PART II

Drainage of Organic Soils

Sacramento-San Joaquin Delta

Florida Everglades

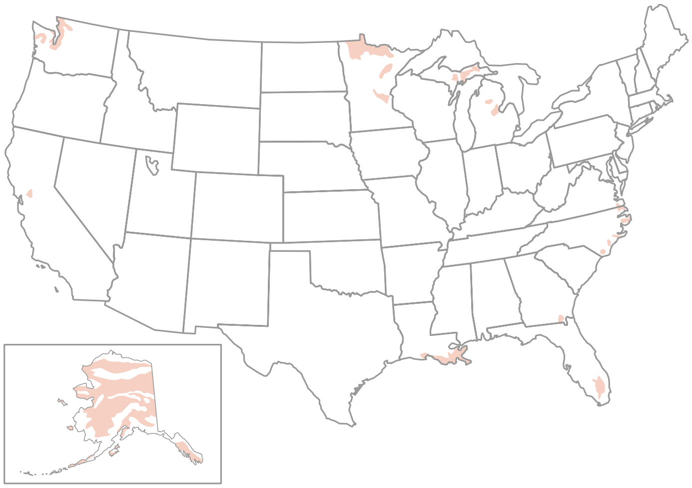
Cultivated peat soils in the Sacramento-San Joaquin Delta

(California Department of Water Resources)

In the U.S. system of soil taxonomy, organic soils or histosols are one of 10 soil orders. They are formally defined as having more than 50 percent organic matter in the upper 30 inches, but may be of lesser thickness if they overlie fragmental rock permeated by organic remains. Organic soil is commonly termed "peat," if fibrous plant remains are still visible, or "muck" where plant remains are more fully decomposed. Other common names for accumulations of organic soil include "bog," "fen," "moor," and "muskeg."

Organic soils generally form in wetland areas where plant litter (roots, stems, leaves) accumulates faster than it can fully decompose. Fibrous peats typically include the remains of sedges and reeds that grew in shallow water. "Woody" peats form in swamp forests. In northerly latitudes with cool, moist climates, many peats are composed mainly of sphagnum moss and associated species. The total area of organic soils in the United States is about 80,000 square miles, about half of which is "moss peat" located in Alaska (Lucas, 1982). About 70 percent of the organic-soil area in the contiguous 48 States occurs in northerly, formerly glaciated areas, where moss peats are also common (Stephens and others, 1984).

Most organic soils occur in the northern contiguous 48 States and Alaska.

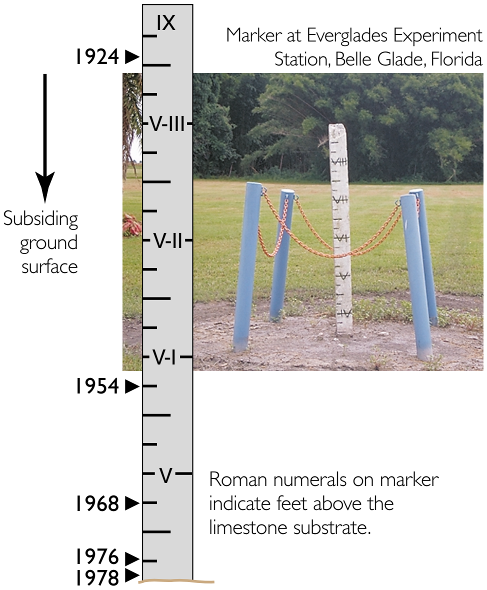


Land subsidence invariably occurs when organic soils are drained for agriculture or other purposes. There are a number of causes, including compaction, desiccation, erosion by wind and water, and, in some cases, prescribed or accidental burning. The effects of compaction and desiccation after initial draining can be dramatic, because organic soils have extremely low density and high porosity or saturated water content (up to 80 to 90 percent).

DRAINED ORGANIC SOILS WILL LITERALLY DISAPPEAR

The most important cause of organic-soil subsidence, however, is a process commonly termed “oxidation.” The balance between accumulation and decomposition of organic material shifts dramatically when peat wetlands are drained. Under undrained conditions, anaerobic microbial decomposition of plant litter—that is, decomposition in the absence of free oxygen—cannot keep pace with the rate of accumulation. One reason is that lignin, an important cell-wall component of all vascular plants, is much more vulnerable to decomposition under aerobic conditions. Oxidation under aerobic conditions converts the organic carbon in the plant tissue to carbon dioxide gas and water. Aerobic decomposition under drained conditions is much more efficient.

Evidence of subsidence in the Everglades is shown on a concrete marker that has been driven through the organic soil into the underlying limestone substrate.



Marker at Everglades Experiment Station, Belle Glade, Florida

Roman numerals on marker indicate feet above the limestone substrate.

The biochemical origin of much organic-soil subsidence was established by 1930 through laboratory experiments with Florida peat that balanced the loss of dry soil weight with rates of carbon-dioxide production (Waksman and Stevens, 1929; Waksman and Purvis, 1932). This early laboratory work also suggested optimal temperature ranges and moisture contents for microbial decomposition. Later field studies and observations have confirmed “oxidation” as the dominant subsidence process in many instances. For example, in the Florida Everglades, sod fields and residential areas—where causal mechanisms such as erosion, burning, and compaction are minimized or absent—have sunk as rapidly as the cultivated land (Stephens and others, 1984). It is believed that oxidation-related soil loss can be halted only by complete resaturation of the soil or complete consumption of its organic carbon content (Wosten and others, 1997).

Whereas natural rates of accumulation of organic soil are on the order of a few inches per 100 years, the rate of loss of drained organic soil can be 100 times greater, up to a few inches per year in extreme cases. Thus, deposits that have accumulated over many millennia can disappear over time scales that are very relevant to human activity.

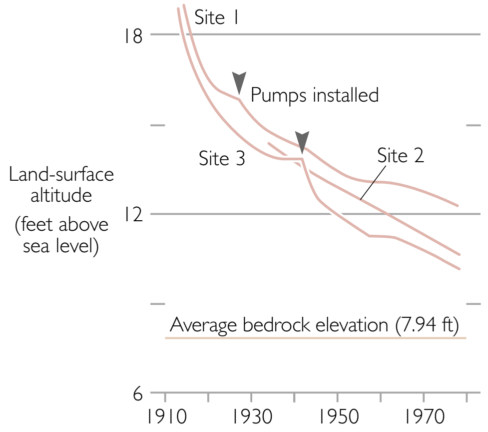
SOME ORGANIC SOILS CAN BE CULTIVATED FOR CENTURIES

Human experience with subsiding organic soils dates back nearly 1,000 years in The Netherlands and several hundred years in the English fen country. The old polders in the western Netherlands were reclaimed for agriculture between the 9th and 14th centuries, and by the 16th century the land had subsided to such an extent that windmills were needed to discharge water artificially to the sea (Shothorst, 1977). Because ground-water levels beneath the polders were still relatively high, the rate of subsidence was relatively low—less than 5 feet total, or 0.06 inches per year, over a roughly 1,000-year period in which progressively more sophisticated drainage systems were developed (Nieuwenhuis and Schokking, 1997). Greatly improved drainage in the 20th century increased the thickness of the drained zone above the water table. As a result, subsidence rates rose to about 0.2 inches per year between the late 1920s and late 1960s, and current rates are more than 0.3 inches per year.

The organic-soil subsidence rates in The Netherlands are still unusually low in a global context. This is due in part to the relatively cool climate, where temperatures are generally below the optimal range for microbial decomposition, and in part to a thin layer of marine clay that caps much of the peat. Larger average rates have been observed elsewhere: up to 3 inches per year over the last 100 years in the Sacramento-San Joaquin Delta, California; about 1 inch per year over the past 100 years in the English fens; and about 1 inch per year for the last 70 years in the Florida Everglades.

Both in the English fens and the Everglades, long-term subsidence rates have been monitored using stone or concrete columns driven into the underlying solid substrate. The history of both areas has been marked by alternate cycles of improved drainage followed by accelerated subsidence and, consequently, inadequate drainage (Stephens and others, 1984), so that the achievements of one generation become the problems of the next (Darby, 1956).

Long-term subsidence rates in the Everglades show cycles. Subsidence slows during periods of poor drainage and accelerates when pumps are installed to improve drainage.



(Stephens and others, 1984)

SACRAMENTO-SAN JOAQUIN DELTA

The sinking heart of the state

S.E. Ingebritsen
U.S. Geological Survey,
Menlo Park, California

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National Geodetic Survey,
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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).

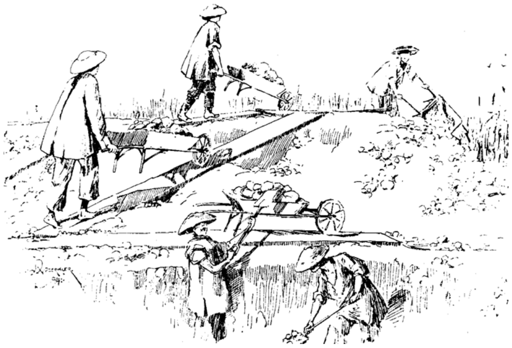
Delta waterways pass through fertile farmland.

(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.

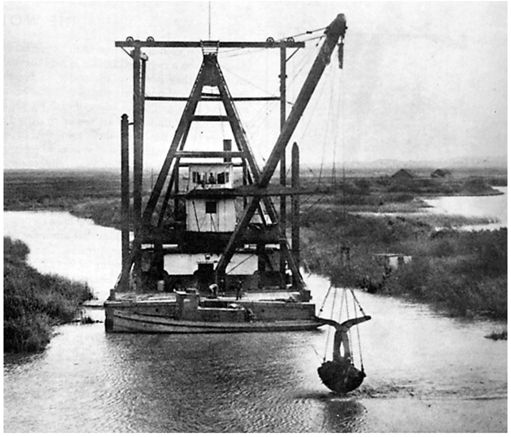
RECLAMATION FOR AGRICULTURE LED TO SUBSIDENCE



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

(Overland Monthly, 1896)

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.



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).

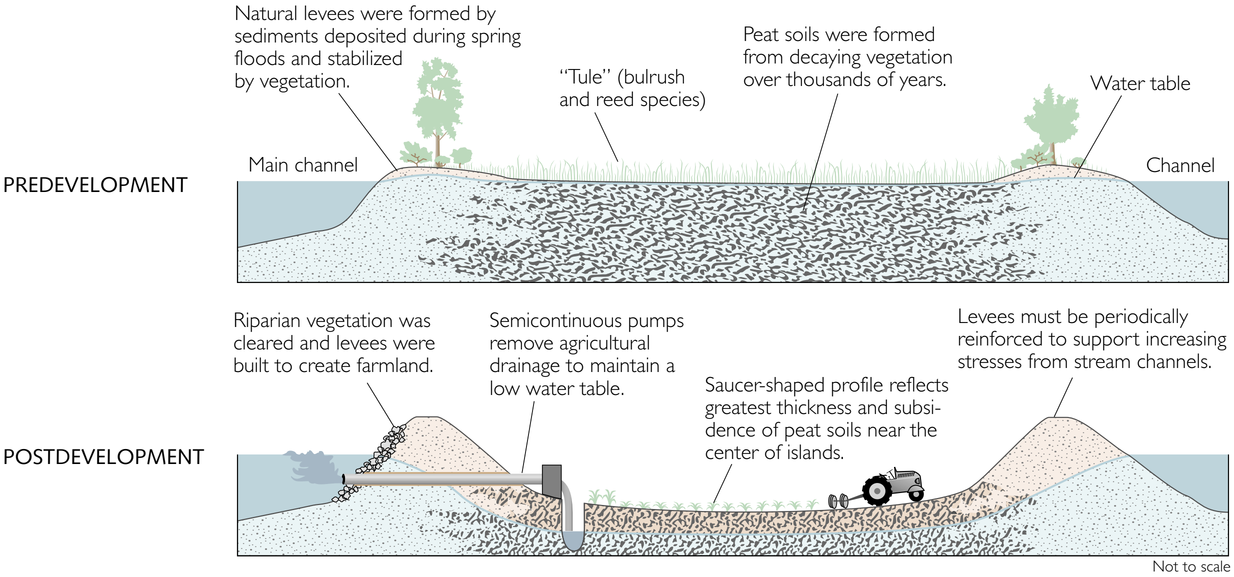
Reclamation and agriculture have led to subsidence of the land surface on the developed islands in the central and western Delta at long-term average rates of 1 to 3 inches per year (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1993). Islands that were originally near sea level are now well below 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.

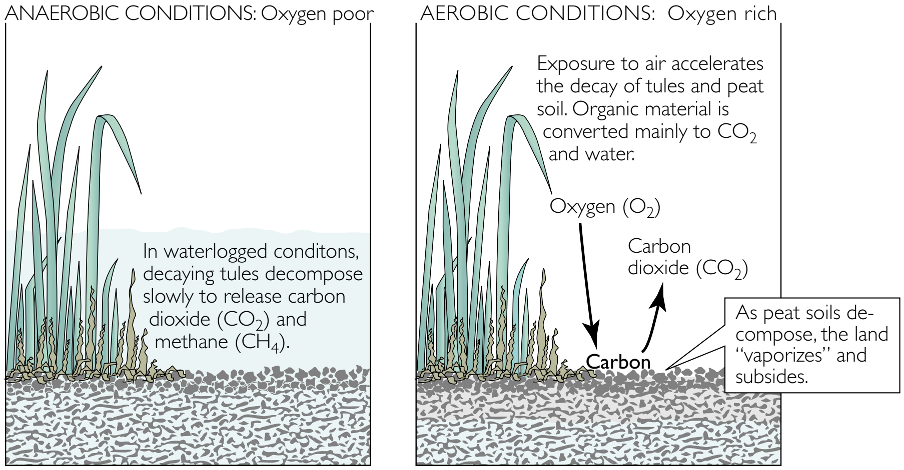
(California Department of Water Resources)



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.

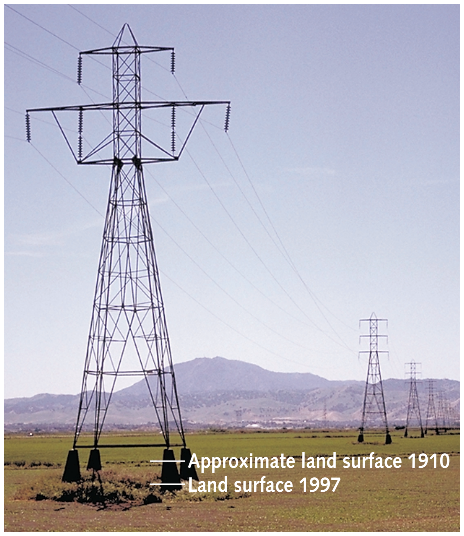


Scientists resolve subsidence mechanisms

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



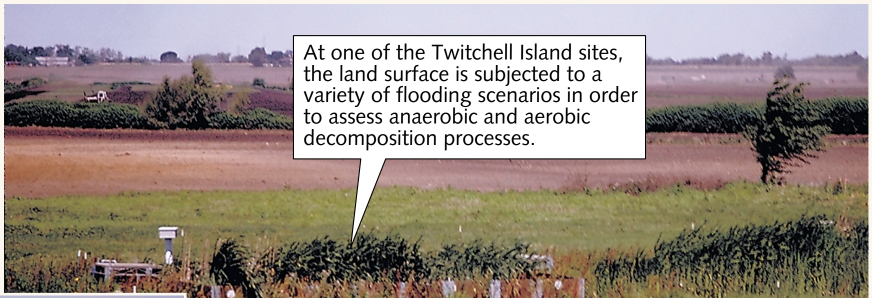
The rate of subsidence has decreased

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

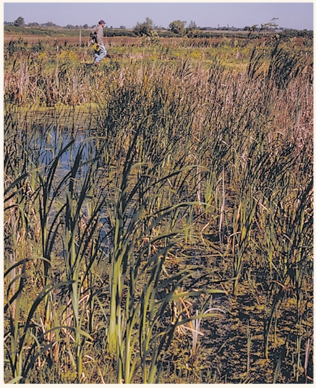
How to slow or reverse subsidence

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 one of the Twitchell Island sites, the land surface is subjected to a variety of flooding scenarios in order to assess anaerobic and aerobic decomposition processes.



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.

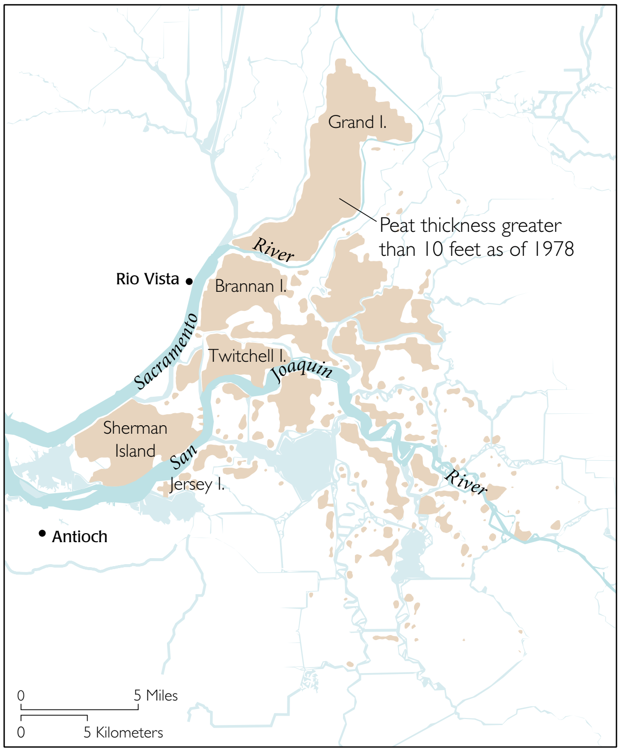
(California Department of Water Resources)

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.

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.

The fertile soils of the Delta are vulnerable to flooding.

(California Department of Water Resources)

Sacramento-San Joaquin Delta

The heart of California's water systems

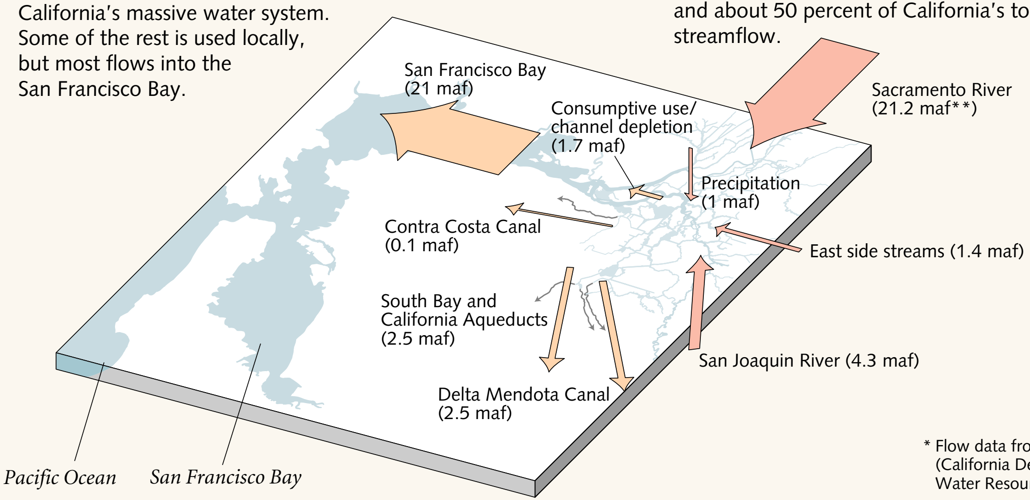
An artificial balance is maintained in the water exchanged between the Delta and the San Francisco Bay. Freshwater inflows regulated by upstream dams and diversions supply water to the Delta ecosystems and to farms and cities in central and southern California. Subsidence of Delta islands threatens the 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.

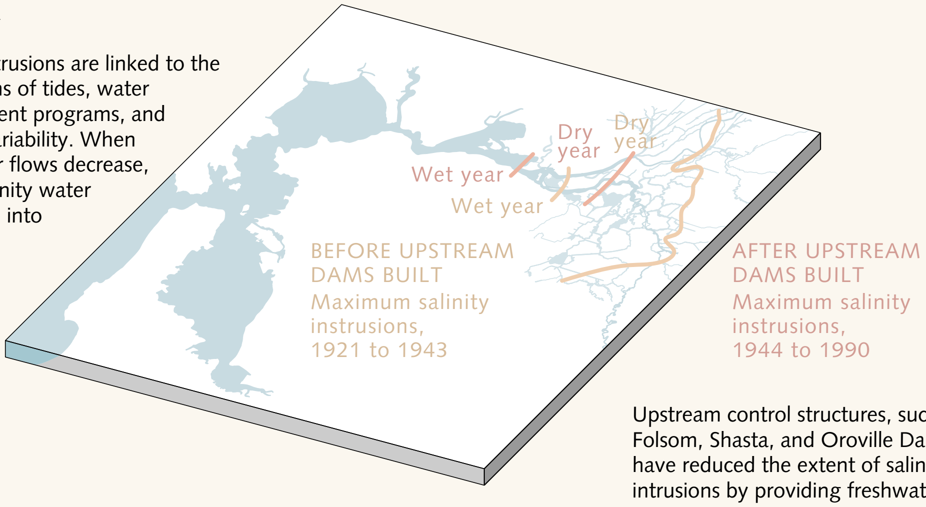


* Flow data from 1980–1991 (California Department of Water Resources, 1993)

** 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.

(California Department of Water Resources)

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.

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.

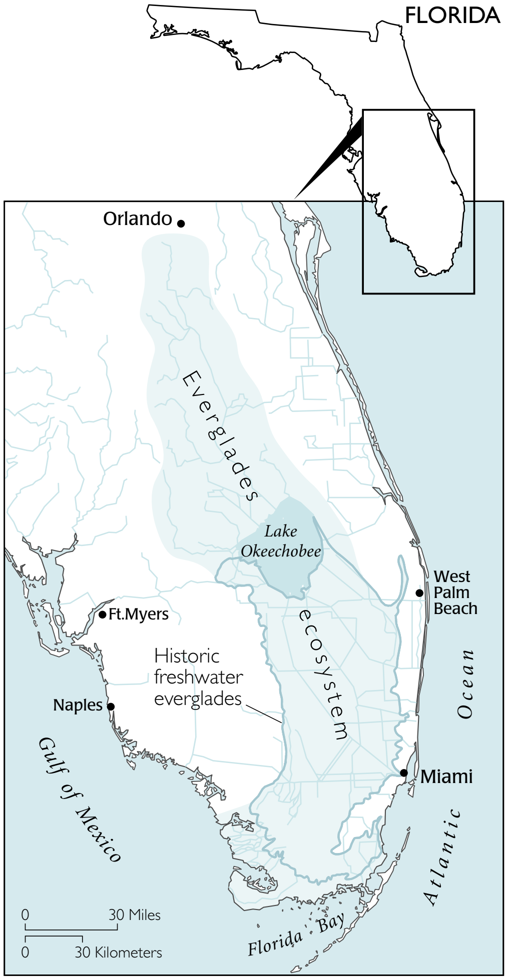
As subsidence progresses, the levee system will become increasingly vulnerable to catastrophic failure during floods and earthquakes. The interrelated issues of Delta land subsidence, water quality, and wildlife habitat will continue to pose a major dilemma for California water managers.

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

(California Department of Water Resources)

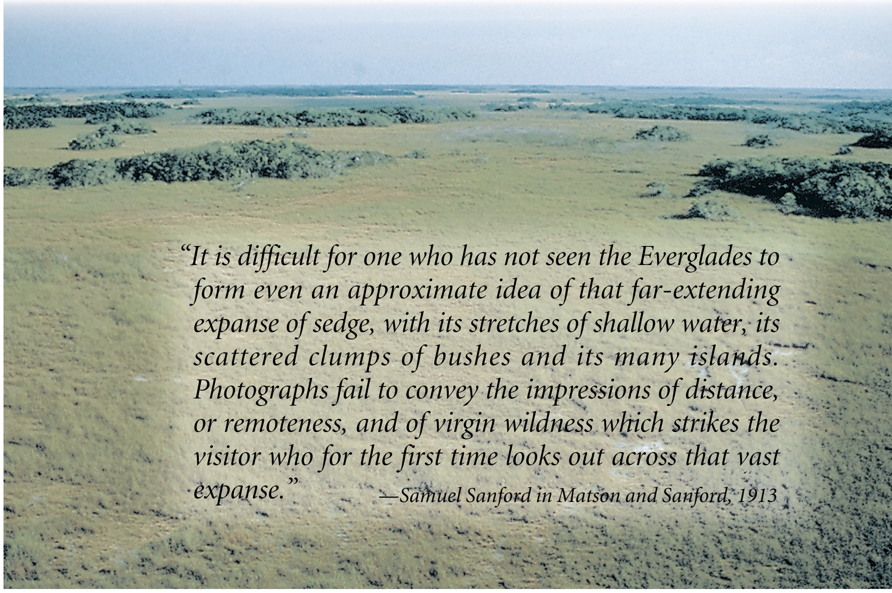
FLORIDA EVERGLADES

Subsidence threatens agriculture and complicates ecosystem restoration



The Everglades ecosystem includes Lake Okeechobee and its tributary areas, as well as the roughly 40- to 50-mile-wide, 130-mile-long wetland mosaic that once extended continuously from Lake Okeechobee to the southern tip of the Florida peninsula at Florida Bay.

Since 1900 much of the Everglades has been drained for agriculture and urban development, so that today only 50 percent of the original wetlands remain. Water levels and patterns of water flow are largely controlled by an extensive system of levees and canals. The control system was constructed to achieve multiple objectives of flood control, land drainage, and water supply. More recently, water-management policies have also begun to address issues related to ecosystem restoration. Extensive land subsidence that has been caused by drainage and oxidation of peat soils will greatly complicate ecosystem restoration and also threatens the future of agriculture in the Everglades.



"It is difficult for one who has not seen the Everglades to form even an approximate idea of that far-extending expanse of sedge, with its stretches of shallow water, its scattered clumps of bushes and its many islands. Photographs fail to convey the impressions of distance, or remoteness, and of virgin wildness which strikes the visitor who for the first time looks out across that vast expanse." —*Samuel Sanford in Matson and Sanford, 1913*

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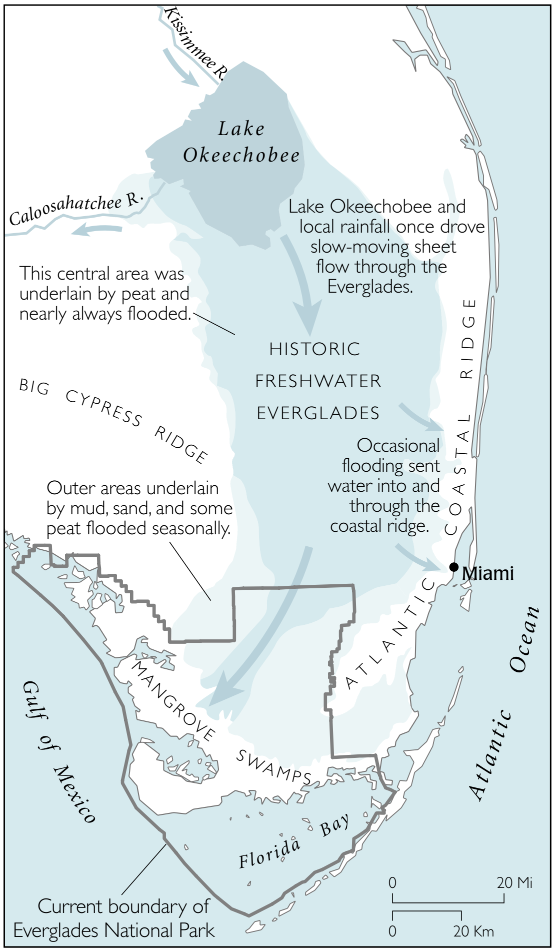
NATURAL FLOW PATTERNS (c.1900)



The Everglades were formed in a limestone basin, which accumulated layers of peat and mud bathed by freshwater flows from Lake Okeechobee.

> *"The outline of this Florida end-of-land, within the Gulf of Mexico, the shallows of the Bay of Florida and the Gulf Stream, is like a long pointed spoon. That is the visible shape of the rock that holds up out of the surrounding sea water the long channel of the Everglades and their borders. The rock holds all the fresh water and the grass and all those other shapes and forms of air-loving life only a little way out of the salt water, as a full spoon lowered into a full cup holds two liquids separate, within that thread of rim."*
>
> *—Marjorie Stoneman Douglas, 1947*

The Everglades ecosystem has, in fact, been badly degraded, despite the establishment of Everglades National Park in the southern Everglades in 1947. Prominent symptoms of the ecosystem decline include an 80 percent reduction in wading bird populations since the 1930s (Ogden, 1994), the near-extinction of the Florida panther (Smith and Bass, 1994), invasions of exotic species (Bodle and others, 1994), and declining water quality in Florida Bay, which likely is due, at least in part, to decreased freshwater inflow (McIvor and others, 1994).

Everglades National Park was created in 1947.

HISTORIC FLOWS WERE SEVERED

A thin rim of bedrock protects south Florida from the ocean. The limestone bedrock ridge that separates the Everglades from the Atlantic coast extends 20 feet or less above sea level. Under natural conditions all of southeast Florida, except for a 5- to 15-mile-wide strip along this bedrock ridge, was subject to annual floods. Much of the area was perennially inundated with freshwater. Water levels in Lake Okeechobee and local rainfall drove slow-moving sheet flow through the Everglades under topographic and hydraulic gra-

Hoover dike (center) was built with digging spoils obtained from a navigable channel (foreground). Lake Okeechobee is at the top of photo.

dients of only about 2 inches per mile. Lake Okeechobee, which once overflowed its southern bank at water levels in the range of 20 to 21 feet above sea level, today is artificially maintained at about 13 to 16 feet above sea level by a dike system and canals to the Atlantic and Gulf coasts.

Early agriculturalists began the drying process

The first successful farming ventures in the Everglades began in about 1913, not on the sawgrass plain itself but on the slightly elevated natural levee south of Lake Okeechobee (Snyder and Davidson, 1994). Early efforts to clear, farm, and colonize the sawgrass area had little success, being plagued by flooding, winter freezes, and trace-nutrient deficiencies. (The soil beneath the sawgrass was later shown to be too low in copper to support most crops and livestock.)

In the 1920s the State of Florida established an Everglades Experiment Station in Belle Glade, and the U.S. Department of Agriculture established a Sugarcane Field Station in Canal Point. The combined efforts of these units gradually solved the plant- and livestock-pathology problems experienced by early farmers. However, the land was still subject to frequent, sometimes catastrophic inundation. The great hurricane of 1928 caused at least 2,000 fatalities and flooded the Everglades Experiment Station for several months.

The damage caused by the 1928 hurricane convinced the Federal government to fund construction of a permanent dike around the southern perimeter of Lake Okeechobee. This more secure protection from flooding cleared the way for intensive settlement of the Everglades. It also permanently severed the natural connection between the Everglades proper and its headwaters. For millennia, the Everglades had been fed by intermittent, diffuse overflow of the imperfect natural levee south of the Lake. Now, its primary water source, other than local rainfall, would be a system of artificial canals.

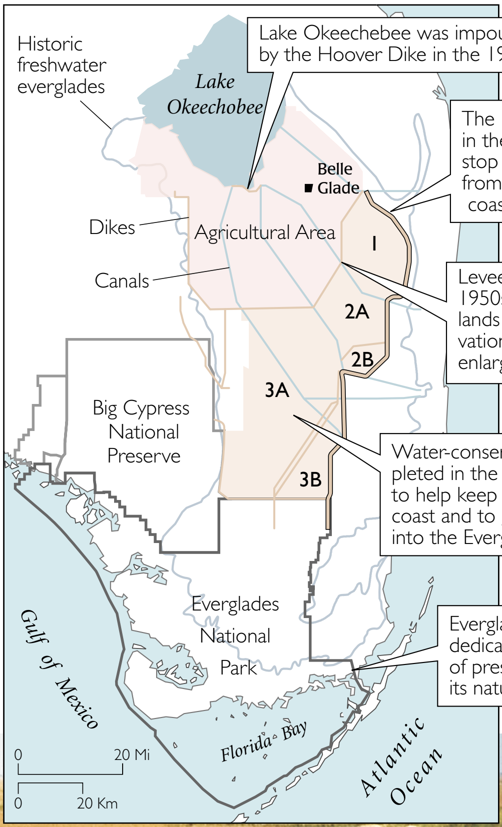
A network of dikes and canals controls water movement, providing optimum irrigation and drainage for sugar cane (left).

Further water-management efforts accelerated development

A comprehensive Federal-State water-management effort in the 1950s and 1960s was prompted by drought and widespread fires in 1944 to 1945 and renewed flooding in 1947 to 1948. The primary motivation was flood control and water supply for the growing urban areas along the Atlantic coast. The drying of the Everglades had clearly contributed to rapid saltwater intrusion in these urbanizing areas during the drought.

A regional flood-control district, the predecessor of today's South Florida Water Management District, was created by the State of Florida in 1949 to manage a coordinated water system. The urbanizing areas that extended west of the natural bedrock ridge were protected from flooding by a high levee known as the "eastern perimeter levee." Although it was originally built to protect and promote development of urbanizing areas along the southeastern

Water-control projects in the Everglades began in the early 1900s. After the fires and floods of the 1940s, much larger water-management projects were implemented.



Lake Okeechobee was impounded by the Hoover Dike in the 1930s.

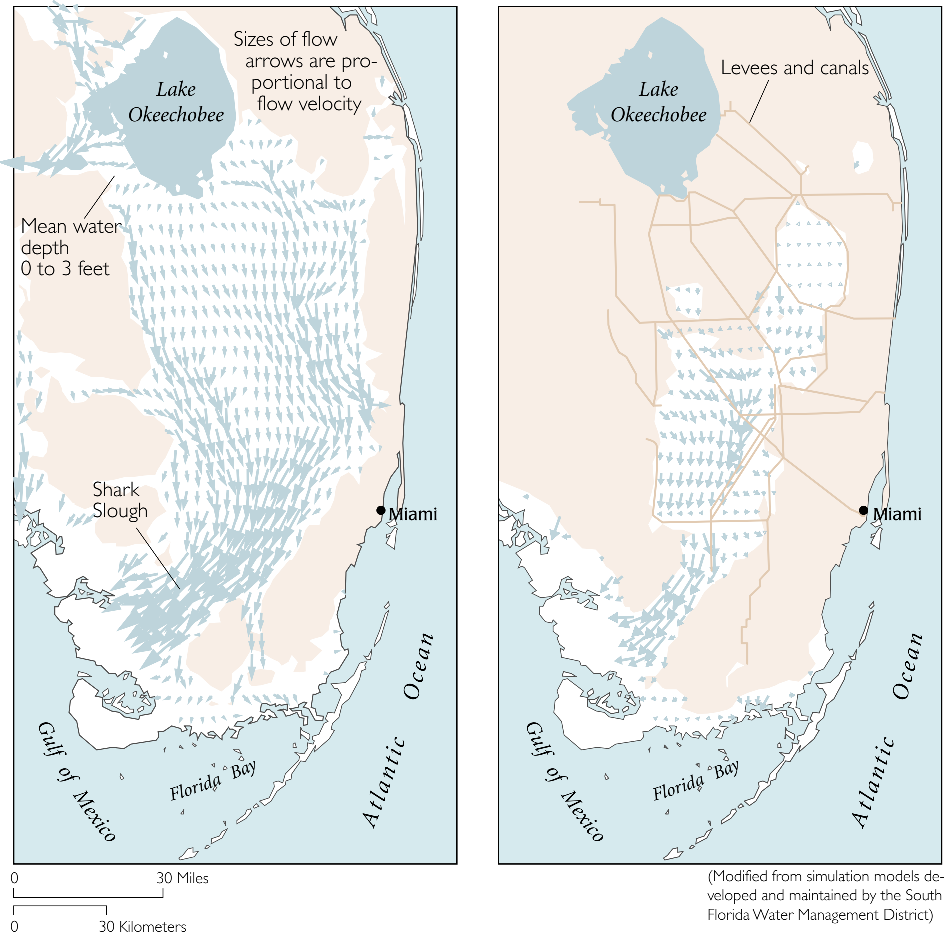
The Eastern Perimeter Levee, built in the early 1950s, was designed to stop sheet flow from the Everglades from encroaching on the urbanizing coastal area.

Levees were built in the late 1950s to partition agricultural lands from the water-conservation areas. Canals were enlarged and pumps installed.

Water-conservation areas, completed in the 1960s, were intended to help keep water away from the coast and to generally manage flow into the Everglades.

Everglades National Park was dedicated in 1947 with the goal of preserving and protecting its natural condition.

Water conservation area 2A is mostly covered with sawgrass.



(Modified from simulation models developed and maintained by the South Florida Water Management District)

Water management has brought significant changes to natural overland flow patterns.

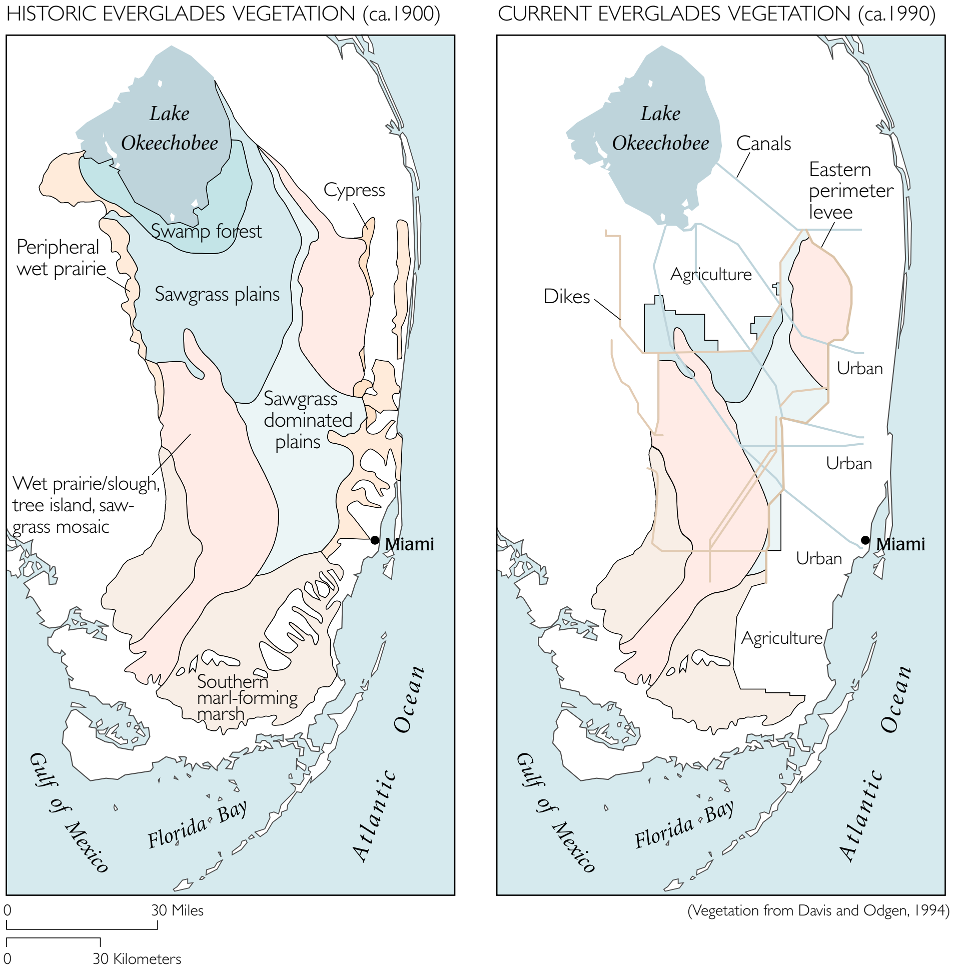
Under natural conditions surface water moved from Lake Okeechobee southward, then turned southwest through a constricted area called Shark Slough.

After canals and dikes were constructed for the agricultural and water-conservation areas, sheet flow practically disappeared from the northern Everglades and diminished to the south.

coast, this levee has, ironically, become the only effective barrier to more extensive urban development of the Everglades (Light and Dineen, 1994).

An area of thick peat soil south of Lake Okeechobee was designated the "Everglades agricultural area." Farther south, other areas of peat soils less suitable for agriculture were designated as "water-conservation areas." These areas are maintained in an undeveloped state, but a system of dikes and canals allows water levels to be manipulated to achieve management objectives that include flood control, water supply, and wildlife habitat.

During dry periods, the level of Lake Okeechobee drops as water is released to provide water to the agricultural area, to canals that maintain ground-water levels in urban areas along the Atlantic coast, and to Everglades National Park. At other times, drainage water pumped from the agricultural area is released into the water-conservation areas, providing needed water but also undesirable amounts of the nutrient phosphorus. In recent years, "best management practices" have helped reduce phosphorus loads from the agricultural area. The managed part of the remaining Everglades—approximately the northern two-thirds—now consists of a series of linked, impounded systems that are managed individually.


HISTORIC EVERGLADES VEGETATION (ca.1900)

CURRENT EVERGLADES VEGETATION (ca.1990)

(Vegetation from Davis and Odgen, 1994)

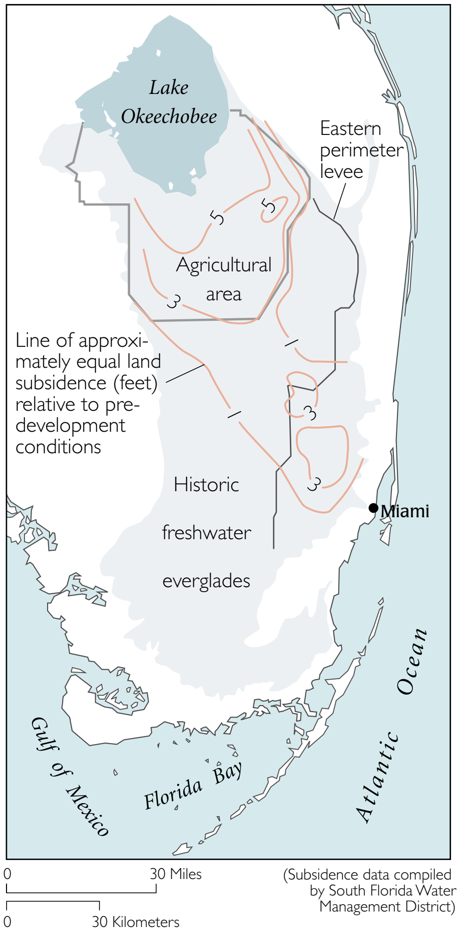
Water management has also changed vegetation patterns. The construction of canals and levees and subsequent draining and development of the land has all but eliminated natural vegetation in the agricultural area and the region east of the eastern perimeter levee.

Land subsidence followed in the wake of development

With the addition of trace nutrients, the peat soil or "muck" beneath the sawgrass proved extremely productive. But the farmers also saw

> "... the cushiony layer of dark muck shrink and oxidize under the burning sun as if it was consumed in thin, airy flames. As the canals and ditches were extended by the local drainage boards, and the peaty muck was dried out and cultivated, it shrank ... It is still shrinking. Every canal and ditch that drained it made a long deepening valley in the surrounding area. On the east and south the subsidence was so great that half that land [drains towards] the lowered lake."
>
> —Marjorie Stoneman Douglas, 1947

In today's Everglades agricultural area, evidence of substantial land subsidence can readily be discerned from the relative elevations of the land surface, the drainage-canal system, and the lake, and from the elevation of older buildings that were built on piles extending to bedrock. Precise measurements are relatively rare, except at particular points or along a few infrequently revisited transects. However, the long-term average rate of subsidence is generally considered to have been between 1 and 1.2 inches per year (Stephens and Johnson, 1951; Shih and others, 1979; Stephens and others, 1984).



(Subsidence data compiled by South Florida Water Management District)

Subsidence is greater in areas that were intentionally drained for urban and agricultural uses.

In uncultivated areas of the Everglades, subsidence is less obvious but probably widespread. Subsidence is not caused by cultivation, but occurs wherever drainage desaturates peat soil. Early engineering efforts focused on drainage alone, and, as a result, much of the area became excessively drained during drought years. The "river of grass" often became a string of drying pools, and great fires swept the Everglades. The drying triggered subsidence, which was then exacerbated by widespread fires. The persistent peat fires sometimes continued smoldering for months before being extinguished by the next rainy season.

Conventional surveying has always been extremely difficult in the Everglades. Stable bedrock bench marks are nonexistent or very distant, the surficial material is soft and yielding, and access is difficult. Current best estimates suggest that there have been 3 to 9 feet of subsidence in the current Everglades agricultural area and that an equally large uncultivated area has experienced up to 3 feet of subsidence. Such elevation changes are tremendously significant to a near-sea-level wetlands system in which flow is driven by less than 20 feet of total relief.

The current management infrastructure and policies have abated land subsidence in undrained areas of the historic Everglades to some extent, although comparison of recent soil-depth measure-

This building at the Everglades Experiment Station was originally constructed at the land surface; latticework and stairs were added after substantial land subsidence.

A sugar mill outside Belle Glade is surrounded by sugar cane fields. Note the dark peat soils in the lower photograph.

ments by the U.S. Environmental Protection Agency (Scheidt, US EPA, written communication 1997) with 1940s estimates of peat thickness (Davis, 1946; Jones and others, 1948) suggest that there has been widespread subsidence in the water-conservation areas over the past 50 years. The northern parts of individual water-conservation areas may still experience some minor subsidence. The southern or downstream parts of the impoundments are generally wetter and may be accumulating peat (Craft and Richardson, 1993a, 1993b), very gradually increasing in elevation. In the drained agricultural and urban areas, subsidence is an ongoing process, except where the peat has already disappeared entirely.

SUBSIDENCE CLOUDS THE FUTURE OF AGRICULTURE

The Everglades agricultural area is now mainly devoted to sugarcane, with considerably smaller areas used for vegetables, sodgrass, and rice. The value of all agricultural crops is currently about $750 million (Snyder and Davidson, 1994).

The eventual demise of agriculture in the Everglades has been predicted for some time (Douglas, 1947; Stephens and Johnson, 1951). The agriculture depends upon a relatively thin, continually shrinking layer of peat soil that directly overlies limestone bedrock. Agronomists have known for many decades that peat-rich soils (histosols), which form in undrained or poorly drained areas, will subside when drained and cultivated. The causes include mechanical compaction, burning, shrinkage due to dehydration, and most importantly, oxidation of organic matter. Oxidation is a microbially mediated process that converts organic carbon in the soil to (mainly) carbon dioxide gas and water.

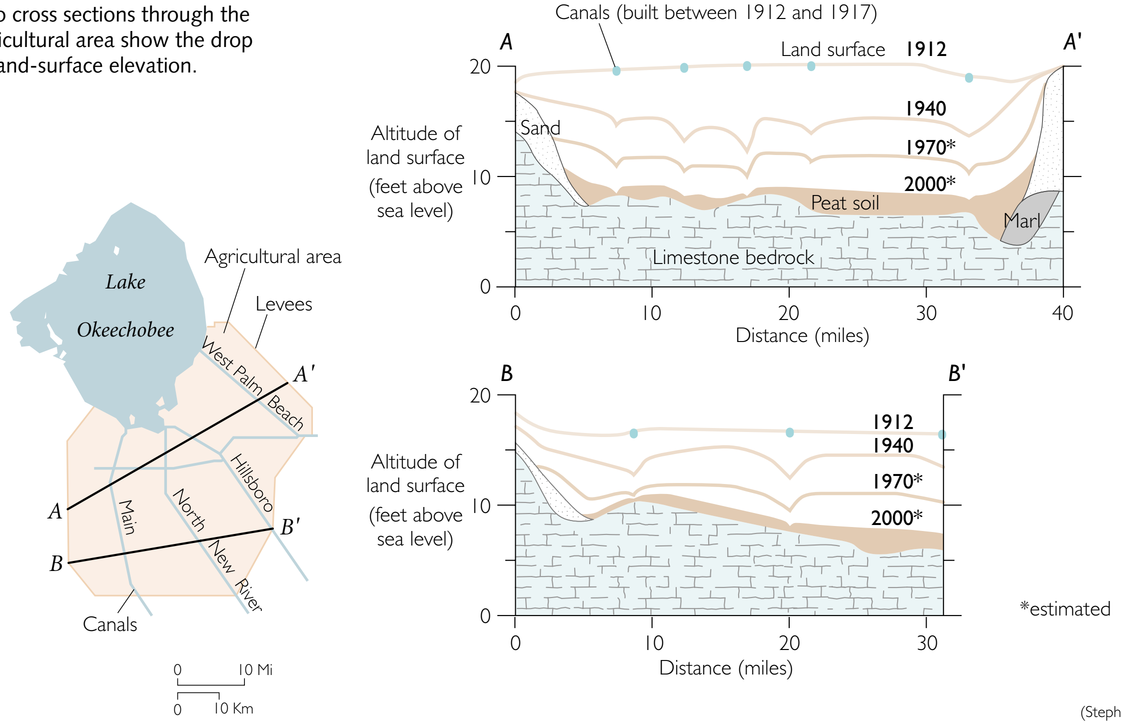
Through photosynthesis, vegetation converts carbon dioxide and water into carbohydrates. Under natural conditions, aerobic microorganisms converted dead plant material (mostly sawgrass root) to peat during brief periods of moderate drainage. Vegetative debris was deposited faster than it could fully decompose, causing a gradual increase in peat thickness. In what is now the Everglades agricultural area, a delicate balance of 9 to 12 months flood and 0 to 3 months slight (0 to 12 inches) drainage for about 5,000 years, with sawgrass the dominant species, led to a peat accretion rate of about 0.03 inches per year. Drainage disrupted this balance so that, instead of accretion, there has been subsidence at a rate of about 1 inch per year.

Peat soils may virtually disappear

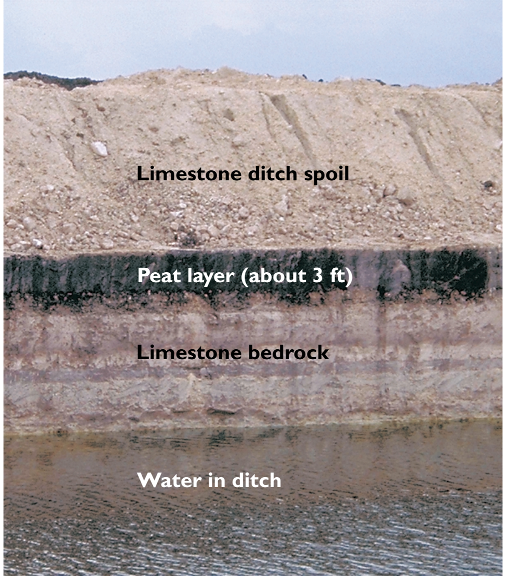
Rates of subsidence in the Everglades are slower than those in the Sacramento-San Joaquin Delta of California, the other major area of peat-oxidation subsidence in the United States; in the Delta, average subsidence rates have been up to 3 inches per year. However, the preagricultural peat thickness was much greater in the Delta (up to 60 feet) than in the Everglades, where initial thicknesses were less than 12 feet. The subsidence rates observed in the Everglades are similar to those observed in the deep peat soils of the English fens during the past 100 years (Lucas, 1982; Stephens and others, 1984).

In the Everglades agricultural area, the initial peat thickness tapered southward from approximately 12 feet near Lake Okeechobee to about 5 feet near the southern boundary. In 1951, Stephens and

Two cross sections through the agricultural area show the drop in land-surface elevation.



(Stephens and Johnson, 1951)



A ditch excavation east of Belle Glade shows peat soil overlying limestone bedrock.

Johnson extrapolated contemporary subsidence trends to predict that by the year 2000 the peat soil would be less than 1 foot thick in about half of the area. They further inferred that much of the area will by then have gone out of agricultural production, assuming that cultivation would not be possible with less than 1 foot of soil over limestone bedrock.

Although the extrapolation of peat thickness done by Stephens and Johnson (1951) appears consistent with measurements made in 1969 (Johnson, 1974), 1978 (Shih and others, 1979), and 1988 (Smith, 1990), little land has yet been retired from sugarcane. One reason is that farmers have managed to successfully produce cane from only 6 inches of peat, by first piling it in windrows to allow successful germination. It also appears possible that the rate of subsidence has slowed somewhat (Shih and others, 1997), due to the combined effects of an increasing nonorganic (mineral) content in the remaining soil, a thinner unsaturated zone dictated by the decreasing soil depth and, perhaps, an increasing abundance of more recalcitrant forms of organic carbon.

The soil-depth predictions of Stephens and Johnson (1951) may prove to have been somewhat pessimistic, but it is clear that agriculture as currently practiced in the Everglades has a finite life expectancy, likely on the order of decades. Extending that life expectancy would require development of an agriculture based on water-tolerant crops that accumulate rather than lose peat (Porter and others, 1991; Glaz, 1995).

SUBSIDENCE COMPLICATES ECOSYSTEM RESTORATION

In a wetland area where natural hydraulic gradients were on the order of inches per mile, and one half-foot land-surface altitude differences are ecologically significant, the fact of several feet of land subsidence substantially complicates ecosystem-restoration efforts.

Subsidence makes true restoration of the Everglades agricultural area itself technically impossible, even in the event that it were po-

Canals and a levee separate constructed wetland from the agricultural area to the right.

litically and economically feasible. Land there that once had a mean elevation less than 20 feet above sea level has been reduced in elevation by an average of about 5 feet. Differential subsidence has significantly altered the slope of the land, precluding restoration of the natural, shallow sheet-flow patterns. If artificial water management and conveyance were now to cease, nature would likely reclaim the land as a lake, rather than the predevelopment sawgrass plains. With removal of the "sponge" of peat and native vegetation, the agricultural area has also lost most of its ability to naturally filter, dampen, and retard storm flows. Other strong impediments to restoration of the Everglades agricultural area include loss of the native seed bank, accumulations of agricultural chemicals in the soil, and the potential for invasion by aggressive exotic species.

A tree island in the Everglades

Subsidence will also complicate efforts to manage the water-conservation areas to the east and south in a more natural condition. For example, the wetlands in these areas are speckled with tree islands, which are an important ecosystem component. Though definitive data are lacking, these tree islands likely have subsided, possibly more than the surrounding area. Thus, restoration of the water-conservation areas will require careful management of water levels in a depth range sufficient to promote appropriate wetland species without further damaging tree islands.

CAREFUL WATER MANAGEMENT IS A KEY TO THE FUTURE

Because of peat loss, agriculture as currently practiced in the Everglades will gradually diminish over the next decades. R.V. Allison, the first head of the Everglades Research Station, likened the peat soil to "the cake which we cannot eat and keep at the same time." His confident prediction that

> "As the use of Everglades lands for agricultural purposes approaches the sunset of ... production, there is little doubt that transition into a wildlife area of world fame will follow, perhaps in an easy and natural manner." —Allison, 1956

now seems overly optimistic. This is still a possible scenario but, as we have noted, the result would be very different from the natural system, due to subsidence. There are also alternative possibilities, including urban development or invention of a sustainable agriculture.

A sustainable agriculture in the Everglades would require at least zero subsidence and, optimally, some peat accretion. Glaz (1995) discussed a program of genetic, agronomic, and hydrologic research aimed at gradually (over a period of 20 to 40 years) making a currently used sugarcane-rice rotation sustainable. Achievement of this goal may prove difficult. However, documented water tolerance of sugarcane (Gascho and Shih, 1979; Kang and others, 1986; Deren and others, 1991), a recently discovered explanation for this water tolerance (Ray and others, 1996), and rapid gains in molecular genetics combine to suggest that substantial reductions in subsidence might be attainable.

Even in the complete absence of agriculture in the Everglades, the existing pattern of urban development and land subsidence would prevent restoration of the natural flow system. Engineered water management and conveyance will be required indefinitely. Land subsidence over a large area south of Lake Okeechobee has created a significant trough within the natural north-south flow system, thereby preventing restoration of natural sheet-flow and vegetation patterns.

The Everglades are currently the subject of a major Federal-State ecosystem restoration effort. "Restoration" is perhaps a misnomer, as the focus of this effort is on more natural management of the remaining 50 percent of the Everglades wetlands, not on regaining the 50 percent that has been converted to urban and agricultural use. Even improving the natural functioning of the remaining wetlands will be a complex problem, due to the lost spatial extent, the hydrologic separation from Lake Okeechobee, and land subsidence. The Everglades will likely continue to be an intensively managed system. However, much as the major engineering effort in the 1950s and 1960s halted the destructive fires and saltwater intrusion of preceding decades, the current restoration effort has the potential to halt and reverse more recent environmental degradation. A major challenge will be to deliver water from Lake Okeechobee through the extensive subsided areas so that it arrives in the undeveloped southern Everglades at similar times, in similar quantities, and with similar quality, as it did prior to drainage and subsidence.