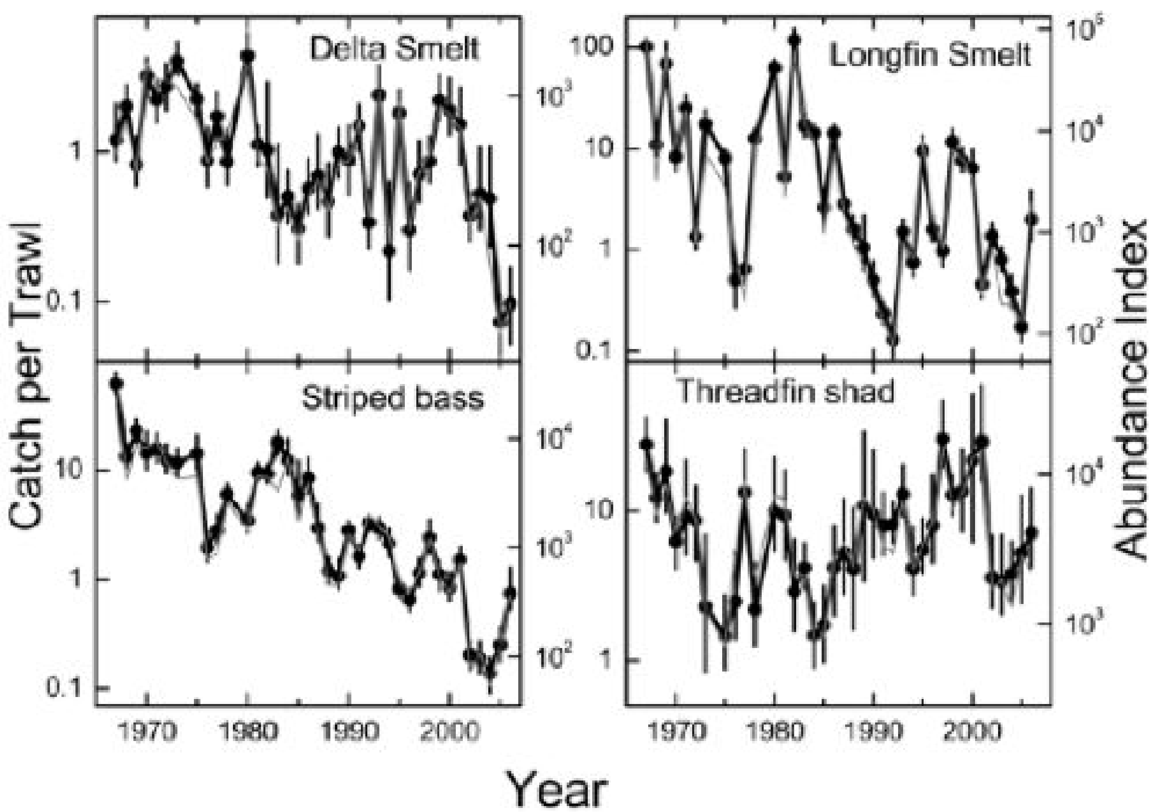

Figure 16. Trends in four pelagic fishes during 1967–2006 based on the fall midwater trawl, a DFG survey that samples the upper San Francisco estuary. Symbols with heavy lines and error bars (left y axis) show mean catch per trawl (all stations) with approximate 95% confidence intervals determined by bootstrap analysis (Kimmerer and Nobriga 2005), and the thin lines (right y-axis) show abundance indices. No sampling occurred in 1974 or 1979. Note that the y-axes are on logarithmic scales. Copied from Sommer et al. (2007).

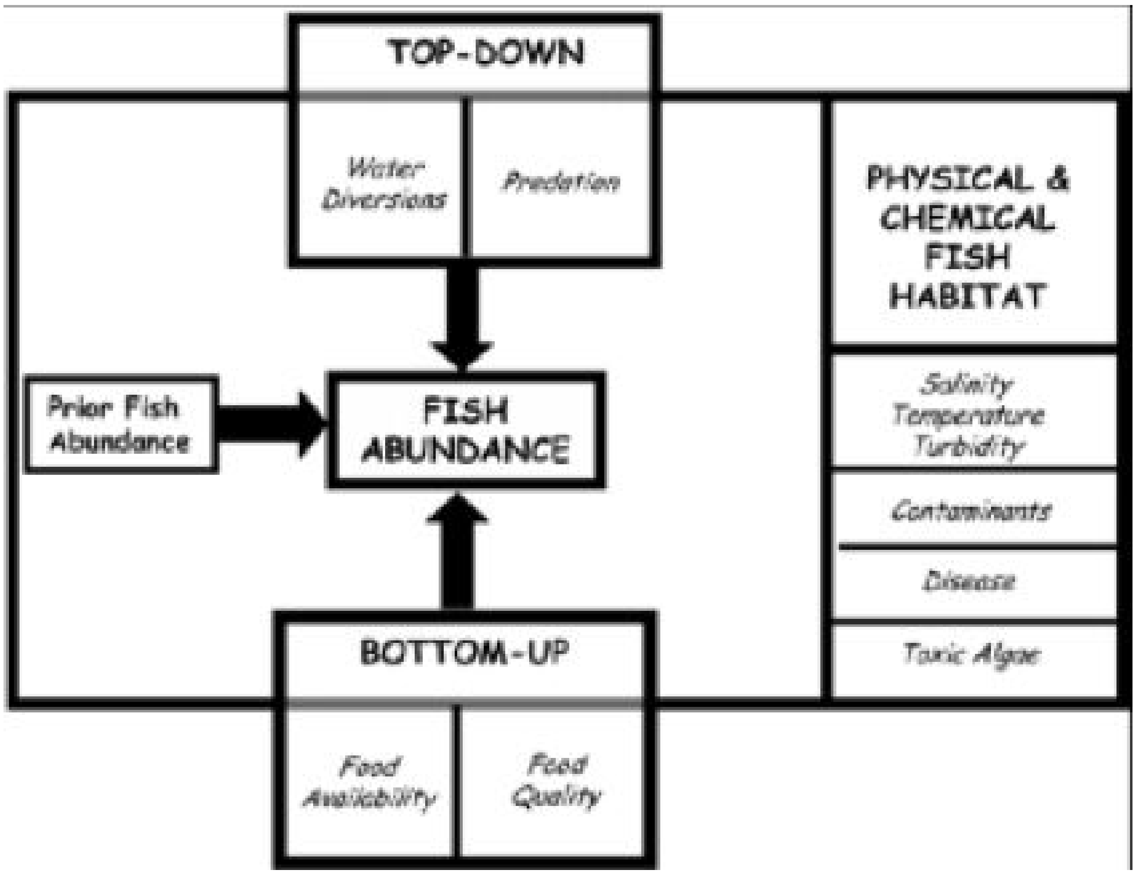

Figure 17. Conceptual model of factors that could play a role in the Pelagic Organism Decline. Copied from Sommer et al. (2007).

abundance remains low. The decline in abundance of Delta smelt was particularly serious as this species is already at low abundance. An investigation was launched to determine what was causing the unusual decline in four pelagic species.

The Pelagic Organism Decline (POD) science team has proposed a conceptual model to guide their thinking and analyses to determine the causes of the decline (Figure 17). The model incorporates all the potential factors that might contribute to the POD. The physical habitat template is represented with particular emphasis on temperature, salinity, turbidity and contaminants and their effects on distribution in the Delta, feeding and death rates. Toxic algae and disease are also listed as potential causes of a higher death rate. Top down effects of predation are included as well as entrainment into the export pumps as a particular cause of increased deaths. Bottom up or foodweb effects are identified, including food availability and food quality as affected by invasive species. Finally, the importance of prior species abundance is included because a small population in the parent generation limits the potential for increase but also reduces any density dependent effects. The conceptual model says nothing about the relative importance of the various factors, only that they all have the potential to contribute to the POD. Nor has subsequent research helped to narrow the field much as the research has largely confirmed the potential for each of the factors to affect abundance. The striped bass is a comparatively well studied species, both in the San Francisco estuary and in its native range so we should be in the best position to understand its changing abundance. Kimmerer (2004) reviewed the research on striped bass and concluded that multiple factors were affecting abundance , including loss through the export pumps, effects of Delta inflow on survival early in life, changes in the capacity of the estuary to support striped bass (due to non-native invaders like the overbite clam), changes in ocean conditions that induce more adult bass to migrate to the ocean where they suffer higher fishing mortality, possible effects of toxic substances, and density dependent effects. Kimmerer (2004) recommended that a range of alternative models be considered when attempting to understand the causes of any decline (or increase) in species abundance. Declines in the other pelagic species are likely also driven by a variety of factors.

Although much emphasis has been placed on aquatic species in the Delta because of the importance of the Delta as a fresh water source, other species of concern have also received some attention. Suisun marsh, for example, is a critical habitat for several listed species and species of concern, including the California black rail (*Laterallus jamaicensis coturniculus*) and the California clapper rail (*Rallus longirostris obsoletus*). The black rail is a secretive resident of the high marsh and Suisun Marsh may support half of the Estuary's population. Relatively high elevation, moist substrate with freshwater influence, 100% vegetative cover, and abundant insects for food are important factors in black rail population success. Rail abundance is enhanced by the presence of relatively undisturbed, or mature, old marsh with unrestricted tidal influence, protection from predators , and relative freedom from the effects of urbanization, hardened edges, rising sea level, and inadvertent hydrological changes. That is to say, the black rail needs habitat that is in short supply in the San Francisco Estuary.

The clapper rail is a rare (and listed) resident species and Suisun marsh is critical habitat for the species. This species needs large areas of tidal marsh with a range of elevations, dominated by *Spartina* or *Scirpus* vegetation, access to tidal channels and abundant refugia from predators. Connectivity of habitats is important for clapper rails so that fragmention of marshes into small parcels is bad for this species. For both rail species, therefore, extensive tidal marsh habitats with suitable areas for breeding, feeding and protection from predators are the key to maintaining the species populations. Also important is protection of their habitats from disturbance and pollution from urban and industrial areas. As urban growth expands around the estuary, these conditions are becoming increasingly rare.

A number of marsh plants that were historically common are now rare. Most of these losses are probably a result of the extensive loss of marshes and changes to existing marshes through levee construction, water flow and salinity management throughout the Delta/estuary. The Goals Project (2000) identified 57 native species in the high salt marsh zone of San Francisco Bay that are now uncommon, rare, or extirpated. Table 6 lists a few examples of these species that occurred in Suisun marsh to illustrate how their abundance has changed over time.

Table 6. Examples of native marsh plants of San Francisco Bay area that were once common but are now rare or extirpated from the Bay (Extracted from Table 1.3 of the Goals Project, 2000)

Species	Historic Observations	Current Abundance
Armeria maritima (Miller) Willd. ssp. *californica* (Boiss) (Common name: sea pink)	Greene 1894: "Along sandy beaches in wet ground..."	Apparently extirpated in San Francisco Bay Estuary
Aster lentus E. Greene [*A. chilensis* Nees. var. *lentus* Jepson], [*A. chilensis* var. *sonomensis* (E. Greene) Jepson] (Common name: Suisun marsh aster)	Greene 1894: [*A. c.* var. *lentus*] "Plentiful along tidal streams in the western part of the Suisun Marsh..." [*A. c.* var. *sonomensis*]"In open plains of the Sonoma Valley, in low subsaline ground."	Rare; restricted primarily to Suisun Marsh. Known from San Francisco Estuary prior to 1960 (Berkeley, Alviso, Napa). Recent status uncertain in San Pablo Bay area tidal marshes.
Baccharis douglasii DC. (Common name: saltmarsh baccharis)	Jepson 1911: "... abundant in the salt marshes about San Francisco Bay."	Now uncommon to rare in alluvial high marsh and upland ecotone, San Pablo Bay area and Suisun Marsh.
Carex densa Bailey [*C. brogniartii* Kunth. var. *densa* Bailey] (Common name: dense sedge)	Jepson 1911: [*C. b.* var. *densa*] "Salt marshes near San Francisco..."	No current reports known from edges of San Francisco Bay or San Pablo Bay tidal marshes.
Cicuta maculata L. var. *bolanderi* (S. Watson) Mulligan [*Cicuta bolanderi* Watson] (Common name: spotted water hemlock)	Jepson 1911: "Suisun marshes, abundant and conspicuous." Munz 1959: "Salt marshes, Marin to Solano and Contra Costa cos."	Uncommon to rare in Suisun Marsh; not currently reported elsewhere in the Estuary.
Cordylanthus mollis Gray ssp. *mollis* (Common name: soft birds beak)	Brewer et al. 1880. "Salt-marshes of San Francisco Bay, at Mare Island and Vallejo, C. Wright, E.L. Greene." Greene 1894: "Brackish marshes about Vallejo and Suisun."	Rare (federally endangered): local in tidal brackish marsh around Napa River, Carquinez Straits tidal marsh, Suisun Marsh area. Presumed extir-pated in Petaluma River marshes.
Lathyrus jepsonii E. Greene var. *jepsonii* Jepson (Common name: Delta Tule pea)	Greene 1894: "Suisun marshes." Jepson 1911: "Suisun marshes."	Occasional to rare in Suisun Marsh. Also occurs locally in tidal brackish marshes along Napa River.
Rumex occidentalis S. Watson [R. fenestratus E. Greene] (Common name: western dock)	Greene 1894: "Frequent in marshy places." Jepson 1911: "Marshes bordering San Francisco Bay."	Infrequent to rare in North Bay, Suisun Marsh area brackish tidal marshes.

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The loss of a species can be a consequence of one or several changes in its environment. Introduction of a new, invasive predator may be sufficient to cause extinction, particularly on islands or in "island like" ecosystems such as estuaries. In other cases, a number of changes in the habitat template combine to make life impossible. Species life history stages are often timed to take advantage of seasonal events in their environment; splittail (*Pogonichthys macrolepidotus*) breed on floodplains during spring freshet, other fish time reproduction to take advantage of the spring plankton bloom, migratory shore birds time their arrival to match spring growth of vegetation. To match the timing of these events, species often have to use environmental cues to anticipate the future. For example, splittail must begin maturing their gonads well in advance of spring freshet. Many species use daylength to predict future events that are mainly driven by temperature change (e.g., spring freshet, spring vegetation growth). Thus, climate change, that alters temperature but not day length, will cause some species to incorrectly predict the timing of an important future habitat condition (Durant et al. 2007). This breakdown in the synchrony between environment and life history is already occurring in some systems (Winder and Schindler 2004).

Drivers of Change. Multiple factors affect species abundance. For pelagic fishes, export pumping was for many years thought to be the dominant factor driving species declines, but more recent analyses suggest that entrainment in the pumps is only one of a number of factors affecting species abundance. While reducing export pumping may assist these species, without attention to other contributing factors, the species may continue to decline. Most of the factors implicated in decline of pelagic species are human influences (introduced species, changing hydrology in the Delta, turbidity, toxic chemicals, fishing). Loss of suitable wetland and terrestrial habitats is also having adverse effects on a large number of other native species and the factors of change are analogous to those in the aquatic environment (species invasions, reduced living space, isolation from tidal influence, toxic chemicals). Over a longer time period, increasing temperature and sea level rise associated with climate change may overshadow the factors that are presently driving these species down. Species will only persist if the physical habitat template remains within their tolerance limits and if predation and competition are not too severe.

Policy Implications. The dynamics of individual species is affected by many factors. For species in decline in the Delta/estuary human influences appear to predominate in their ongoing decline. For pelagic fish species, emphasis has been placed on water exports as a cause of decline and for wetland species, loss of marsh area. Although these factors are undoubtedly important, it may not be sufficient simply to reduce exports or maintain a certain acreage of marsh. Pelagic fishes are also affected by changing food web dynamics and toxic substances. Marsh species are also affected by disturbance and pollution from adjacent urban or industrial sites. Rather than focusing on single factor solutions, a multifactorial, ecosystem based approach to species conservation is more likely to be successful. Maintaining ecosystem structure and function appropriate for the species of interest is essential.

The Delta/estuary system has been changed dramatically since European colonization and many species are probably at the limit of their ability to cope with the changes. Further change in the physical template is occurring as a result of climate change and continued human development. As a consequence, loss of some species from the ecosystem may be inevitable. However, this should not be an excuse for abandoning policies to conserve native biodiversity. Rather it implies a need for more creative forms of biodiversity conservation, such as establishment of refuge populations where conditions remain suitable.

Section 6. The Impact of Species Invasions

Just as the physical template of the Delta/estuary has been dramatically altered by human activity, so has the community or organisms living there been dramatically altered by deliberate and inadvertent introduction of new species. Human mediated species invasion is a global phenomenon and is considered by some ecologists as one of the greatest threats to ecological integrity and biodiversity conservation (Mack et al. 2000). Species invasions also have economic consequences. Pimentel et al. (2005) estimate that invasive species impose an economic cost of $120 billion annually on the US economy. Mack et al. (2000) offer this blunt assessment:

"The global consequences of failing to address the issue of invasions effectively would be severe, including wholesale loss of agricultural, forestry and fishery resources in some regions and disruption of the ecological processes that supply natural services on which the human enterprise depends. Given their current scale, biotic invasions have also taken their place alongside human-driven atmospheric and oceanic change as major agents of global change, and left unchecked, will influence these other forces in profound but still unpredictable ways." (Mack et al. 2000, p1).

The Bay-Delta ecosystem is highly invaded. The aquatic ecosystem has been described as the most invaded estuary on earth (Cohen and Carleton 1998). Cohen and Carleton (1998) identified 234 exotic species that had established in the estuary and Delta since the arrival of Europeans and another 125 species that might be invaders. About twice as many marine or brackish water species had invaded as freshwater species. Furthermore, the evidence strongly suggested that the rate of invasion was increasing; between 1961 and 1995 a new invader was established every 3 months compared to about 1 a year over the preceding century. Non-native species were not only common, they were also the dominant species in many habitats including soft bottom burrowing and surface living communities, fouling communities, estuarine zooplankton and freshwater fish. In these communities, 40-100% of common organisms and up to 97% of all organisms are exotic. In this highly invaded community, a few high profile native species (Delta smelt, splittail (*Pogonichthys macrolepidotus*), Chinook salmon (*Oncorhynchus tshawytscha*), longfin smelt, and a few others) struggle to survive.

The shallow water, marsh and terrestrial habitats of the Delta have received less public attention but are also heavily invaded. The invaders, Brazilian waterweed (*Egeria densa*) and water hyacinth (*Eichhornia crassipes*) form dense mats in shallow water habitats, providing hiding and nursery habitat primarily for alien fish species. Recent sampling of these shallow water habitats collected 39 fish species of which 24 (62%) were alien. Alien species made up 96% of the numbers captured and most of these were centrarchids (e.g., bluegill sunfish, largemouth bass) (Brown and Michniuk 2007). In saltmarshes, various cord grass species (e.g., *Spartina alterniflora, S. angelica*) are invading while in brackish and freshwater marshes perennial pepperweed (*Lepidium latifolium*) and Giant Reed (*Arundo donax*) are species of concern (Table 7).

Grossinger et al. (1998), reviewed the current distribution and level of concern for marsh invaders and recommended immediate efforts to eradicate *S. angelica*, as it is the most aggressive invasive cordgrass in the world. They also recommended eradication of other invasive cordgrasses (*S. alterniflora, S. densiflora, S. patens*) as well as glasswort (*Salsola soda*), before densities and distribution made eradication unlikely. Species like the giant reed and purple loosestrife (*Lythrum salicaria*), that are widely distributed, will need coordinated and concerted management to keep in check.

Table 7. Introduced plant species of concern in marshes of the San Francisco estuary (copied from Grossinger et al. 1998)

Fresh to Brackish Tidal Marsh	Brackish to Saline Tidal Marsh
Key Species of concern	**Key Species of Concern**
Lepidium latifolium	*Spartina alterniflora*
	Spartina densiflora
Potential Species of Concern	**Potential Species of Concern**
Arundo donax	*Salsola soda*
	Spartina anglica
	Spartina patens
Watch List	**Watch List**
Carpobrotus edulis	*Carpobrotus edulis*
Cortaderia jubata	*Cortaderia jubata*
Cortaderia selloana	*Cortaderia selloana*
Iris Pseudacorus	
Lythrum salicaria	

The factors governing species invasion remain controversial and it is still virtually impossible to predict whether or not a given species will be successful in a new environment. Invaders tend to be generalist species with broad geographic ranges whereas those that are extirpated tend to be local and endemic, so that invasions are most threatening to unique local flora and fauna. Invasions tend also to be most successful in highly disturbed habitats where they can exploit newly created habitat (e.g., road cuts, ploughed fields, recently drained or flooded areas). What ecologists call propagule pressure (the frequency with which the invader is introduced to the new environment) also improves the likelihood that a species will gain a foothold in the new environment, after which it can spread to other locations. The majority of invaders settle into the local community without causing obvious or dramatic change, which may contribute to complacency about invasions. A few, however, have proven capable of causing massive change and their effects can be reason enough to take a much more aggressive approach to limiting invasions and tackling invaders once they are detected.

Drivers of Change. The primary drivers of change in invasive species are the multiplicity of human activities that contribute new invaders to the ecosystem. Historically, many alien species were deliberately introduced for economic (e.g., *Eucalyptus*) or recreational (e.g., striped bass) purposes. Although some deliberate introductions still occur (both official and unofficial), most new species introductions today are accidental or incidental, linked to commercial activities like horticulture, the aquarium trade, bait fishes, and agriculture, or as hitchhikers on personal or commercial transport (in ballast water, on the hulls of ships, in airplane wheel wells, in food or other commodity imports, in the mud on the shoes or in the clothes of international travelers, etc.). A recent study of invasions reaching Antarctic islands that are reserved for research illustrates just how difficult it is to control species invasions. Whinam et al. (2007) made thorough searches of clothing, containers and foodstuffs shipped to research encampments in the Antarctic and found that, even if containers, clothing and food were cleaned prior to shipment, invaders still got through.

Policy Implications. Species invasions have the capacity to alter dramatically local ecosystem structure and function and to change or reduce the nature of environmental services that the ecosystem can provide. In general, the problem needs to be given much higher priority than in the past, and not just directed at species that are known or suspected to have economic impact (e.g., zebra and quagga mussels, *Dreissena polymorpha, D. bugensis*). The United Nations' Global Invasive Species Program (GISP) recommends a multifaceted, multibarrier approach to minimizing invasions and the impact of invasions that includes prevention of introduction, early detection of new invaders, aggressive eradication or containment of invasions, management of established invaders and mitigation of invader impact. In a highly invaded system like the Delta/estuary, management and mitigation must be prominent components of any invasive species plan. Reducing the potential for further invasions is also crucial. Early detection and aggressive eradication are also possible for intertidal, marsh and upland species, especially plants.

Section 7. Ecosystem-based Management of the Delta/estuary

The Delta/estuary is a fully functioning ecosystem that provides a high level of ecosystem services to local and state residents. However, in its present configuration it is no longer able to provide a number of the ecological services that it has provided in the past (e.g., abundant striped bass to sustain an active recreational fishery, healthy populations of a variety of native species such as Delta smelt, California clapper rail, salt marsh harvest mouse, and soft bird's beak). The overall capacity of the Delta/estuary to deliver ecological services has also declined as humans have altered the landscape, replacing high productivity marsh and native upland ecosystem patches with lower productivity urban and agricultural ecosystem patches (although the direct provision of services to humans have gone up). This section will discuss the kinds of things that need to be done from an ecological perspective to restore the capacity of the Delta/estuary to provide the lost ecosystem services. Although some specific examples will be given, these are intended as illustrations of suitable restoration actions. The intent is not to provide a blueprint for restoration but to show how the principles discussed earlier could be applied.

As discussed, the Delta/estuary is a landscape comprised of interacting ecosystem patches, each with its own functional characteristics. The dynamics of each ecosystem patch is determined partly by processes that take place within the patch but also by exchanges between patches. Some ecosystem patches are dominated by exchange processes (e.g., urban ecosystem, Delta open water ecosystem) whereas others are dominated by internal dynamics (e.g. upland forest ecosystem, vernal pool ecosystem). At a larger scale, the Delta ecosystem is one ecosystem patch within the larger mosaic of central valley, western Sierras, coast ranges and coastal ocean and, on a larger scale still, the Delta/estuary is connected to the arctic, the tropics, and the open North Pacific Ocean through the migrations of birds and salmon. As a patch in this larger mosaic, the Delta exchanges materials and organisms with other ecosystems. From upstream patches it receives fresh water, sediment, nutrients, contaminants, plankton and juvenile fish. From the ocean it receives water, salt, plankton and adult fish. From the atmosphere it receives water, nutrients and contaminants. Some of these deliveries are processed or stored within the Delta/estuary; others are passed through to upstream or oceanic patches. Ecosystem patches within the Delta/estuary also exchange materials and organisms. This brief summary of points made earlier emphasizes that the Delta/estuary is a very dynamic system. The dynamics are not only spatial but also temporal on scales ranging from minutes (bacterial reproduction) to hours (tides) to seasons (hydrology, zooplankton and Delta smelt life cycles) to years (Chinook and longfin smelt life cycle) to decades (El Nino, Pacific Decadal Oscillation, Sturgeon life cycle) to centuries (long term climate cycles, historic changes in sea level). Managing this dynamics to encourage production of desired ecosystem services is the key to a sustainable Delta.

The list of ecosystem services provided to society by the Delta/estuary is impressive: drinking water; irrigation water; urban land; agricultural land; recreational land and water; commercial and recreational fisheries; flood and storm surge attenuation; transportation and utility corridors; waste absorption and detoxification; native species biodiversity; waterfowl hunting; opportunities for research and education; magnificent vistas. A fundamental premise of ecology is that ecosystems have a finite capacity to provide ecosystem services. The listing of multiple native species as threatened or endangered is s strong signal that the capacity of the Delta/estuary ecosystem to provide certain services has been compromised or exceeded. To restore the viability of the listed species, it is likely that present and future delivery of some other services will have to be reduced. In particular, it is likely that more water and more land will have to be allocated to sustain native species. Unfortunately, it is not possible to say with certainty how much water and how much land and how it should be located within the Delta/estuary. Ecological theory and practice does, however, provide important insights into ways to design a sustainable ecosystem mosaic and ways to address the high uncertainty in ecological prediction. These insights are encompassed within the developing framework of ecosystem-based management.

Although its application remains controversial, the concept of ecosystem-based management has a long history and can be traced back at least to Aldo Leopold's (1949) land ethic. Various authors have specified principles that underlie the concept (ESA 1995, Grumbine 1994, Healey 1998). The more numerous principles put forward by these authors can be further synthesized into three broad principles that capture the essence of ecosystem-based management and are consistent with the concept of sustainable development:

1. The human economy and society are integral to and completely dependent on the natural ecological processes of assimilation, regeneration and primary production that sustain the global biosphere. This is the principle of inclusiveness;
2. Human actions that are directed at one component of the system have consequences, both positive and negative, for many other system components and this cannot be ignored in management decision-making. This is the principle of interconnectedness;
3. The capacity of ecosystems, both local and global, to sustain the human economy and society is limited and vulnerable to impacts from human use and technology. A healthy human society can only exist within a healthy, productive ecosystem. This is the principle of stewardship.

There is a fundamental difference between ecosystem-based management and traditional resource management (Table 8). The principles of ecosystem-based management highlight the critical interdependency among the human economy, human society and ecological processes of production and assimilation that were described earlier. Under ecosystem-based management, human use of resources is ultimately constrained by ecological processes of assimilation, reorganization and renewal. Although the importance of ecological limits has long been recognized by ecological science and is incorporated into production models for renewable resources, it has not been a factor in neoclassical economics (Daly 1996). This disconnection between ecological and economic thinking has contributed to the breakdown in ecosystem services from the Delta/estuary and other human dominated resource systems. Ecosystem-based management offers a way to reconnect ecological and economic concepts in resource management.

Table 8. A comparison of underlying concepts and principles in traditional resource management and ecosystem-based management

Traditional Resource Management	**Ecosystem Based Management**
The human system is separate and independent from the ecosystem	Human systems are an integral and interdependent part of the ecosystem
Individual natural resources can be managed as though they were independent of each other	Management of individual resources must take account of the interconnections in the ecosystem
For all practical purposes, planetary resources have unlimited capacity to sustain human life and wellbeing	The capacity of planetary resources to sustain human health and well being is limited and requires active stewardship

Reestablishing the capacity of the Delta/estuary to provide the full range of desired ecosystem services on a sustained basis will require a reconsideration of the current status and trends in land and water use as well as a sensitivity to how key drivers of change will affect future status and trends. Three critical elements of restoring ecosystem structure and function will be considered here: size, arrangement and interaction of ecosystem patches within the Delta; temporal and spatial variation in habitat within patches; and implications of climate change for ecosystem sustainability.

Size, Arrangement and Interaction of Ecosystem Patches. Agricultural land is currently the biggest land use in the Delta at > 550,000 acres but agricultural lands are being replaced by urban lands (Table 3). Urban lands represented about 74,000 acres in 2004 but were growing rapidly (Table 3). Suisun Marsh is the largest remaining wetland ecosystem patch in the Delta and, at 85,000 acres, represents about 10% of total Delta area. The majority of Suisun Marsh is not natural marsh but seasonal wetland managed primarily for duck production. Since the Delta was historically a giant marsh, Suisun Marsh and other tiny marshes constitute remnants of the former system. Given the reduced state of many native wetland species that evolved and flourished in a much larger wetland ecosystem, it could be argued that the remaining tidal and seasonal marsh is insufficient to sustain them. Two other unique, but historically much smaller, ecosystem patches that have experienced significant reduction in size with attendant danger to their unique flora and fauna are Antioch Dunes and vernal pools. A remnant patch of the dune ecosystem is protected as Antioch Dunes National Wildlife Refuge and harbors several rare and endangered species including Lange's Metalmark butterfly and Antioch dunes evening primrose. Vernal pools are highly dispersed within the Delta and are threatened by various kinds of development. To restore failing ecosystem services, larger and more numerous patches of critical ecosystem types in the Delta will be needed.

In planning for increased amounts of critical ecosystem types, patch size and arrangement are important considerations. Foreman (1995) argues for an "aggregates plus outliers" design rule. That is to say, restoration should include a few large patches with interspersed smaller patches to provide connectivity or "stepping stones" for species movement. For wetland expansion, Cache slough and lower Yolo bypass as well as Mokulmne and Cosumnes flood plains appear to offer the most obvious opportunities for creating relatively large patches. Cache slough is particularly attractive as it connects easily with Suisun Marsh and there is sufficient elevation range to absorb modest sea level rise and still retain freshwater marsh. Smaller, outlying patches could also be developed, such as the proposed flood bypass on the San Joaquin River or fringing marshes around Delta islands.

Connectivity to permit effective exchange among ecosystem patches is as important as creating the right kinds of ecosystem patches. The Delta as a whole is connected to upstream watersheds, so that what happens upstream has implications for the Delta. The wetland patches discussed above also need strong connection to the rest of the Delta/estuary but also to adjacent, semi-natural, upland habitats if they are to function properly. At present, the trend in urban expansion is to ring the Delta with concrete and steel. Significant vegetated corridors need to be protected, ideally including stream and river valleys, to connect the large wetland areas with productive upland ecosystems and to protect them from the damaging toxic runoff from urban storm drains.

A serious complication in creating seasonally flooded wetlands is that mercury sequestered in soils can be mobilized and concentrated through the food chain. Benefits of expanded wetland area will have to be balanced with costs of increased toxicity. However, a lot of mercury is still being delivered to the estuary from abandoned mine sites upstream in Cache Creek and, as part of the restoration, these sites should be stabilized. Other contaminants from human activity in the Delta and in adjacent ecosystems also impact the capacity of the Delta to provide services. An overall reduction in the discharge of toxic substances into the Delta would enhance its capacity to provide other kinds of ecosystem services.

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Current water allocation is as likely as land use to have compromised the capacity of the Delta/estuary to sustain a variety of native species. Freshwater inflows to a delta/estuary perform a wide variety of functions, delivering nutrients and sediment, redistributing sediment, transporting species and organic material, driving circulation processes. There are numerous observations that estuarine fish abundance or productivity is positively related to freshwater flows (Lloret et al. 2001, Loneragan and Bunn 1999), including the Sacramento-San Joaquin delta (Sommer et al. 1997, Kimmerer 2004). However, the relationship is not always positive (Costa et al. 2007). Furthermore, relationships previously established for the Delta/estuary appear to have changed in recent years. It is difficult to say, therefore, how much environmental water is needed in the Delta.

Temporal And Spatial Variation In Habitat Within Patches. Delta/estuaries are naturally variable both temporally and spatially and estuarine species have the capacity to tolerate or even exploit that variability. Tidal and seasonal flooding of low lying land in a Delta estuary, for example, allows mobile aquatic species to invade and exploit marginal habitats when water levels are high but makes them available to mobile terrestrial species when the waters recede. Sedentary species in these habitats must be able to withstand intermittent flooding and drying and often variable salinity. Relatively few species are able to tolerate such conditions but those that are can be spectacularly abundant (consider the Tule marshes of pre-European times). Much of human development in the Delta has been directed at reducing its inherent variability, stabilizing land and water and salinity in ways that maximize direct human benefit. By reducing habitat variability, human development of the estuary may have placed native species at a disadvantage. Lund et al (2007) argued that the key to restoring native biodiversity was to reestablish the lost variability:

"To address the problems of the Delta's native species, a fundamental change in policy is needed. A Delta that is heterogeneous and variable across space and time is more likely to support native species than is a homogeneously fresh or brackish Delta." (Lund et al. 2007, p viii)

Habitat heterogeneity has been associated with increased species diversity, so that introducing more spatial and temporal variability into the Delta may, indeed, improve conditions for native species (Tews et al. 2004). Unresolved questions, however, are how much variability and of what type? Tews et al. (2004) showed that habitat heterogeneity had to occur at scales that were important to the organisms of interest, otherwise a heterogeneous habitat might simply appear fragmented to the organism and, therefore, of reduced value. To be effective, therefore, variability might have to be introduced at more than one scale. In addition, Tews et al. (2004) identified what they called "keystone structures", or particular elements of habitat that determined a species response to heterogeneity. Participants at a workshop on the variable delta hosted by the CALFED Science Program generally agreed with the proposition that increased variability would benefit native species but were not able to say how much variability would be beneficial[1]. Various kinds of variability were discussed, including increasing salt intrusion into the Delta as a means to control invasive species and blocking a number of connecting channels around Delta islands to increase variation in water residence time and local salinity patterns. All of these measures require further research and evaluation before they can be applied. In addition, some forms of variation (salinity for example) would create major problems for water users in the Delta. Gates and other barriers might provide a means to separate variable from more homogeneous areas of the Delta.

The dominant place of non-native species in the Delta/estuary ecosystem greatly increases the complexity and uncertainty of any measures to improve native species abundance. As the natural habitat for many of these species is deltas and estuaries, restoring a more natural variability may also make conditions more favorable for non-native species. In nearby rivers and streams, however, natural flow variability appeared to favor native over non-native species (Marchetti and Moyle 2001, Brown and Ford 2002). A similar result is possible in the estuary but long term success will require that new invasions be kept to a minimum.

Introducing substantial variability on various time and space scales into the physical template of the Delta/estuary would constitute a major change of policy direction. Properly designed, however, such variability is capable of enhancing the capacity of the Delta/estuary to sustain ecological services that are degraded and continuing to decline. Furthermore, as Lund et al. (2007) point out, big change is on the way driven by global climate change. The challenge is to manage coming change in such a way that overall ecosystem service is kept high while shifting more resources to recovery of declining species.

Implications Of Climate Change For Ecosystem Sustainability. Climate change has the potential to impose a very different physical template on the Delta/estuary. Changes in hydrology and sea level will threaten infrastructure in and around the Delta (Mount and Twiss 2005). These factors plus rising temperature threaten species survival. Even if current efforts to reduce greenhouse gas emissions are ultimately successful, we still face a prolonged period of climate warming and sea level rise with many uncertainties in environmental response. Furthermore, as climate change acts differently on different aspects of the environment, ecological processes that were synchronized will be decoupled with uncertain consequences for many species. Management policies need to be robust to the many and uncertain implications of

[1] http://science.calwater.ca.gov/pdf/workshops/SP_workshop_variable_final_report_072707.pdf

climate change. The sustainable system must be flexible and have extra capacity built in to deal with unexpected change.

Resilience, Reversibility And Precaution In Ecosystem-Based Management. Ecosystem-based management involves a more holistic approach to resource use. Sustainable ecosystem designs integrate across human and environmental needs and recognize that the indirect (non-market) contribution of ecosystems to human well being (through waste absorption and recycling, for example) are as significant as the direct contributions (through drinking water, for example). Costanza et al. (1997) estimated that the value of non-market ecosystem services provided by various coastal ecosystem types ranged from $1610/ha/y for continental shelf waters to $22,332/ha/y for estuaries and from $969/ha/y for forests to $19,580/ha/y for wetlands and floodplains. Maintaining productive upland, wetland and open water ecosystem patches, therefore, is not simply a matter of aesthetics but of economics as these ecosystems provide economically valuable services that are not recorded in GNP.

Maintaining an ecosystem mosaic with a high capacity to deliver non-market services also makes the ecosystem more resilient (able to absorb stressors but retain its basic structure and function, Folk et al. 2002). Robust ecosystem design and management policy is design and policy that sustains or enhances resilience in the system. As ecosystem-based management incorporates the human economy and society, benefits of resilience extend to the human economy and society as well. Resilient natural ecosystems help to sustain resilient human systems.

Resilient systems incorporate as much reversibility as possible into their infrastructure. Ecosystems, economies and societies that are diversified (i.e., variable in their structure and dynamics) and can adjust modes of production, delivery and consumption in response to a changing environment are more resilient to stressors. The future has always been uncertain but given the rapid pace of global change, socially, economically and environmentally, sustainable systems also need to be capable of anticipating stress and responding appropriately. The precautionary principle argues that corrective action should be taken in the apprehension of an adverse outcome from human activity without waiting for "scientific certainty". The precautionary principle has the effect of shifting burden of proof for the safety of human actions from society as a whole to individual users of resources and is consistent with a beneficiary pays policy. Although the application of this principle is controversial, it has been enshrined in numerous international treaties and is the basis of environmental law in the European Union (Foster et al. 2000).

Adaptive Management As A Tool For Ecosystem Based Management. Uncertainty is an inherent feature of ecosystems. Much as we rail against it, uncertainty is what makes social and economic gambles exciting. In environmental management, uncertainty derives from both the inherent variability of natural self-organizing systems and from our limited knowledge of how they function. Lack of understanding of system dynamics can become an obstacle to progress in management (Walters 1996). However, continuing with business as usual (BAU) may not be the best policy. In situations where valued ecosystem services are declining, BAU is clearly an inappropriate policy. Adaptive management provides a set of tools for addressing uncertainty in understanding and moving forward with innovative policies while at the same time improving understanding of system dynamics. Adaptive management provides the tools necessary to integrate ecological science into resource management policy so that decisions will be both economically and ecologically sustainable.

The various steps in adaptive management are all familiar to most policy makers and resource managers (Figure 18). The process differs from standard resource management mainly in its transparent acknowledgement of uncertainty and incomplete understanding, in treating policy implementation as an opportunity to learn about the system, and in its emphasis on orderly feeding back of information into the decision process. The steps in adaptive management include: assembly and analysis of relevant data; specification of management goals; development of policy alternatives; exploration of alternatives by simulation modeling; selection and implementation of policies; and monitoring and evaluation of policy consequences (Figure 18). Depending on the level of understanding revealed by the analysis of existing information, policies may be implemented first as a program of targeted research to increase understanding, as pilot projects or as large scale implementation. To the extent possible, implementation should be designed both to address the problem and to provide information about how the system responds to human intervention. The most effective form of policy implementation to increase understanding is termed active adaptive management. In this form of adaptive management, policy implementation is deliberately designed to stress the system in ways that will provide information. Active adaptive management is only practical in situations where the benefits of improved understanding significantly outweigh the costs. Otherwise, policies are implemented based on the most probable model of system behavior and monitored to ensure that the system is responding as expected (passive adaptive management). Walters (1986) provides details of the analytic tools and procedures for determining whether active or passive adaptive management should be implemented.

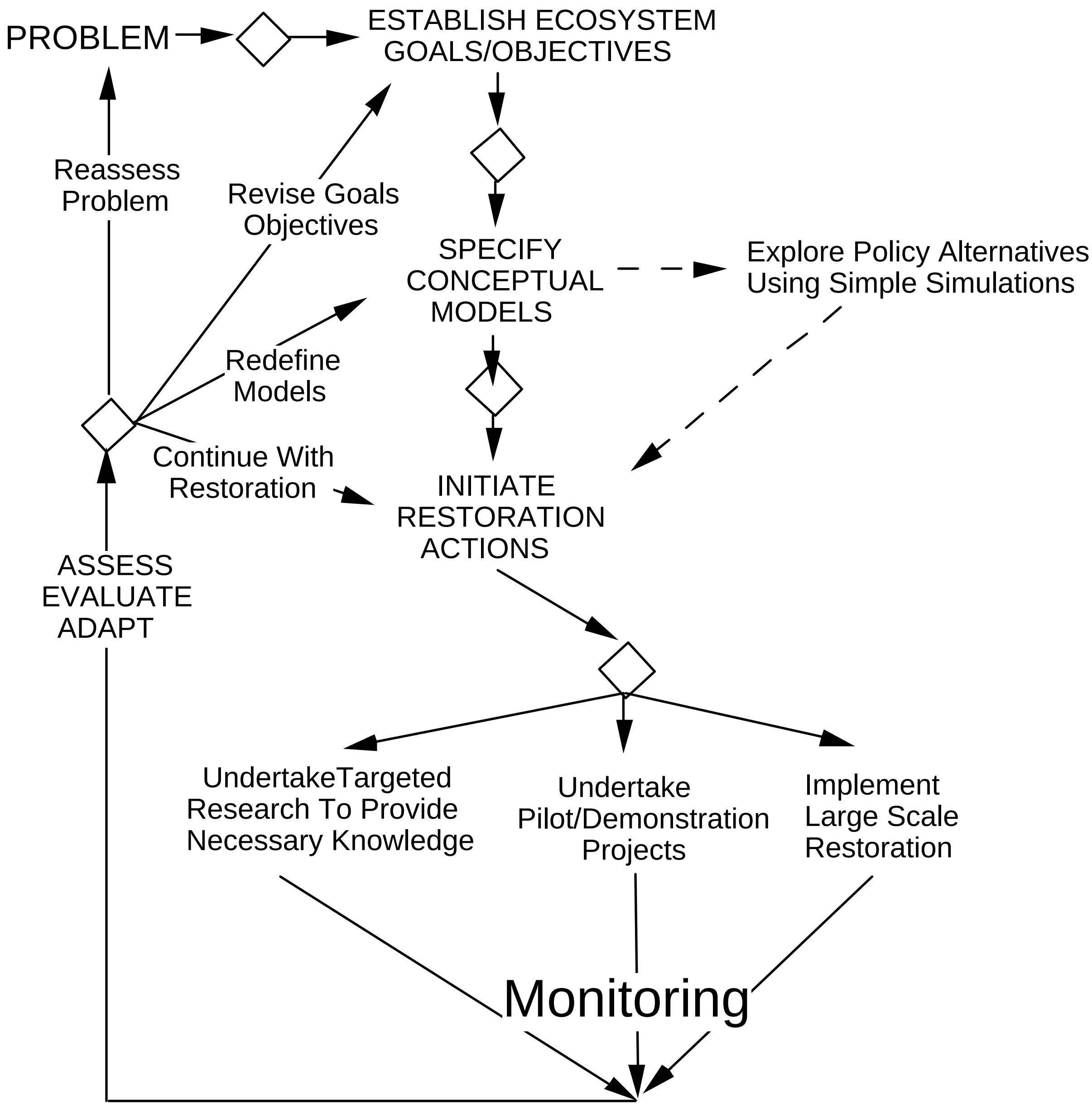

Figure 18. The flow chart of adaptive management in the context of ecological restoration. Diamonds represent major decision nodes in the process. The process can be adapted to any major management action with uncertain consequences.

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Monitoring, analysis and policy assessment on a regular basis are crucial aspects of adaptive management. If learning is to occur, monitoring programs need to be designed to assess the model of system behavior on which the management policy was based. Unfortunately, monitoring and assessment are frequently cut in the face of limited resources and unlimited problems that need attention. Failure to undertake the monitoring and assessment components of adaptive management renders the technique effectively useless. In designing sustainable, ecosystem based management of the Delta/estuary, therefore, it is important to hard wire monitoring and assessment into the governance system.

Drivers of Change. The primary factors driving regulatory agencies toward ecosystem-based management are legislation and international agreements that commit nations and societies to take an holistic approach to species and biodiversity conservation. At its inception, the CALFED ecosystem restoration program recognized that a species by species approach to conservation in the Delta was not working and that a new methodology was needed. The program was designed around the philosophy and concepts of ecosystem-based management and adaptive management. Its operational approach was restoration of ecosystem function. Although the conceptual design was appropriate, implementation of adaptive management was not fully realized.

Policy Implications. Management of human activity and uses of the landscape and water is integral to successful management and conservation of desired species, ecosystem types and biodiversity in the Delta/estuary. Management plans and decisions need to be informed by a landscape perspective that recognizes the interrelationship among patterns of land and water use, patch size, location and connectivity, and species success. The landscape perspective needs to be developed at several physical and temporal scales (e.g., patches within the delta, delta within the valley and temporal scales of patch dynamics and evolution). Appropriate time and space scales of variability are needed to provide for the needs of endangered native species. Achieving a sustainable balance of ecosystem services and biodiversity conservation in the Delta is likely to require allocating considerably more land and water to support natural and semi-natural systems than at present. However, restoring the capacity of the system to provide non-market services will increase resilience of the socioeconomic system as well as the environmental system. Sustainable governance for the Bay-Delta should be based on the concept of ecosystem-based management (EBM), a concept that integrates society, economy and the environment and uses adaptive management as a tool for addressing uncertainty. EBM was adopted as the guiding philosophy of CALFED but implementation has only been partial. A more aggressive and committed implementation process is needed in the future.

Section 8. Conclusions

The Delta/estuary is a vibrant productive ecosystem. However, declining abundance of a range of native species and listing of more than 30 as threatened or endangered shows that the present configuration of the ecosystem is not able to deliver important ecological services. Many factors probably contribute to the declines in native species but particularly important are human caused changes to the physical habitat template of the estuary (hydrography, landforms, chemistry) and competition from non-native invasive species. Redesigning land use and geometry of the Delta/estuary and reallocating water to increase habitat space, habitat connectivity, and habitat variability are key to restoring the capacity of the Delta/estuary system to support threatened and endangered species. In effect, more resources (land and water) need to be allocated to support non-market ecosystem services. Although this will mean modest reduction in some other services, the ecosystem will be more resilient, which will have positive benefits for the resilience of the socio-economic system as well. Exactly how much land and water need to be allocated to sustain non-market services is not known precisely. However, ecosystem principles provide guidance in making preliminary allocations. In terms of land allocation, the aggregate plus outliers principle suggests that most new habitat should be in large patches with outlying patches to provide refugia and connectivity among large patches. Positive relationships between fish species and Delta inflows also argues for increased inflows but the amounts and patterns of inflow to maximize ecosystem benefits need further research and discussion. Reconfiguring the Delta landscape to recover valued ecosystem functions in the context of current conditions is challenging enough. However, conditions are changing rapidly due to global warming, population growth and other factors. Ecosystem design and policy need to be robust to these anticipated changes. Ecosystem-based management provides a set of principles and tools (most notably, adaptive management) to address these challenges and develop an ecosystem mosaic that is resilient and able to deliver a broad range of ecological services into the future.

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