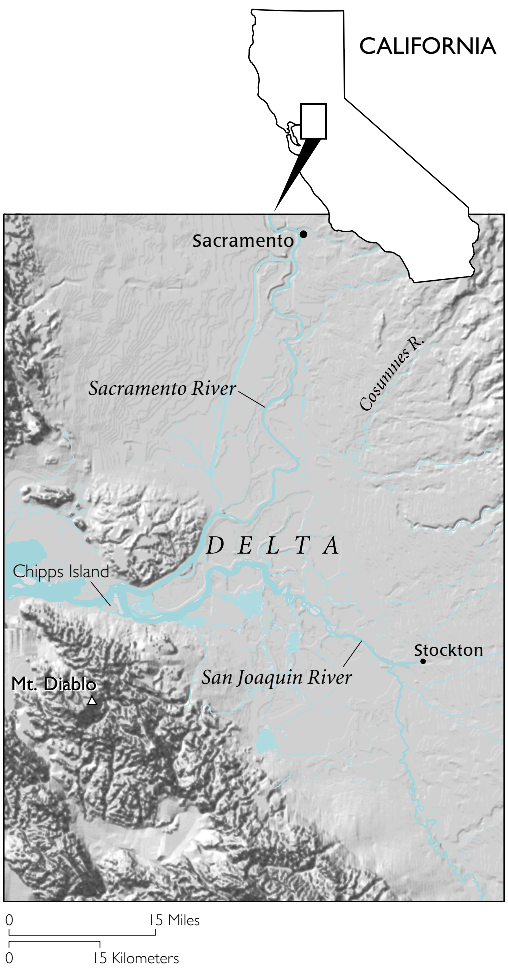
Sacramento-San Joaquin Delta

The sinking heart of the state



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The Sacramento-San Joaquin Delta of California was once a great tidal freshwater marsh. It is blanketed by peat and peaty alluvium deposited where streams originating in the Sierra Nevada, Coast Ranges, and South Cascade Range enter San Francisco Bay.

In the late 1800s levees were built along the stream channels and the land thus protected from flooding was drained, cleared, and planted. Although the Delta is now an exceptionally rich agricultural area (over $500 million crop value as of 1993), its unique value is as a source of freshwater for the rest of the State. It is the heart of a massive north-to-south water-delivery system. Much of this water is pumped southward for use in the San Joaquin Valley and elsewhere in central and southern California.

The leveed tracts and islands help to protect water-export facilities in the southern Delta from saltwater intrusion by displacing water and maintaining favorable freshwater gradients. However, ongoing subsidence behind the levees increases stresses on the levee system, making it less stable, and thus threatens to degrade water quality in the massive north-to-south water-transfer system. Most subsidence in the Delta is caused by oxidation of organic carbon in peat soils.

THE DELTA MARSHES TEEMED WITH WILDLIFE

When Spanish explorers first viewed the Delta from Mount Diablo in 1772, the Sacramento and San Joaquin Rivers were in flood, and they mistook it for a great inland sea. In fact, the prehistoric Delta consisted largely of "tule" (bulrush) and reed marshes that were periodically submerged, with narrow bands of riparian forest on the natural levees along major stream channels. Exceptionally abundant fish and game supported a large


(The Nature Conservancy)

Native American population. When the Spanish first set foot in the Delta, they found the deer and tule elk trails to be so broad and extensive that they first supposed that the area was occupied by cattle. Similarly, American soldiers exploring the Delta in the 1840s found waterfowl to be so abundant and tame that they were mistaken for domestic fowl. The Native Americans were also able to harvest abundant local shellfish and the salmon that migrate through the Delta en route to spawning grounds in streams of the Sierra Nevada and southern Cascades.

The tule marshes of the Delta once teemed with migratory birds and fish.

(The Nature Conservancy)

Trappers from the Hudson Bay Company and elsewhere visited the Delta periodically between 1827 and 1849, drawn by the initially abundant beaver and river otter. By the beginning of the California Gold Rush in 1849, the Native American population of the Delta had been nearly destroyed by intermittent warfare with the Spanish and Mexicans and great epidemics of malaria (?) and cholera (1833) and smallpox (1839) (Dillon, 1982). Shortly after the Gold Rush, a great effort to control and drain the Delta for agriculture began. Levees were built along the stream channels, and the land thus protected from flooding was drained, cleared, and planted. The results of such reclamation seemed miraculous—in a letter to a friend, early settler George McKinney reported cabbages weighing 53 pounds per head and potatoes 33 inches in circumference (Dillon, 1982).

Agriculture and water now dominate the landscape

Today, the Delta is largely devoted to agriculture, and includes about 55 islands or tracts that are imperfectly protected from flooding by over 1,000 miles of levees. Many of the islands in the central Delta are 10 to nearly 25 feet below sea level because of land subsidence associated with drainage for agriculture. There are also numerous smaller, unleveed islands that remain near sea level. Remnants of the natural tule marsh are found on the unleveed "channel" or "tule" islands and along sloughs and rivers. The strips of natural riparian forest have nearly vanished, except on some of the larger channel islands, but relicts can be viewed at the Nature Conservancy's Cosumnes River Preserve in the northeastern Delta.

Although the Delta is an exceptionally productive agricultural area, its unique value to the rest of the State is as a source of freshwater. The Delta receives runoff from about 40 percent of the land area of California and about 50 percent of California's total streamflow. It is the heart of a massive north-to-south water-delivery system whose giant engineered arterials transport water southward. State and Federal contracts call for export of up to 7.5 million acre-feet per year from two huge pumping stations in the southern Delta near the Clifton Court Forebay (California Department of Water Resources, 1993). About 83 percent of this water is used for agriculture and the remainder for various urban uses in central and southern California. Two-thirds of California's population (more than 20 million people) gets at least part of its drinking water from the Delta (Delta Protection Commission, 1995).

Delta waterways pass through fertile farmland.

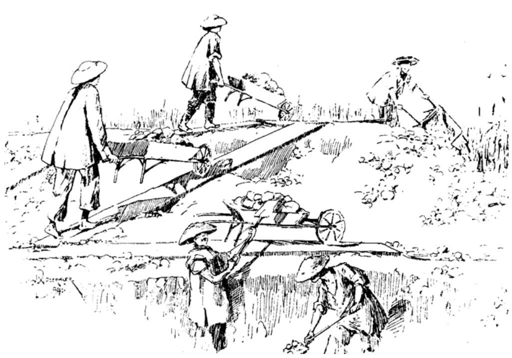
(California Department of Water Resources)

The Delta soils are composed of mineral sediments delivered by the rivers and of peat derived from decaying marsh vegetation. The peat began accumulating about 7,000 years ago and, prior to settlement, accumulated at a rate just sufficient to keep up with the average postglacial sea-level rise of about 0.08 inches per year (Atwater, 1980). The total thickness of peat was as large as 60 feet in the extreme western areas. The mineral sediments are more abundant on the periphery of the Delta and near the natural waterways, whereas the peat soils are thickest in former backwaters away from the natural channels—that is, towards the centers of many of the current islands.

The waterways of the entire Delta are subject to tidal action—tidal surges from San Francisco Bay are observed 5 hours later along the Cosumnes River in the eastern Delta. The position of the interface between the saline waters of the Bay and the freshwaters of the Delta depends upon the tidal cycle and the flow of freshwater through the Delta. Before major dams were built on rivers in the Delta watershed, the salinity interface migrated as far upstream as Courtland along the Sacramento River (California Department of Water Resources, 1993). Today, releases of freshwater from dams far upstream help reduce landward migration of the salinity interface during the summer months. A complicated formula agreed upon by all relevant parties attempts to maintain the two parts per thousand salinity interface near Chipps Island at the western edge of the Delta.

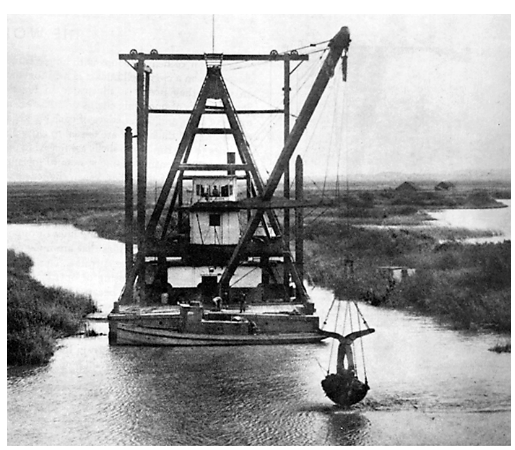
RECLAMATION FOR AGRICULTURE LED TO SUBSIDENCE

Sustained, large-scale agricultural development in the Delta first required levee-building to prevent frequent flooding. The levee-surrounded marshland tracts then had to be drained, cleared of tules, and tilled. The labor force for the initial levee-building effort consisted mainly of Chinese immigrants who arrived in large numbers upon completion of the Transcontinental Railroad in 1869. Between 1860 and 1880, workers using hand tools reclaimed about 140 square miles of Delta land for agriculture. The Chinese labor force was paid about a dollar per day, or at a piecework rate of 13 cents per cubic yard of material moved. After about 1880 the clamshell dredge, still in use today, became the dominant reclamation tool.



Chinese laborers built many of the early levees in the Delta.

(Overland Monthly, 1896)



A clamshell dredge operates near Sherman Island, ca. 1907.

(National Maritime Museum, San Francisco)

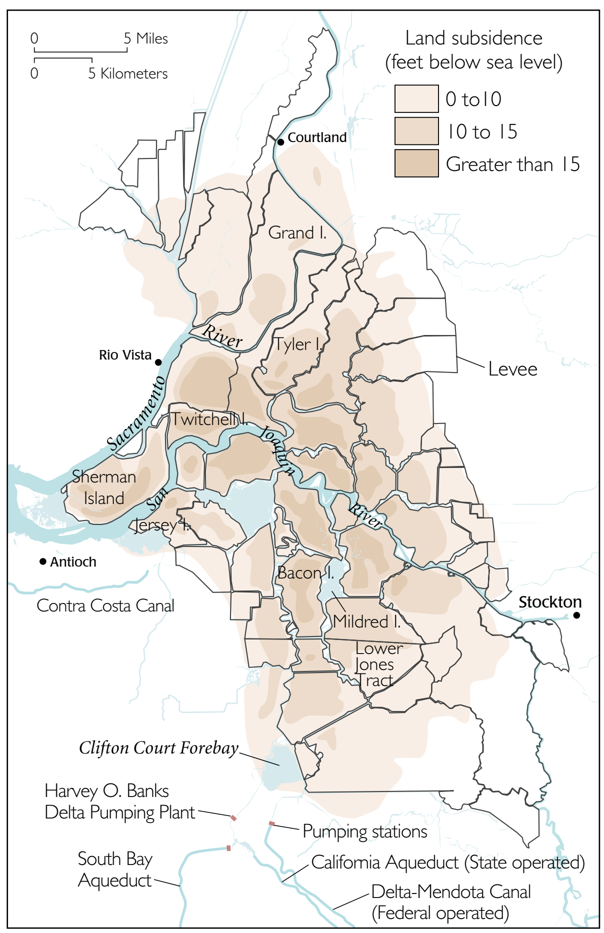
Levees and drainage systems were largely complete by 1930, and the Delta had taken on its current appearance, with most of its 1,150-square-mile area reclaimed for agricultural use (Thompson, 1957).

Reclamation and agriculture have led to subsidence of the land surface on the developed islands in the central and western Delta at long-term average rates of 1 to 3 inches per year (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1993). Islands that were originally near sea level are now well below sea level, and large areas of many islands are now more than 15 feet below sea level. The land-surface profile of many islands is somewhat saucer-shaped, because subsidence is greater in the thick peat soils near their interior than in the more mineral-rich soils near their perimeter. As subsidence progresses the levees themselves must be regularly maintained and periodically raised and strengthened to support the increasing stresses on the levees that result when the islands subside. Currently, they are maintained to a standard cross section at a height 1 foot above the estimated 100-year-flood elevation.

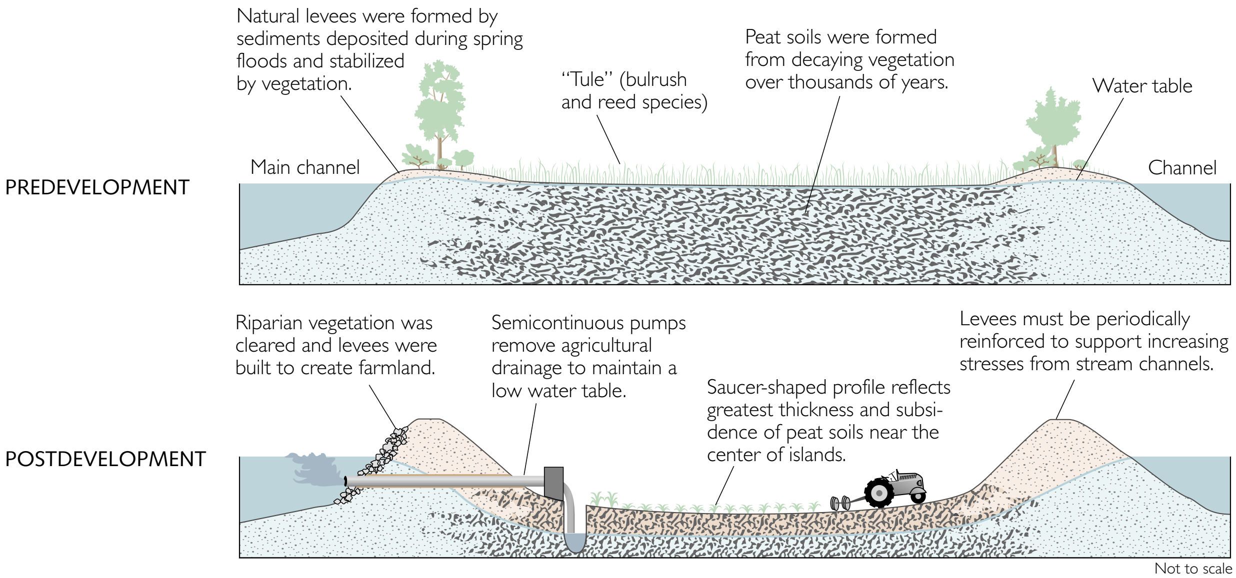
"Watch that first step!"

The land surface has subsided beneath a Delta house, 1950.

Water levels in the depressed islands are maintained 3 to 6 feet below the land surface by an extensive network of drainage ditches, and the accumulated agricultural drainage is pumped through or over the levees into stream channels. Without this drainage the islands would become waterlogged.



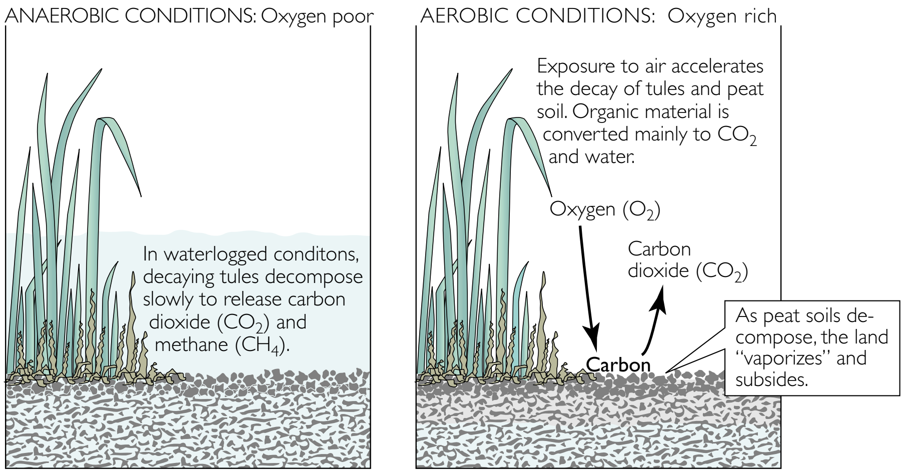
(California Department of Water Resources)



Decomposing peat soils are the main cause of subsidence

The dominant cause of land subsidence in the Delta is decomposition of organic carbon in the peat soils. Under natural waterlogged conditions, the soil was anaerobic (oxygen-poor), and organic carbon accumulated faster than it could decompose. Drainage for agriculture led to aerobic (oxygen-rich) conditions. Under aerobic conditions microbial activity oxidizes the carbon in the peat soil quite rapidly. Most of the carbon loss from the soil occurs as a flux of carbon-dioxide gas to the atmosphere.

Pumps, such as these on Twitchell Island, remove agricultural drainage while maintaining the water table at a level low enough to sustain agriculture.

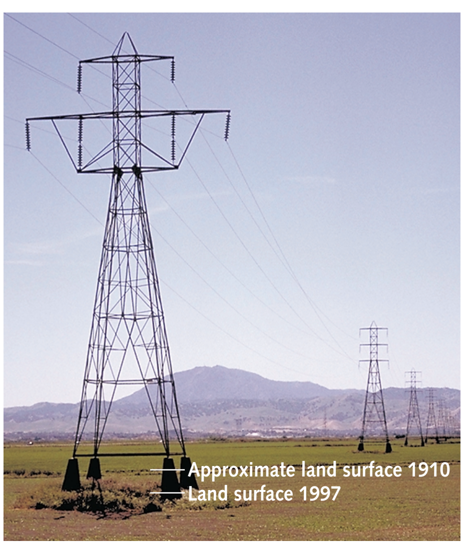


Scientists resolve subsidence mechanisms

There has been some debate as to the causes and mechanisms of subsidence in the Delta. Possible causes include deep-seated compaction related to the removal of subsurface fluids (oil, gas, and water) and the near-surface oxidation and mass wasting of organic soils. This debate seems to have been resolved in favor of the carbon oxidation/gas flux hypothesis. Extensometer measurements have shown that deep-seated subsidence due to natural-gas production and ground-water withdrawal is minimal. Further, pockets of unreclaimed marshland on channel islands remain at sea level. Age-dating of sediment cores from these islands indicates low sedimentation rates and, by inference, minimal subsidence in unreclaimed areas (Rojstaczer and others, 1991). These studies made it clear that Delta subsidence is a near-surface process, but did not establish how the carbon loss takes place. Further studies by the USGS, in cooperation with the California Department of Water Resources, resolved this issue by simultaneously measuring subsidence and carbon fluxes at several sites (Deverel and Rojstaczer, 1996). The increased gaseous flux of carbon dioxide was sufficient to explain most of the carbon loss and measured subsidence, whereas the dissolved organic carbon (DOC) pumped from the islands in agricultural drainage could account for only about 1 percent of the carbon loss.

The USGS experiments also showed that rates of carbon-dioxide production increase with increasing temperature and decrease with increasing soil moisture. These results are consistent with field and laboratory measurements from the Florida Everglades, where subsidence is occurring by the same mechanism, albeit at a smaller rate of about 1 inch per year.

These transmission towers on Sherman Island show evidence of subsidence



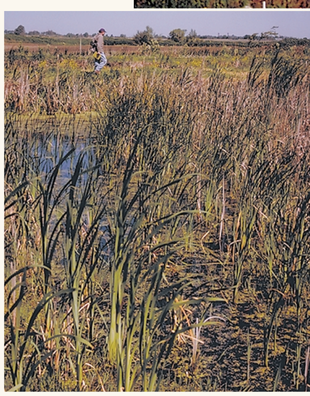
The rate of subsidence has decreased

The best evidence for long-term rates of subsidence comes from two sources—measurements of the exposure of transmission-line

How to slow or reverse subsidence

Scientists look for answers with controlled experiments

Investigations on various islands in the Sacramento-San Joaquin Delta have shown that microbial decomposition of organic-rich soils is causing the land to"vaporize" and disappear. Ongoing experiments at two sites on Twitchell Island in the western Delta focus on assessing the factors that affect the rate and timing of carbon-dioxide production.



At the other site (not shown), which will be permanently flooded, the effects of vegetative cover on the potential for biomass accumulation will be assessed.

Tules will be planted on subsets of this site and will spread throughout the site. They will decompose relatively slowly under flooded conditions. It is anticipated that plant-litter accumulations will become peat-like material over time and eventually increase land-surface elevations measured relative to stable markers set in mineral soil beneath the peat.

FUTURE STRATEGIES

Possible long-term management strategies for various Delta islands include:

1. Shallow flooding to slow peat oxidation and reverse subsidence through biomass accumulation.
2. Shallow flooding combined with thin-layer mineral deposition (a possibly beneficial reuse of dredge material).
3. Continued agricultural use of areas with shallow peat and/or low organic-matter content, under the assumption that the maximum additional subsidence will not destabilize the levees.
4. Blending mineral soil with peat soil to decrease the rate of carbon dioxide (CO_2) release and allow continued agricultural use.
5. Addition of thick layers of mineral soil, possibly using controlled levee breaches or deposition of dredge material, to slow peat oxidation and raise land-surface elevation.
6. Deep flooding to create freshwater reservoirs.

These strategies may be implemented in a mosaic throughout the Delta that creates a substantial diversity of wildlife habitat—uplands, open water, shallow permanent wetlands, and seasonal wetlands.

foundations on Sherman and Jersey Islands in the western Delta and repeated leveling surveys on Mildred and Bacon Islands and Lower Jones Tract in the southern Delta (Weir, 1950; Rojstaczer and others, 1991). The transmission lines in the western Delta were installed in 1910 and 1952. They are founded on pylons driven down to a solid substrate, so that comparison of the original foundation exposure with the current exposure allows estimates of soil loss. The southern Delta transect was surveyed 21 times between 1922 and 1981; in 1983 further surveys were precluded when Mildred Island flooded. Both data sets indicate long-term average subsidence rates of 1 to 3 inches per year, but also suggest a decline in the rate of subsidence over time, probably due to a decreased proportion of readily decomposable organic carbon in the near surface (Rojstaczer and Deverel,1993). In fact, rates of elevation loss measured at three selected sites in 1990 to 1992 were less than 0.4 inches per year, consistent with the inferred slowing of subsidence (Deverel and Rojstaczer, 1996). However, all of these sites were near island edges, and likely underestimate the average island-wide elevation loss.

MANY MANAGEMENT ISSUES ARE RELATED TO SUBSIDENCE

The management issues raised by land subsidence range in scale from those faced by individual farmers to the possible global-scale

Living with possible levee failure

Approximately 1,100 miles of levees need to be maintained

Levee failure has been common in the Sacramento-San Joaquin Delta since reclamation began in the 1850s. Each of the islands and tracts in the Delta has flooded at least once, with several flooding repeatedly. About 100 levee failures have occurred since the early 1890s. Initially, most of the failures were caused by overtopping during periods of spring flooding. Although construction of upstream reservoirs since the 1940s has reduced the threat of overtopping, it has not reduced the incidence of levee failure.

Tyler Island levee was breached in a 1986 flood.

(California Department of Water Resources)

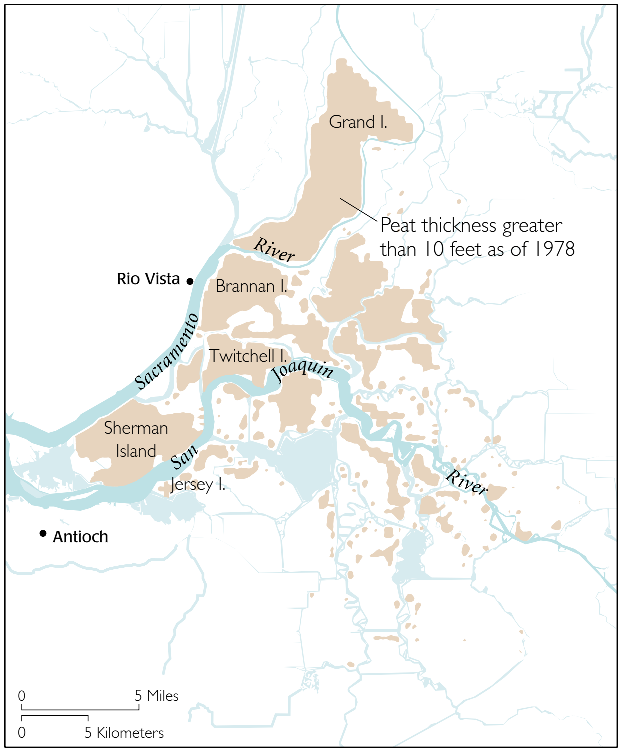
Dredge material is used to reinforce levees.

EARTHQUAKES

The Delta sits atop a blind fault system on the western edge of the Central Valley. Moderate earthquakes in 1892 near Vacaville and in 1983 near Coalinga demonstrate the seismic potential of this structural belt.

The increasing height of the levee system has prompted growing concern about the seismic stability of the levees. The concern is based on the proximity of faulting, the nature of the levee foundations, and the materials used to build the levees. Many levees consist of uncompacted weak local soils that may be unstable under seismic loading. The presence of sand and silt in the levees and their foundations indicates that liquefaction is also a possibility. Although no historic examples of seismically induced levee failure are known in the Delta, the modern levee network has not been subjected to strong shaking. Levees were either smaller or nonexistent in 1906 when the region was strongly shaken by the great San Francisco earthquake.

Areas with peat thickness over 10 feet have a great potential for continued subsidence.



(Peat-thickness estimates are from the California Department of Water Resources, written communication, 1998)

issue posed by the carbon-dioxide flux, with its possible link to climate change. At the most local level, individual farmers or reclamation districts must maintain drainage networks on the islands and pump the agricultural drainage back into waterways. These costs increase gradually as subsidence progresses.

As subsidence continues, levees must be enlarged

The costs of levee construction and maintenance are borne by the State of California and the Federal government, as well as by local reclamation districts. These costs also increase as subsidence progresses, forcing levees to be built higher and stronger. In 1981 to 1986 the total amount spent on emergency levee repairs related to flooding was about $97 million, and in 1981 to 1991 the amount spent on routine levee maintenance was about $63 million (California Department of Water Resources, 1993). Thus the annual cost of repair and maintenance of Delta levees in the 1980s averaged about $20 million per year.

The fertile soils of the Delta are vulnerable to flooding.

(California Department of Water Resources)

Subsidence could affect California's water system

Much larger costs might be incurred if land subsidence indirectly affects the north-to-south water-transfer system, which is predicated on acceptable water quality in the southern Delta. The western Delta islands, in particular, are believed to effectively inhibit the inland migration of the salinity interface between Bay and Delta. If these are flooded, the water available to the massive pumping facilities near the Clifton Court Forebay might become too saline to use.

Sacramento-San Joaquin Delta

The heart of California's water systems

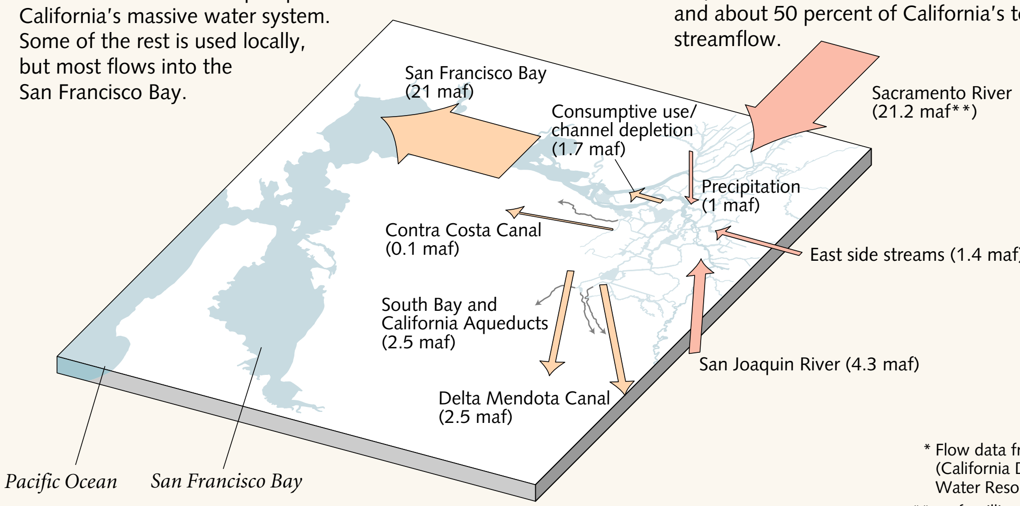
An artificial balance is maintained in the water exchanged between the Delta and the San Francisco Bay. Freshwater inflows regulated by upstream dams and diversions supply water to the Delta ecosystems and to farms and cities in central and southern California. Subsidence of Delta islands threatens the stability of island levees and the quality of Delta water. Delta levee failures would tip the water-exchange balance in favor of more saltwater intrusion, which can ruin the water for agriculture and domestic uses. Several aqueducts would be affected. Any reductions in the supply of imported Delta water could force water purveyors in many parts of the State to meet water demand with groundwater supplies. And this, in turn, could renew land subsidence in Santa Clara and San Joaquin Valleys and exacerbate subsidence in the Antelope Valley and other areas currently reliant on imported Delta water supplies and prone to aquifer-system compaction.

Annual Outflow*

An amount equivalent to about 25 percent of the Delta's outflow is pumped into California's massive water system. Some of the rest is used locally, but most flows into the San Francisco Bay.

Annual inflow

The Delta receives runoff from about 40 percent of the land area of California and about 50 percent of California's total streamflow.

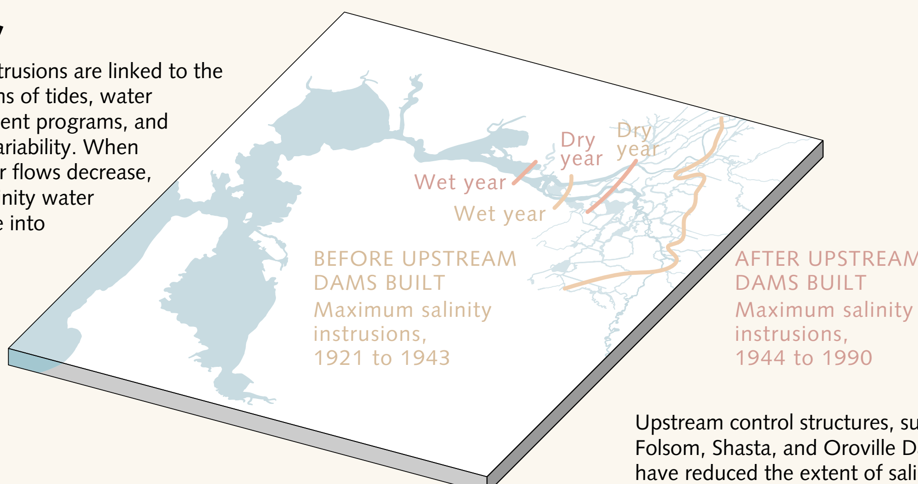


* Flow data from 1980–1991 (California Department of Water Resources, 1993)

** maf: millions of acre feet

Salinity

Salinity intrusions are linked to the interactions of tides, water management programs, and climatic variability. When freshwater flows decrease, higher salinity water can move into the Delta.



Upstream control structures, such as Folsom, Shasta, and Oroville Dams, have reduced the extent of salinity intrusions by providing freshwater releases during the summer and fall.

The Harvey O. Banks pumping plant at the southern edge of the Delta lifts water (lower right) into the California aqueduct (center left). The white towers on the upper left are wind turbines that generate electricity.

(California Department of Water Resources)

The timing of levee breaks and flooding is critical in this regard. Fortunately, most flooding occurs in winter and spring, when major saltwater intrusion is less likely. However, there are occasional levee failures under low-flow conditions. These can cause major short-term water-quality problems, even if the flooded areas are later reclaimed. During one island flooding under low-flow conditions, chloride levels reached 440 parts per million (ppm) at the Contra Costa Canal intake, well above the California standard for drinking water of 250 ppm (California Department of Water Resources, 1995).

The statewide water-transfer system in California is so interdependent that decreased water quality in the Delta might lead to accelerated subsidence in areas discussed elsewhere in this Circular. Both the Santa Clara and San Joaquin Valleys rely, in part, on imported water from the Delta to augment local supplies and thereby reduce local ground-water pumpage and arrest or slow subsidence. Degradation of the Delta source water could well lead to increased ground-water use, and renewed subsidence, in these and other areas in California.

Peat soil agriculture plays a minor role in climate change

The fact that most subsidence in the Delta, and in other drained wetlands, is caused by carbon oxidation suggests that such subsidence might affect atmospheric carbon-dioxide levels. The worldwide annual production of atmospheric carbon due to agricultural drainage of organic soils has been estimated to be as much as 6 percent of that produced by fossil fuel combustion (Tans and others, 1990). However, current rates of carbon-dioxide production in the Delta are likely to be significantly less than those caused by the initial agricultural expansion into virgin areas (Rojstaczer and Deverel, 1993). The gradual slowing of subsidence is associated with a declining rate of carbon-dioxide production.

THE FUTURE OF THE DELTA POSES MANY CHALLENGES

In cases where subsidence is due to aquifer-system compaction, it can often be slowed or arrested by careful water-use management. In cases where subsidence is due to peat oxidation, such as the Delta, it can be controlled only by major changes in land-use practice. In standard agricultural practice, the ultimate limiting factor is simply the total peat thickness; that is, the availability of organic carbon in the soil. In the Florida Everglades, the original peat thickness was less than 12 feet, and most of the potential subsidence has already been realized. In much of the cultivated area of the Delta, however, substantial thicknesses of peat remain, so that there is great potential for further subsidence.

Like the Everglades, the Delta is currently the subject of a major Federal-State restoration effort that includes attempts to improve wildlife habitat. These attempts have focused on the periphery of the Delta, avoiding the central areas with significant amounts of subsidence. As in the Everglades, much of the extensively subsided area is impractical to restore and will continue to be intensively managed.

As subsidence progresses, the levee system will become increasingly vulnerable to catastrophic failure during floods and earthquakes. The interrelated issues of Delta land subsidence, water quality, and wildlife habitat will continue to pose a major dilemma for California water managers.

This view of the Delta was taken looking westward with Mount Diablo on the horizon.

(California Department of Water Resources)