Changing ecosystems: a brief ecological history of the Delta [1]

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February 2010

The San Francisco Estuary is a young estuary, about 6-10,000 years old in its present location. It became established during periods of high climatic variability (reflected in extreme floods and long droughts) compared to the relatively stable past 150 years. The Delta was formed as a huge freshwater marsh through the interaction of river inflow and the slow rise of sea level with the growth and decay of tules and other plants. This interaction resulted in the deposition of large amounts of organic matter, creating layers of peat that kept pace with sea level rise. These peat layers formed the soils of most of the present Delta 'islands', which were actually complex patches of floodable marsh. The channels among the islands were historically shifting, winding distributaries of the entering rivers that moved inflowing water through the Delta, providing access to upstream areas for large runs of migratory fish. The movement and quality of water in these channels was strongly affected by tidal action. These attributes also created a complex of diverse and shifting habitats that supported a wide variety of functions for an ecological system in which there was no clear separation between aquatic and terrestrial components.

Imposed on this complex of physical structures was a highly variable hydrologic flow regime, both seasonally and across years. The basic seasonal pattern had high flows in winter and spring, with variability resulting from the timing of rain storms and of snow melt from the surrounding mountains. Inter-annual variability was generated by natural variation in precipitation, including long periods of drought and occasional years with huge floods. The natural system of wetlands, riparian terraces, and floodplains in the Central Valley helped mute the effects of variation in stream flow, while the Estuary's immense marshlands muted tidal energy, keeping much of the Delta a freshwater system through which the tides gently pulsed . The pre-modern estuary would have had a strong upstream-downstream gradient in salinity and other water quality variables, from the freshwater Delta interior to the saltwater Bay. However, long periods of drought (decades, unlike any experienced in modern times) would presumably have favored movement of salt water farther into the eastern Delta, while wet periods would have favored keeping more of the estuary fresh or brackish.

The Delta ecosystem is noted in historical records for having a high abundance of organisms, many of them highly migratory to take advantage of seasonal abundances of food and habitat. Migratory fishes included at least 12 kinds of salmon, smelt, sturgeon, and lamprey, while resident fishes included Sacramento perch, thicktail chub, and other endemic fishes. The high (ca. 80%) endemism of the fishes reflected both the isolation of the Central Valley from other watersheds and unique adaptations to local conditions. The abundance of these fishes resulted in large 19th century and Native American fisheries. Likewise, large populations of both migratory and resident waterfowl took advantage of the extensive wetlands, especially in winter, including 26 species of ducks and geese. Arguably, the historical Delta was the centerpiece of the Pacific flyway, contributing heavily to the estimated 10 million or more

[1] For ease of reading no citations are provided in the text of this essay. Most of the information can be found in more detail in the suggested readings at the end. Scientific names of fishes mentioned can be found in these papers as well, or in Moyle (2002).

waterfowl that annually overwintered in the Central Valley. It was also rich habitat for large mammals such as tule elk, grizzly bears, and beaver.

Such abundance implies high productivity, which was likely generated by nutrients from the extensive riparian corridors, marshes and seasonal floodplains. High connectivity among the habitats allowed the dispersion of these nutrients throughout the system and into the estuarine food webs, supporting the dense fish populations. These elements formed the key conditions for the historical estuary to function as a center of biotic abundance and diversity in central California. The arrival of Euro-Americans in Central California changed all that. In this essay, we discuss the series of major ecological changes that led to the present Delta and to the likely next ecosystem shift. We then provide some principles upon which to manage flows to try to direct change, rather than to just react to it.

Figure 1. An idea of what much of the Delta looked like at one time comes from the recently reflooded Liberty Island, which has rapidly become a wetland with shallow tidal sloughs winding through patches of tules and other emergent plants. Photo by P. Moyle, September, 2008.

Major change in the Delta

The Sacramento-San Joaquin Delta has undergone significant physical and biological modification over the past 150 years. These modifications involve the reclamation of 700,000 acres of tidal marsh and adjoining floodplains, along with significant changes in riverine and tidal hydrology, as well as water quality. The aquatic components of the ecosystem (the focus of this essay) became increasingly divorced from the terrestrial components. These changes, along with invasions of alien species, caused the decline and extinction of the native biota of the Delta, most notably fishes, and maintain an environment that is increasingly hostile to native species of all sorts, from birds to beetles. In this section, we briefly describe these changes and their consequences, in order to provide some idea of what kinds of features need to be restored or replaced to bring native aquatic organisms back to abundance.

Habitats for Delta native fishes have changed immensely from pre-European settlement conditions because of extreme landscape changes (Figure 1). The estuary originally contained vast areas of seasonal and permanent wetlands. The elimination of these wetlands reflected massive human-caused changes to the landscape resulting from alterations of hydrologic patterns by dams and diversions, upstream land use changes, tidal marsh reclamation, and channelization of rivers and tidal channels. As a result, the San

Francisco Estuary is one of the most highly modified and controlled estuaries in the world. The estuarine ecosystem has lost much of its former variability and complexity as indicated by major declines of many of its native fishes. Contributing to declines have been continual invasions of alien species and large changes in water quality from pollution and upstream diversions of fresh water.

Figure 2. View of Delta today, where tidal wetlands been replaced by farmland and the rivers have confined channels. Note the sharp separation of aquatic and terrestrial habitats. Photo by P. Moyle, May 2009.

The changes to the Delta can be described as a series of ecosystem shifts, in which the ecosystem undergoes rapid change in its characteristics and biotic players, to settle for a short period into a new state in which change is slowed, although the new state often perceived as stable by short-sighted humans. These shifts are not reversible, because of fundamental changes in processes and species. Although the Delta has been undergoing more or less continuous rapid change since the mid-19th century, we envision four basic steps or plateaus in the process of ecosystem shifts leading to today's Delta. These four steps or states are: (a.) Gold Rush Delta, (b) Development and Diversion Delta, (c) Dam Delta, and (d) Interim Delta.

Gold Rush Delta. The gold rush fueled the invasion of California by millions of people, who directly and indirectly transformed the Delta ecosystem. Hydraulic mining washed huge amounts of sediment into the rivers, shallowing channels and bays, increasing flooding and tidal energy (movement, extent, and force of the tides), and temporarily burying wetlands. Mining also introduced many tons of toxic mercury into the system. At the same time the conversion of wild land to farms began, resulting in diking and dredging of rivers and Delta channels to reduce flooding. Large trees were removed from riparian areas and snags were removed from rivers to improve navigation and reduce flood hazards. To feed the growing numbers of humans, unrestricted fisheries for salmon and other native fishes developed, which markedly reduced fish populations. These populations had already been decimated by silt-laden water, sedimentation of habitat, and destruction of spawning and rearing habitats in gold-containing rivers. The Delta was transformed by this activity to an actively aggrading physical system and a rapidly degrading biological system, although in many areas wetlands with natural drainages still remained. Levees (with frequent failures) were built, tules removed by burning and plowing, and crops were grown on islands, often fertilized by burning peat soils to release nutrients. This started the rapid subsidence of some islands. Native salmon and other fishes declined to the point where fisheries could no longer be supported but some alien species boomed, especially those such as striped bass and American shad that were adapted to rivers with high sediment loads.

Diversion and Development Delta. In the first half of the 20th century, Delta islands became increasingly fixed in place as levees were raised and strengthened and as farming intensified. Following the end of hydraulic mining, inflows decreased during summer as the result of upstream agricultural diversions, while winter flows were probably much spikier because floodplains, with their ability to temporarily store water, had been disconnected from rivers by levees. Once "Bay-ward" estuarine marshes were diked and drained, and upstream water diversions in summer became large, tidal energy moved salt water further upstream during dry periods, through relatively deep narrow channels. As development modified the inflowing rivers and their floodplains, and as more alien species invaded, the native fauna and flora steadily declined. Some native fishes that once supported fisheries disappeared altogether (thicktail chub, Sacramento perch). At the same time, the presence of well-defined salinity gradients and high seasonal outflows allowed the system to continue to function as an estuary, if in a diminished fashion. While sewage and industrial wastes were increasingly dumped into the system due to growing human populations, dilution seems to have been sufficient to keep water quality effects modest. Some estuarine species such as delta smelt, striped bass, and splittail continued to thrive and salmon populations began to recover from the destructive effects of unlimited fisheries and hydraulic mining.

The Dam Delta. The big rim dams, developed mostly since the 1940s, dramatically changed river flow patterns. They were built to stabilize the downstream environments by providing increased water for summer irrigation, protection from floods, and decreased salinity intrusion into the central Delta. They decreased flows in winter and changed the timing of high flow periods (except for extreme flood flows). While the San Joaquin River largely lost its natural summer flows, the Sacramento River had increased summer flows. Winter water was stored and released, increasing freshwater inflow to the Delta, shifting it back more toward a freshwater system but with less diversity of physical habitats and altered hydrology and water quality. The initial shifts started in the 1950s when the federal pumping plants in the south Delta started operating, exporting water into the Delta-Mendota Canal. One benefit of the increased summer inflows was increased dilution of urban and agricultural waste water in summer, when fish kills were most likely, although new pesticides were also making the waste water more toxic. Until the nearby state pumps started operating in the late 1960s, further increasing exports, the Delta retained many estuarine characteristics, allowing estuarine-dependent species to persist in fairly large numbers (*e.g.,* delta smelt, longfin smelt). Striped bass showed a gradual decline in response to changing conditions but the sport fishery continued unabated. Fall Chinook salmon numbers in the Sacramento River were sustained by hatcheries, maintaining both sport and ocean commercial fisheries. However, the hatcheries replaced as much as supplemented wild salmon populations and, with the combined effects of tributary dams blocking spawning habitat, numbers of late fall, winter, and spring Chinook salmon plummeted, largely unnoticed. As farming and urbanization intensified in the Delta, wintering waterfowl populations began shifting from the Delta and Suisun Marsh to refuges and flooded rice paddies in the Sacramento and San Joaquin valleys. Despite these cumulative declines, the bucolic Delta of this period seems to be the model for what many people would like the Delta to be in the future.

The Interim Delta. The Delta of today is a highly altered system on the brink of further dramatic change. Starting in about the 1970s, the aquatic ecosystem of the Delta shifted towards a new biological regime after a half-century of being managed to limit its variability. The new Delta ecosystem supports an assemblage of primarily alien species that thrive in fairly clear, warm, fresh water with strong tidal fluxes. Essentially, aquatic habitat in the Delta has become simplified into a system of rip-rapped canals, cross-hatched by navigation cuts, that convey fresh water for export from and through the Delta during summer and to reduce freshwater outflows at other times of the year. Suisun Bay and Marsh have become largely brackish water systems, with San Francisco Bay a largely marine system. Such prolonged stabilization, combined with a relatively rapid influx of alien species, has caused an ecosystem shift that is also reflected in the overall low and declining productivity of the upper San Francisco Estuary compared with other estuaries worldwide, and the apparent loss of resiliency by pelagic fish populations that previously rebounded during periods of favorable environmental conditions. The demand for low-salinity water and altered hydrology in support of pumping operations has reduced variability in salinity during the critical summer months, favoring the expansion of ecosystem-altering species such as overbite clam in Suisun Bay and Brazilian waterweed in the Delta. Similarly, alien freshwater fish species typically associated with aquatic vegetation have increased dramatically and currently dominate Delta food webs. These river and lake species include Mississippi silverside, largemouth bass, and multiple sunfish species. Native species have collapsed, so that there are now seven fish species listed under the ESA that depend on the Delta, with additional listings likely.

Numerous other factors bedevil the Delta's native fishes, such as new contaminants (*e.g.,* pyrethroids, artificial hormones), reduced invertebrate food supply, altered food webs, disease, harmful algal blooms, and lack of tidal marsh and floodplain habitat. Nevertheless, the factor that fish experience in common is the known change in Delta hydraulics caused by pumping water for export from the South Delta, with all its secondary effects. The current ecosystem created by the pumping, however, is temporary. Another major change is on its way.

The Next Delta. The Delta ecosystem is likely to dramatically shift again *within* 50 years due to large-scale levee collapse in the Delta and Suisun Marsh. Major levee failures are inevitable due to continued subsidence, sea level rise, increasing frequency of large floods, and high probability of earthquakes. These significant changes will create large areas of open water and increased salinity intrusion, as well as new tidal and subtidal marshes. Other likely changes include reduced freshwater inflow during prolonged droughts, altered hydraulics from reduced export pumping, and additional alien invaders (*e.g.,* zebra and quagga mussels). The extent and effects of all these changes are unknown but much will depend on how the estuary is managed in response to change or even before change takes place. Overall, these major changes in the estuary's landscape are likely to promote a more variable, heterogeneous estuary, especially in the Delta and Suisun Marsh. This changed environment is likely to be better for desirable estuarine species; at least it is unlikely to be worse. Even if major changes were somehow avoided, examination of sea level rise for "unimpaired" flows (Figure 3) indicates that salinity will intrude an additional 5 km for each foot of sea level rise and increase variability in Delta water quality. At this point we have a choice: declare the situation to be hopeless and keep using reactive, fragmented policies OR use the best available knowledge to predict likely changes and work with these changes to create a more fish-friendly and human-friendly Delta.

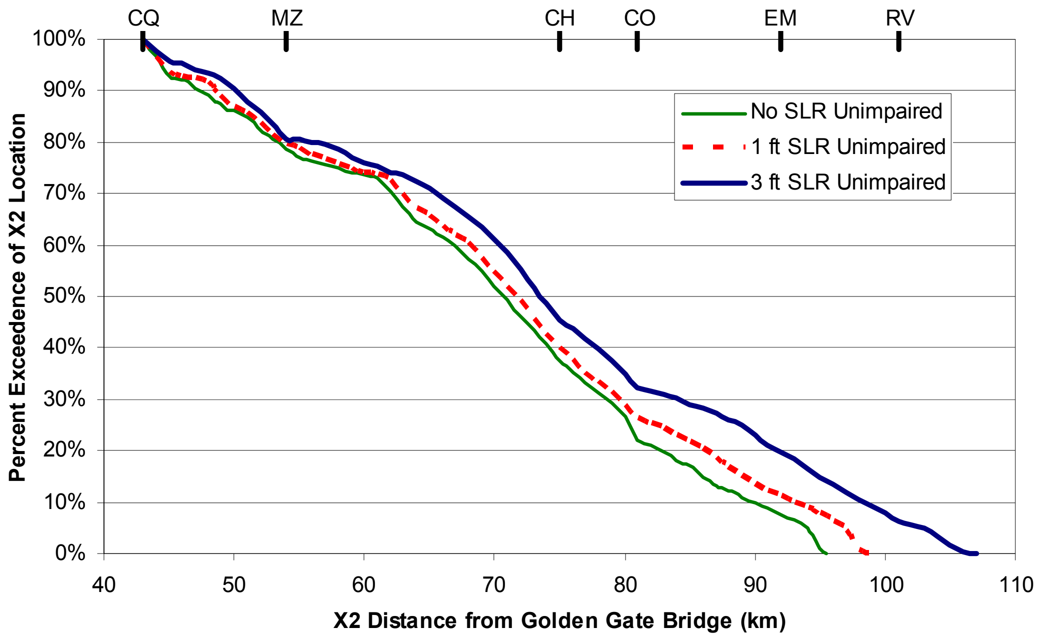

Figure 3 Effects of sea level rise on salinity intrusion for unimpaired flows. CQ – Carquinez Strait, MZ – Martinez Bridge, CH – Chipps Island, CO – Collinsville, EM – Emmaton, RV – Rio Vista

Flows and the Changing Delta

We have proposed five key points that need to be taken into consideration when developing a flow regime for the Delta. Here we comment briefly on what Delta history tells us about these points.

1. **Environmental flows are more than just volumes of inflows and outflows.** The frequency, timing, duration, and rate of change of flows, as well as the occurrence of overbank flows also are biologically important. There is no one correct flow number. Seasonal, interannual, and spatial variability, to which our native species are adapted, are as important as quantity. Biological responses to flows rest on combinations of quantity, timing, duration, frequency and how these inputs vary spatially in the context of a delta that is geometrically complex, highly altered by humans, and fundamentally tidally driven. Overall, the freshwater flows under our control are small, yet important, when compared to the influence of the uncontrolled flows and the influence of the tides.

2. **Recent flow regimes both harm native species and encourage non-native species.** Flows to and within the estuary affect turbidity, salinity, aquatic plant communities, and nutrients that are important to both native and non-native species. Flows and habitat structure are often mismatched and favor non-native species. It will be imperative to better understand the appropriate interaction between flow and habitat which favors native species over now-dominant, non-native species.

3. **Flow is a major determinant of habitat and transport.** Effects of flow on transport and habitat are controlled by the geometry of the waterways. These will change through time, so flow regimes needed to maintain desired habitat conditions will also change through time. Delta inflows affect habitat and biological resources in three different ways: flood plain activation, in-Delta net flows and transport, and Delta outflows.

4. **Recent Delta environmental flows are insufficient to support native Delta fishes for today's habitats.** Flow can be modified to benefit native fishes and flow modification is one of the few immediate actions available. However, the links between flows and fish response are often indirect and not fully resolved. Habitat restoration, contaminant and nutrient reduction, changes in diversions, control of invasive species, and island flooding all interact with flow to affect aquatic habitats. Flow and physical habitat interact in many ways but they are not interchangeable. Future habitat improvements may change response of native fishes to flow and allow flow prescriptions to be revisited.

5. **A strong science program and a flexible management regime are essential to improving flow criteria.** Long-term research to develop the next generation of models linking hydrodynamics and population dynamics is crucial for refining flow criteria. Monitoring alone is inadequate; peer-reviewed scientific studies on ecological processes are essential to provide guidance on how functions change with climate change, changing geomorphology, island flooding, habitat restoration, new flow-control structures, emerging contaminants, and new invasive species. Scientific synthesis must integrate results and make scientific insights useful for policy purposes. Any set of flow criteria should include the capacity to readily adjust the flows to adapt to changing future conditions and improved understanding.

Finally, it is worth being reminded that the positive changes in the Delta ecosystem resulting from improved flow or flow patterns will benefit humans as well as fish and wildlife, especially when accompanied by large-scale habitat restoration and pollution reduction. The changes could, among other things, improve water quality for agriculture and urban consumption, increase fish catches and consumption safety, increase abundance of endangered species (perhaps to the point where delisting can occur), provide increased open space and parkland for recreation, and reduce threats associated with harmful algal blooms and other consequences of ecosystem degradation. In general, an ecosystem which favors native estuarine species is going to be of higher value to humans than one that does not.

Recommended Readings

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