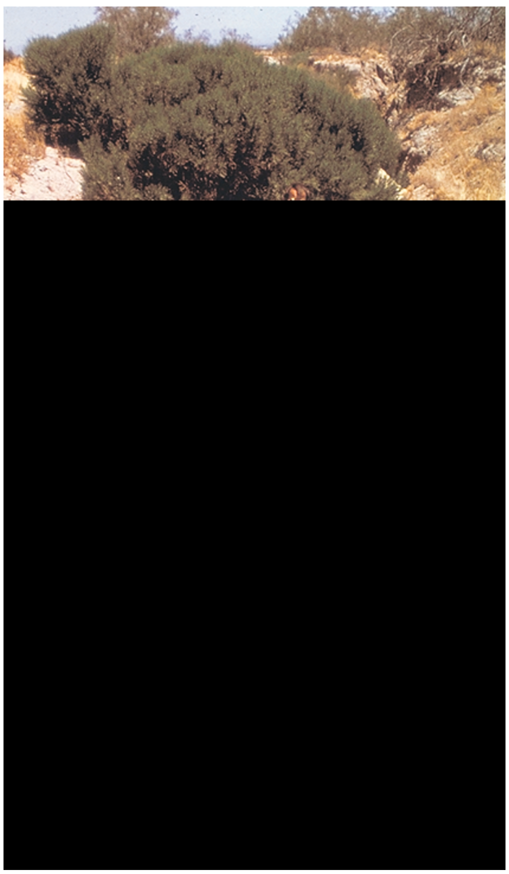
Introduction

Land subsidence in the United States



This earth fissure formed as a result of differential compaction of the aquifer system near Mesa, Arizona.

Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to subsurface movement of earth materials. Subsidence is a global problem and, in the United States, more than 17,000 square miles in 45 States, an area roughly the size of New Hampshire and Vermont combined, have been directly affected by subsidence. The prinicipal causes are aquifer-system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost (National Research Council, 1991). More than 80 percent of the identified subsidence in the Nation is a consequence of our exploitation of underground water, and the increasing development of land and water resources threatens to exacerbate existing land-subsidence problems and initiate new ones. In many areas of the arid Southwest, and in more humid areas underlain by soluble rocks such as limestone, gypsum, or salt, land subsidence is an often-overlooked environmental consequence of our land- and water-use practices.

In 1991, the National Research Council estimated that annual costs in the United States from flooding and structural damage caused by land subsidence exceeded $125 million. The assessment of other costs related to land subsidence, especially those due to ground-water withdrawal, is complicated by difficulties in identifying and mapping the affected areas, establishing cause-and-effect relations, assigning economic value to environmental resources, and by inherent conflicts in the legal system regarding the recovery of damages caused by resource removal under established land and water rights. Due to these "hidden" costs, the total cost of subsidence is probably significantly larger than our current best estimate.

We explore the role of underground water in human-induced land subsidence through illustrative case histories. Extraction and drainage of ground water play direct roles in land subsidence by causing the compaction of susceptible aquifer systems and the dewatering of organic soils. The catastrophic formation of sinkholes in susceptible earth materials, although fundamentally a natural process, can

Subsidence occurs worldwide

Three famous examples of subsidence

AQUIFER-SYSTEM COMPACTION IN MEXICO CITY

In Mexico City, rapid land subsidence caused by groundwater withdrawal and associated aquifer-system compaction has damaged colonial-era buildings, buckled highways, and disrupted water supply and waste-water drainage. Maximum rates of subsidence approach 2 feet per year and total subsidence during the 20th century is as great as 30 feet (New York Times International, January 29, 1998). In the downtown area, the steel casings of wells drilled deep enough to penetrate beneath the subsiding aquifer system now protrude 20 feet or more above ground. The progressive sinking of the urban area has rendered the original waste-water drainage system ineffective, and forced construction of a new, deep, 124-mile-long sewer network.

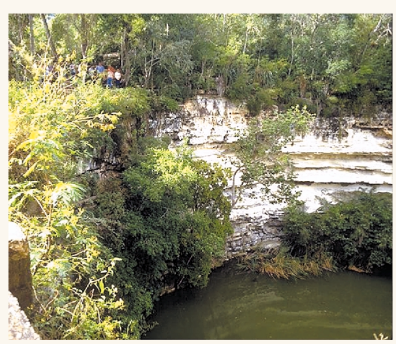
The main Cathedral in Mexico City leans to the left after centuries of subsidence.

ORGANIC-SOIL SUBSIDENCE AND THE DUTCH LANDSCAPE

It is said that "God created the world, but the Dutch created Holland." Near-sea-level marshlands in the western Netherlands began to be drained for agriculture between the 9th and 14th centuries, and by the 16th century the land had subsided to the extent that windmills were needed to artificially discharge water to the sea. The classic Dutch landscape of dikes, canals, and windmills reflects centuries of reclamation and consequent subsidence. Average subsidence rates have increased during the 20th century because of greatly improved drainage.

DISSOLUTION-COLLAPSE FEATURES ON THE YUCATAN PENINSULA

The low-lying Yucatan Peninsula of eastern Mexico is covered by a blanket of limestone, and dissolution of the limestone by infiltrating rainwater has created a highly permeable aquifer, comparable to the Floridan aquifer of the Florida peninsula. Infiltration of rainwater is so rapid that there are no surface streams. For millennia, human civilizations relied on sinkholes formed by collapse of rock above subsurface cavities—locally known as cenotes—for water supply. Great troves of Mayan relics have been found in some cenotes.



Cenote at Chichén Itzá, Mexico

(Clive Ruggles, Leicester University, UK, 1986)

During the construction of a railroad northeast of Valdez, Alaska, the permafrost's thermal equilibrium was disrupted, causing differential thawing that warped the roadbed. The railroad was abandoned in 1938, but subsidence has continued.

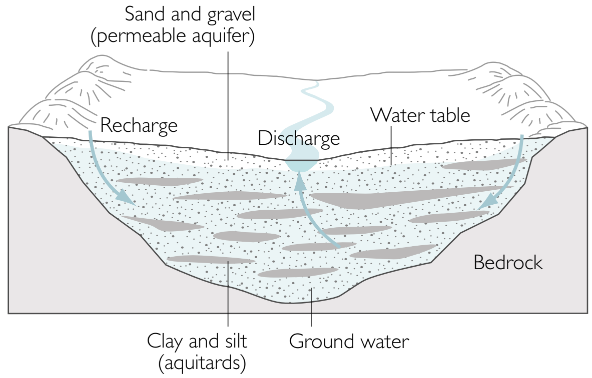
also be triggered by ground-water-level declines caused by pumping, or by infiltration from reservoir impoundments, surface-water diversions, or storm runoff channels. The case histories illustrate the three basic mechanisms by which human influence on ground water causes land subsidence—compaction of aquifer systems, dewatering of organic soils, and mass wasting through dissolution and collapse of susceptible earth materials. We also examine the role that science and water-management groups play in mitigating subsidence damages.

Several other types of subsidence involve processes more or less similar to the three mechanisms just cited, but are not covered in detail in this Circular. These include the consolidation of sedimentary deposits on geologic time scales; subsidence associated with tectonism; the compaction of sediments due to the removal of oil and gas reserves; subsidence of thawing permafrost; and the collapse of underground mines. Underground mining for coal accounts for most of the mining-related subsidence in the United States and has been thoroughly addressed through Federal and State programs prompted by the 1977 Surface Mining Control and Reclamation Act. No such nationally integrated approach has been implemented to deal with the remaining 80 percent of land subsidence associated with ground-water processes.

Oil and gas removal in Long Beach, California caused subsidence. Levees were built to prevent flooding of the oil fields and port facilities.

Subsidence pits and troughs formed above the Dietz coal mines near Sheridan, Wyoming. The coal mines were in operation from the 1890s to the 1920s.

An undeveloped aquifer system is in balance between recharge and discharge. Pumping for urban or agricultural uses disrupts this balance and may cause subsidence to occur.



Mining ground water We begin with five case histories in which overdraft of susceptible aquifer systems has resulted in regional, permanent subsidence and related ground failures. In alluvial aquifer systems, especially those that include semiconsolidated silt and clay layers (aquitards) of sufficient aggregate thickness, long-term ground-water-level declines can result in a vast one-time release of "water of compaction" from compacting aquitards, which manifests itself as land subsidence. Accompanying this release of water is a largely nonrecoverable reduction in the pore volume of the compacted aquitards, and thus an overall reduction in the total storage capacity of the aquifer system. This "water of compaction" cannot be reinstated by allowing water levels to recover to their predevelopment status. The extraction of this resource for economic gain constitutes ground-water mining in the truest sense of the term.

The five case studies demonstrate how agricultural and municipal-industrial ground-water use have combined to deplete critical ground-water resources and create costly regional-scale subsidence. We begin in the "Silicon Valley" in northern California, where early agricultural ground-water use contributed to subsidence that has increased flood risks in the greater San Jose area. Silicon Valley (properly the Santa Clara Valley) was the first place in the United States where subsidence due to ground-water pumpage was recognized; since the late 1960s, the ground-water resource there has been successfully managed to halt subsidence. In nearby San Joaquin Valley, the single largest human alteration of the Earth's surface topography resulted from excessive ground-water pumpage to sustain an exceptionally productive agriculture. In the Houston-Galveston area in Texas, early production of oil and gas, and a long history of ground-water pumpage, have created severe and costly coastal-flooding hazards and affected a critical environmental resource—the Galveston Bay estuary. In Las Vegas Valley ground-water depletion and subsidence have accompanied the conversion of a desert oasis into a thirsty and fast-growing metropolis. Finally, in south-central Arizona, importation of Colorado River water and conversion of water-intensive agriculture to lower-water-demand urban land uses has helped to partly arrest subsidence and forestall further fissuring of the Earth's surface.

The organic soils of the Florida Everglades are quickly disappearing.

Cover collapse sinkhole in Winter Park, Florida, 1981

Drainage of organic soils Land subsidence invariably occurs when organic soils—soils rich in organic carbon—are drained for agriculture or other purposes. The most important cause of this subsidence is microbial decomposition which, under drained conditions, readily converts organic carbon to carbon-dioxide gas and water. Compaction, desiccation, erosion by wind and water, and prescribed or accidental burning can also be significant factors.

The total area of organic soils in the United States is roughly equivalent to the size of Minnesota, about 80,000 square miles, nearly 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). Moss peat is composed mainly of sphagnum moss and associated species. It is generally very acidic (pH 3.5 to 4) and, therefore, not readily decomposed, even when drained. However, where moss peat is amended for agricultural cultivation, for example through fertilization and heavy application of lime to raise the pH, it can decompose nearly as rapidly as other types of organic soils.

Our two case studies of organic-soil subsidence focus on examples of rapid subsidence (1 to 3 inches/year) caused by decomposition of the remains of shallow-water sedges and reeds. In the Sacramento-San Joaquin Delta of California and the Florida Everglades, continuing organic-soil subsidence threatens agricultural production, affects engineering infrastructure that transfers water supplies to large urban populations, and complicates ongoing ecosystem-restoration efforts sponsored by the Federal and State governments.

Collapsing cavities The final two case studies deal with the sudden and sometimes catastrophic land subsidence associated with localized collapse of subsurface cavities—sinkholes. This type of subsidence is commonly triggered by ground-water-level declines caused by pumping and by enhanced percolation of water through susceptible rocks. Collapse features tend to be associated with specific rock types having hydrogeologic properties that render them susceptible to dissolution in water and the formation of cavities. Evaporite minerals (salt, gypsum and anhydrite) and carbonate minerals (limestone and dolomite) are susceptible to extensive dissolution by water. Salt and gypsum are, respectively, almost 7,500 and 150 times more soluble than limestone, the rock type often associated with catastrophic sinkhole formation.

Evaporite rocks underlie about 35 to 40 percent of the United States, although in many areas at depths so great as to have no discernible effect at land surface. Natural solution-related subsidence has occurred in each of the major salt basins (Ege, 1984) throughout the United States. The high solubilities of salt and gypsum permit cavities to form in days to years, whereas cavity formation in carbonate bedrock is a very slow process that generally occurs over centuries to millennia. The slow dissolution of carbonate rocks favors the stability and persistence of the distinctively weathered landforms known as karst. Carbonate karst landscapes comprise more than 40 percent of the humid United States east of the longitude of Tulsa, Oklahoma (White and others, 1995). Human activities can facilitate the formation of subsurface cavities in these susceptible materials and trigger their collapse, as well as the collapse of pre-existing subsurface cavities. Though the collapse features tend to be highly localized, their impacts can extend beyond the collapse zone via the potential introduction of contaminants to the ground-water system. Our two cavity-collapse case studies—Retsof, New York and west-central Florida—focus on human-induced cavity collapses in salt and limestone, respectively.

The role of science In a final section we discuss the role of science in defining subsidence problems and understanding subsidence processes. A combination of scientific understanding and careful management can minimize the subsidence that results from developing our land and water resources.

Part I

Mining Ground Water

Santa Clara Valley, California

San Joaquin Valley, California

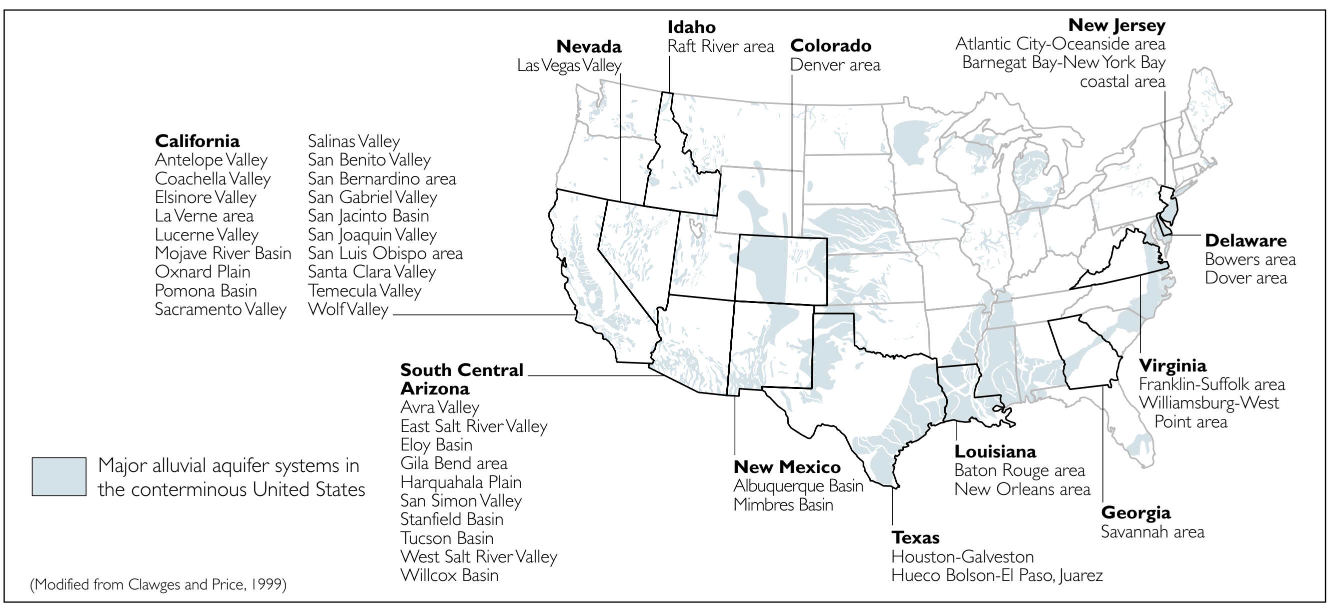
Houston-Galveston, Texas

Las Vegas, Nevada

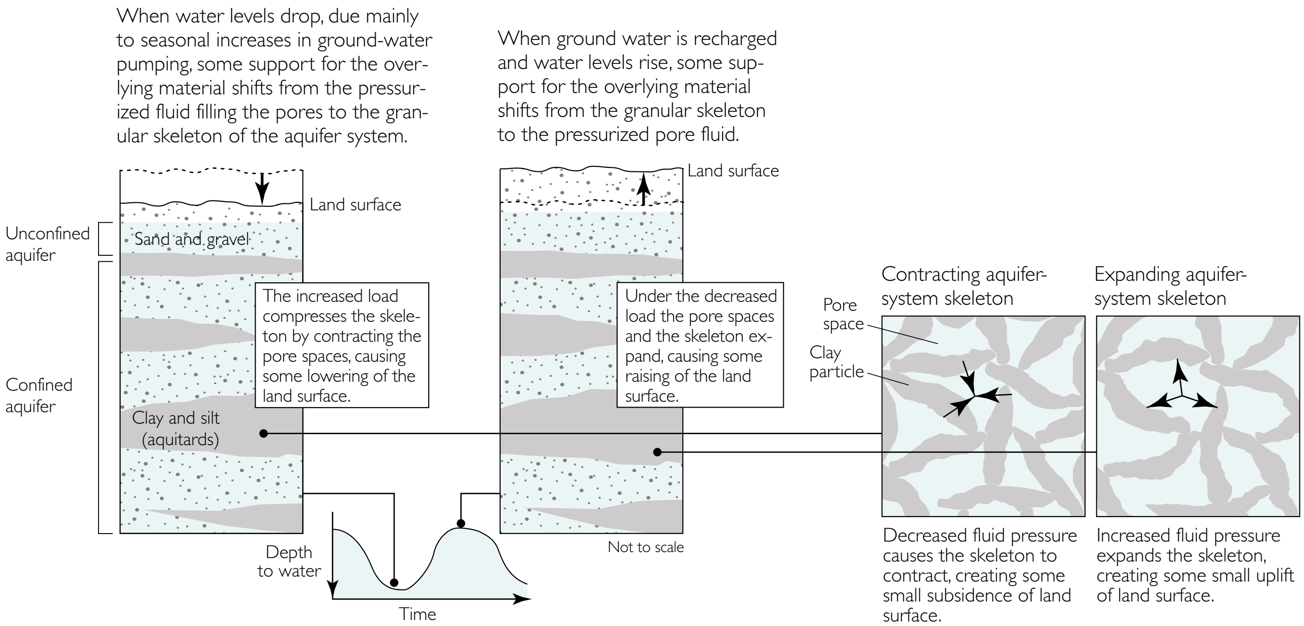
South-Central Arizona

Permanent subsidence can occur when water stored beneath the Earth's surface is removed by pumpage or drainage. The reduction of fluid pressure in the pores and cracks of aquifer systems, especially in unconsolidated rocks, is inevitably accompanied by some deformation of the aquifer system. Because the granular structure—the so-called "skeleton"—of the aquifer system is not rigid, but more or less compliant, a shift in the balance of support for the overlying material causes the skeleton to deform slightly. Both the aquifers and aquitards that constitute the aquifer system undergo deformation, but to different degrees. Almost all the permanent subsidence occurs due to the irreversible compression or consolidation of aquitards during the typically slow process of aquitard drainage (Tolman and Poland, 1940). This concept, known as the aquitard-drainage model, has formed the theoretical basis of many successful subsidence investigations.*

Areas where subsidence has been attributed to ground-water pumpage



* Studies of subsidence in the Santa Clara Valley (Tolman and Poland, 1940; Poland and Green, 1962; Green, 1964; Poland and Ireland, 1988) and San Joaquin Valley (Poland, 1960; Miller, 1961; Riley, 1969; Helm, 1975; Poland and others, 1975; Ireland and others, 1984) in California established the theoretical and field application of the laboratory derived principle of effective stress and theory of hydrodynamic consolidation to the drainage and compaction of aquitards. For reviews of the history and application of the aquitard drainage model see Holzer (1998) and Riley (1998).

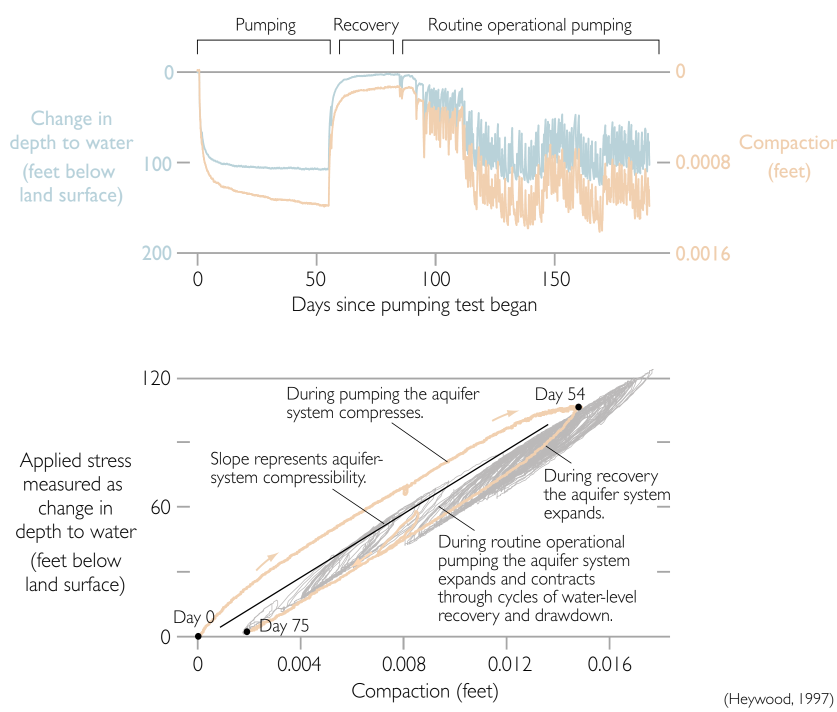


REVERSIBLE DEFORMATION OCCURS IN ALL AQUIFER SYSTEMS

The relation between changes in ground-water levels and compression of the aquifer system is based on the principle of effective stress first proposed by Karl Terzaghi (Terzaghi, 1925). By this principle, when the support provided by fluid pressure is reduced, such as when ground-water levels are lowered, support previously provided by the pore-fluid pressure is transferred to the skeleton of the aquifer system, which compresses to a degree. Conversely, when the pore-fluid pressure is increased, such as when ground water recharges the aqui-

Mostly recoverable (elastic) deformation was observed during and following a pumping test near Albuquerque, New Mexico. Changes in the water level due to cyclic pumping were accompanied by alternating cycles of compression and expansion of the aquifer system.

A measure of the change in applied stress is the change in water level.



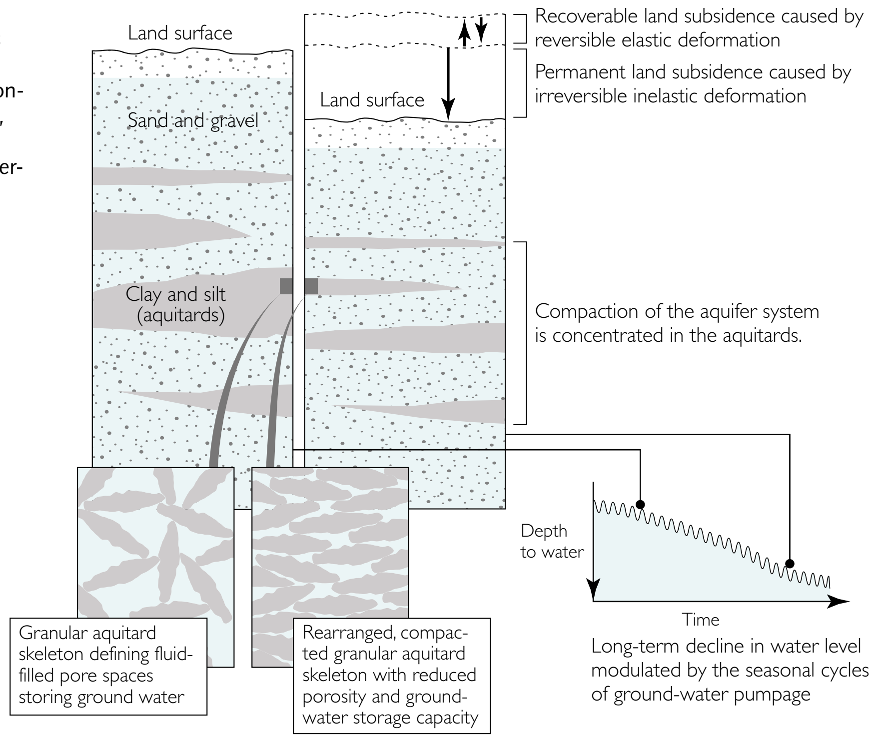
(Heywood, 1997)

fer system, support previously provided by the skeleton is transferred to the fluid and the skeleton expands. In this way, the skeleton alternately undergoes compression and expansion as the pore-fluid pressure fluctuates with aquifer-system discharge and recharge. When the load on the skeleton remains less than any previous maximum load, the fluctuations create only a small elastic deformation of the aquifer system and small displacement of land surface. This fully recoverable deformation occurs in all aquifer systems, commonly resulting in seasonal, reversible displacements in land surface of up to 1 inch or more in response to the seasonal changes in groundwater pumpage.

INELASTIC COMPACTION IRREVERSIBLY ALTERS THE AQUIFER SYSTEM

The maximum level of past stressing of a skeletal element is termed the preconsolidation stress. When the load on the aquitard skeleton exceeds the preconsolidation stress, the aquitard skeleton may undergo significant, permanent rearrangement, resulting in irreversible compaction. Because the skeleton defines the pore structure of the aquitard, this results in a permanent reduction of pore volume as the pore fluid is "squeezed" out of the aquitards into the aquifers. In confined aquifer systems subject to large-scale overdraft, the volume of water derived from irreversible aquitard compaction is essentially equal to the volume of subsidence and can typically range from 10 to 30 percent of the total volume of water pumped. This represents a one-time mining of stored ground water and a small permanent reduction in the storage capacity of the aquifer system.

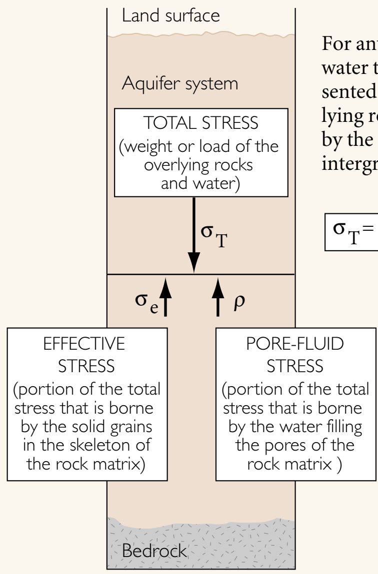
When long-term pumping lowers ground-water levels and raises stresses on the aquitards beyond the preconsolidation-stress thresholds, the aquitards compact and the land surface subsides permanently.



Aquitard Drainage and Aquifer-System Compaction

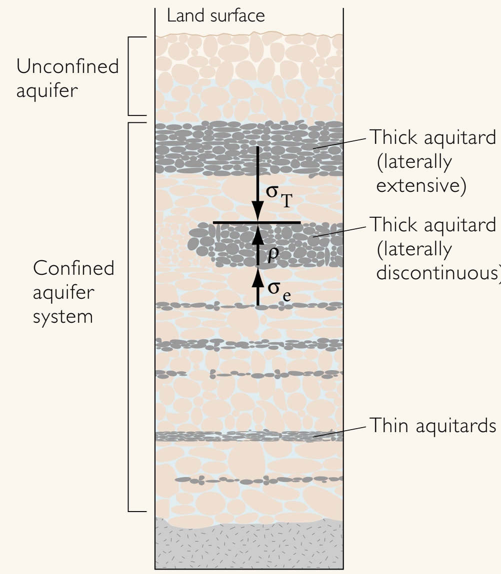
The Principle of Effective Stress

This principle describes the relation between changes in water levels and deformation of the aquifer system.



For any arbitrary plane below the water table, the total stress represented by the weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

$$\sigma_T = \sigma_e + \rho$$

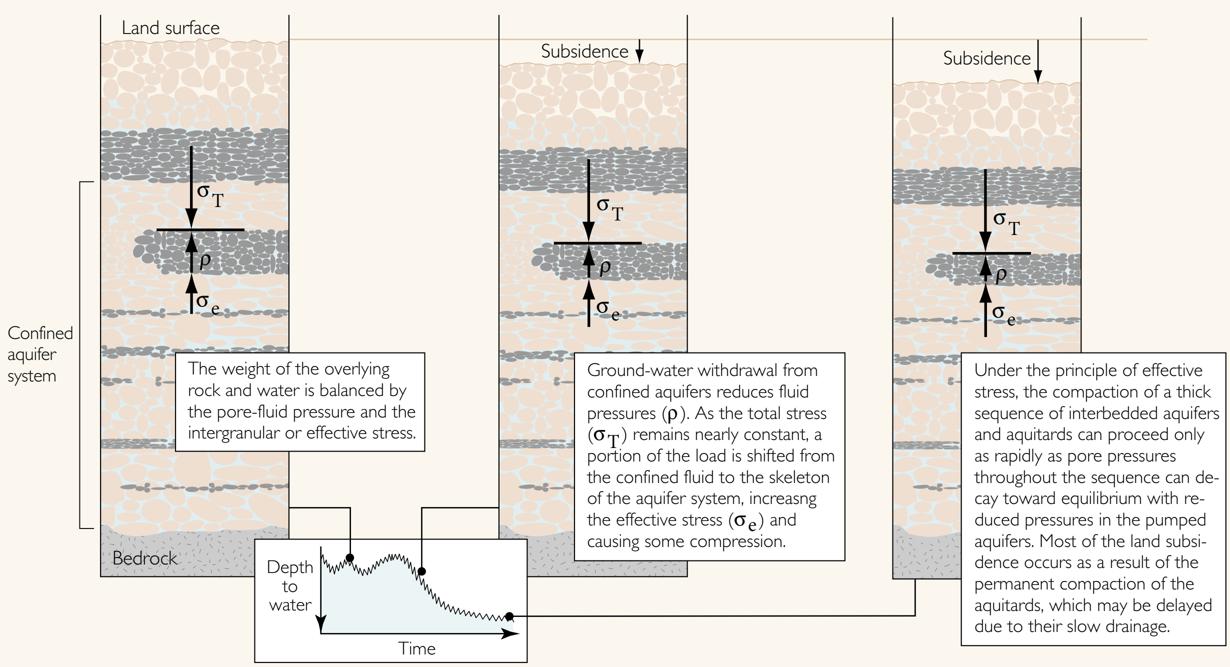


PROLONGED CHANGES IN GROUND-WATER LEVELS INDUCE SUBSIDENCE

Prior to the extensive development of ground-water resources, water levels are relatively stable—though subject to seasonal and longer-term climatic variability.

During development of ground-water resources, water levels decline and land subsidence begins.

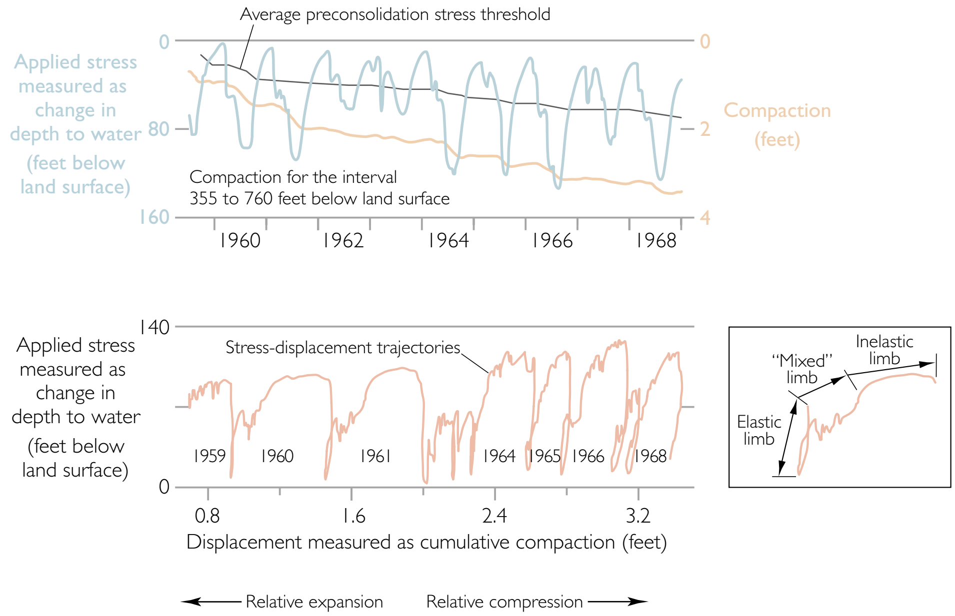
After ground-water pumping slows or decreases, water levels stabilize but land subsidence may continue.



More than 2.5 feet of permanent (inelastic) compaction was observed near Pixley, San Joaquin Valley, California during a 10-year period.

The high summer demand for irrigation water combined with the normally wetter winters causes ground-water levels to fluctuate in response to seasonal pumpage and recharge. The annual cycles of alternating stress increase and decrease are accompanied by cycles of compression and slight expansion of the aquifer system.

Compression proceeds most rapidly when the stress is larger than the preconsolidation stress threshold. Beyond this threshold almost all of the compression is permanent (inelastic) and attributed to the compaction of fine-grained aquitards.



(Riley, 1969)

Aquitards play an important role in compaction

In recent decades increasing recognition has been given to the critical role of aquitards in the intermediate and long-term response of alluvial aquifer systems to ground-water pumpage. In many such systems interbedded layers of silts and clays, once dismissed as nonwater yielding, comprise the bulk of the ground-water storage capacity of the confined aquifer system! This is by virtue of their substantially greater porosity and compressibility and, in many cases, their greater aggregate thickness compared to the more transmissive, coarser-grained sand and gravel layers.

Because aquitards are by definition much less permeable than aquifers, the vertical drainage of aquitards into adjacent pumped aquifers may proceed very slowly, and thus lag far behind the changing water levels in adjacent aquifers. The duration of a typical irrigation season may allow only a modest fraction of the potential yield from aquitard storage to enter the aquifer system, before pumping ceases for the season and ground-water levels recover in the aquifers. Typically, for thick aquitards, the next cycle of pumping begins before the fluid pressures in the aquitards have equilibrated with the previous cycle. The lagged response within the inner portions of a thick aquitard may be largely isolated from the higher frequency seasonal fluctuations and more influenced by lower frequency, longer-term trends in ground-water levels. Because the migration of increased internal stress into the aquitard accompanies its drainage, as more fluid is squeezed from the interior of the aquitard, larger and larger internal stresses propagate farther into the aquitard.

When the internal stresses exceed the preconsolidation stress, the compressibility increases dramatically, typically by a factor of 20 to

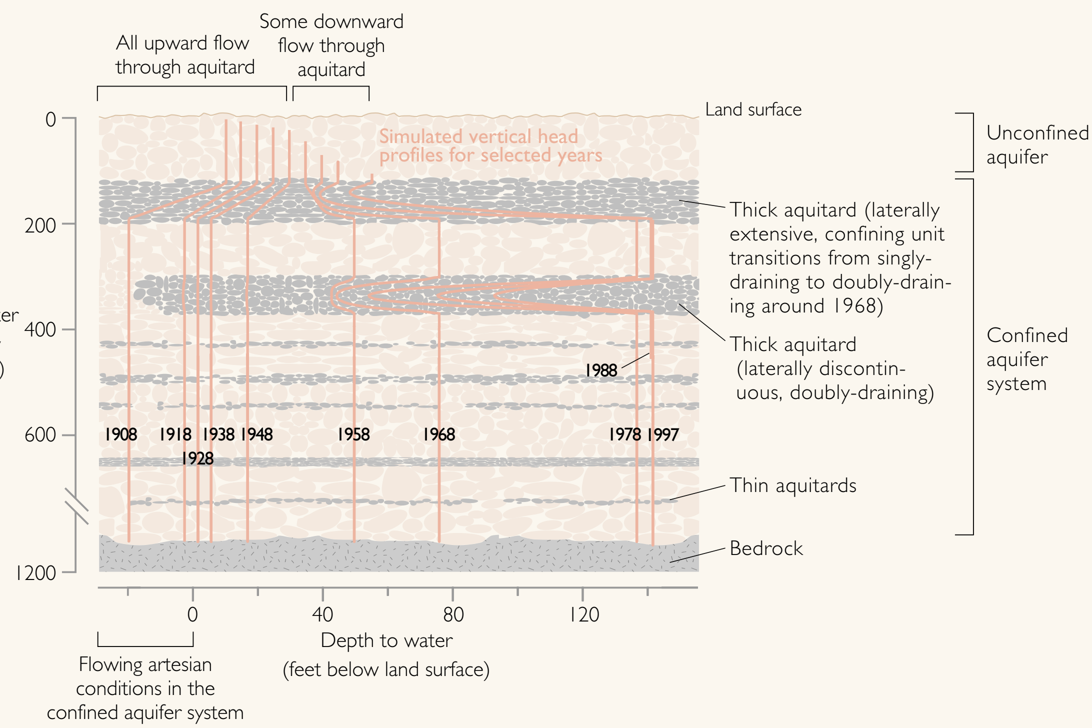
> *". . . the term **aquitard** has been coined to describe the less-permeable beds in a stratigraphic sequence. These beds may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow, but their permeability is not sufficient to allow the completion of production wells within them."*
>
> *—Freeze and Cherry, 1979*

Aquitard Drainage and Aquifer-System Compaction

The Theory of Hydrodynamic Consolidation

The theory describes the delay in draining aquitards when water levels are lowered in adjacent aquifers, as well as the residual compaction that may continue long after water levels are initially lowered.

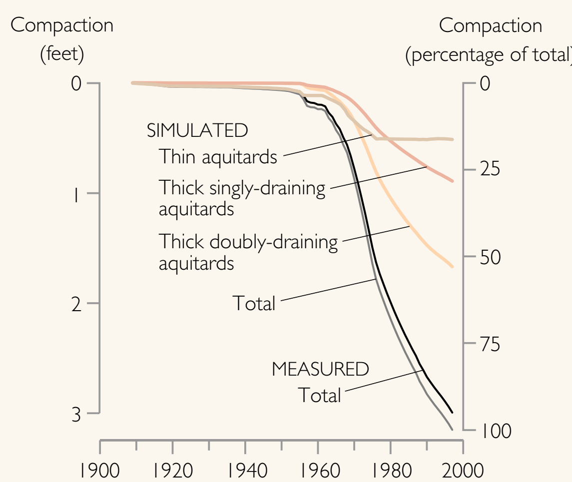
During a 90-year period (1908–1997) of ground-water development in the Antelope Valley, California, the response of water levels in two thick aquitards lags the declining water level in the aquifer. A laterally discontinuous aquitard draining from both upper and lower faces approaches fluid-pressure equilibrium with the adjacent aquifers more rapidly than an overlying laterally extensive aquitard that has a complex drainage history, including a gradient reversal.*



RESIDUAL COMPACTION

Significant amounts of compaction began occurring in the late 1950s after water levels in the aquifers had fallen some 60 feet. Initially, most of the compaction occured in the faster-draining thin aquitards within the aquifers. Subsequently most of the compaction occured in the two thickest and most slowly draining aquitards. Despite stabilization of ground-water levels in the aquifers, more than 0.3 feet of compaction has occurred since 1990, due to residual compaction.

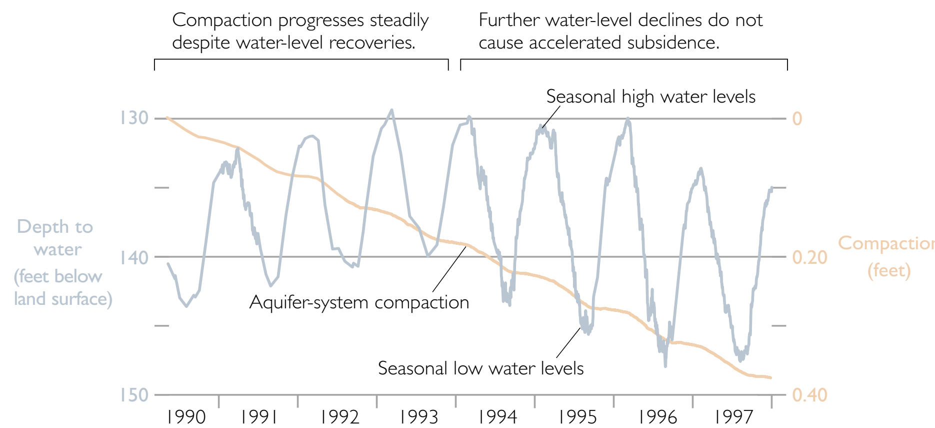
Simulations predict that another 1.3 feet of compaction may ultimately occur even if ground-water levels remain at 1997 levels.



*These results from an aquifer system in Antelope Valley, Mojave Desert, California are based on field measurements and computer simulations of aquitard drainage. They illustrate the history of ground-water-level changes and compaction in the aquifers and aquitards throughout the period of ground-water resource development, 1908-97.

(Michelle Sneed, USGS. written communication, 1998)

100 times, and the resulting compaction is largely nonrecoverable. At stresses greater than the preconsolidation stress, the lag in aquitard drainage increases by comparable factors, and concomitant compaction may require decades or centuries to approach completion. The theory of hydrodynamic consolidation (Terzaghi, 1925)—an essential element of the "aquitard drainage model"—describes the delay involved in draining aquitards when heads are lowered in adjacent aquifers, as well as the residual compaction that may continue long after drawdowns in the aquifers have essentially stabilized. Numerical modeling based on Terzaghi's theory has successfully simulated complex histories of compaction observed in response to measured water-level fluctuations (Helm, 1978).



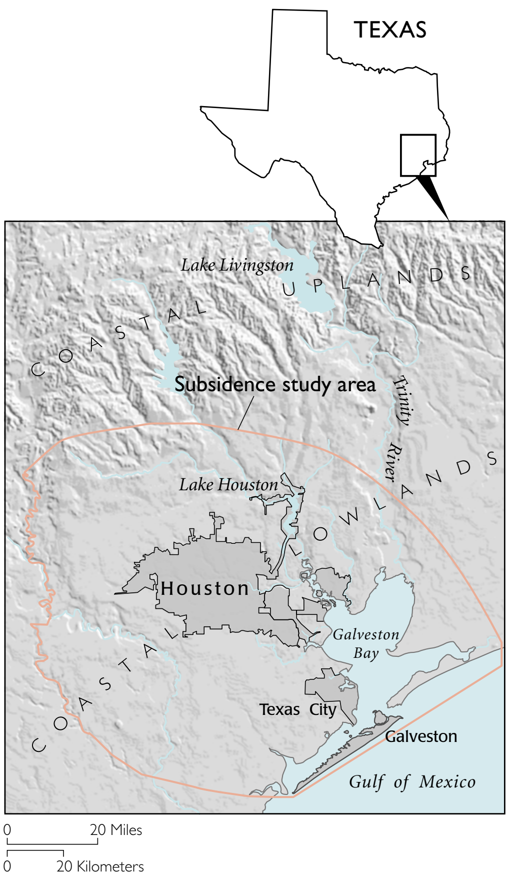
(Michelle Sneed, USGS, written communication, 1998)

Hydrodynamic lag, which is a delay in the propagation of fluid-pressure changes between the aquifers and aquitards, can be seen at this site in the Antelope Valley, Mojave Desert, California.

The responses to changing water levels following eight decades of ground-water development suggest that stresses directly driving much of the compaction are somewhat insulated from the changing stresses caused by short-term water-level variations in the aquifers.

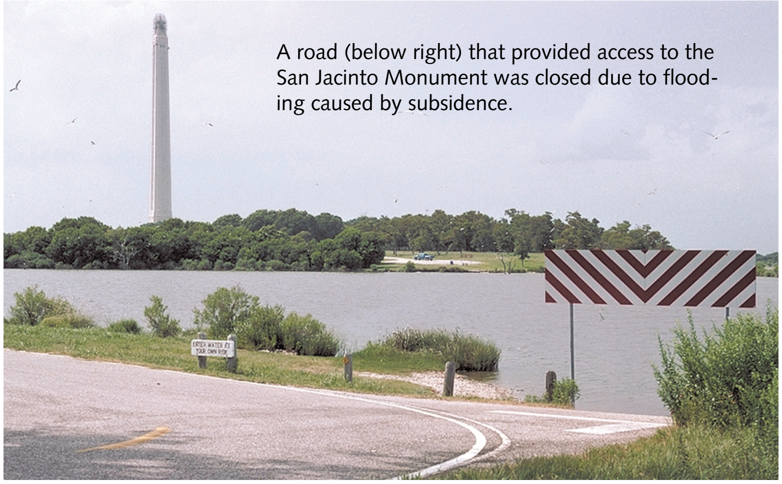
Houston-Galveston, Texas

Managing coastal subsidence



The greater Houston area, possibly more than any other metropolitan area in the United States, has been adversely affected by land subsidence. Extensive subsidence, caused mainly by ground-water pumping but also by oil and gas extraction, has increased the frequency of flooding, caused extensive damage to industrial and transportation infrastructure, motivated major investments in levees, reservoirs, and surface-water distribution facilities, and caused substantial loss of wetland habitat.

Although regional land subsidence is often subtle and difficult to detect, there are localities in and near Houston where the effects are quite evident. In this low-lying coastal environment, as much as 10 feet of subsidence has shifted the position of the coastline and changed the distribution of wetlands and aquatic vegetation. In fact, the San Jacinto Battleground State Historical Park, site of the battle that won Texas independence, is now partly submerged. This park, about 20 miles east of downtown Houston on the shores of Galveston Bay, commemorates the April 21, 1836, victory of Texans led by Sam Houston over Mexican forces led by Santa Ana. About 100 acres of the park are now under water due to subsidence, and



A road (below right) that provided access to the San Jacinto Monument was closed due to flooding caused by subsidence.

Laura S. Coplin
U.S. Geological Survey, Houston, Texas

Devin Galloway
U.S. Geological Survey, Menlo Park, California

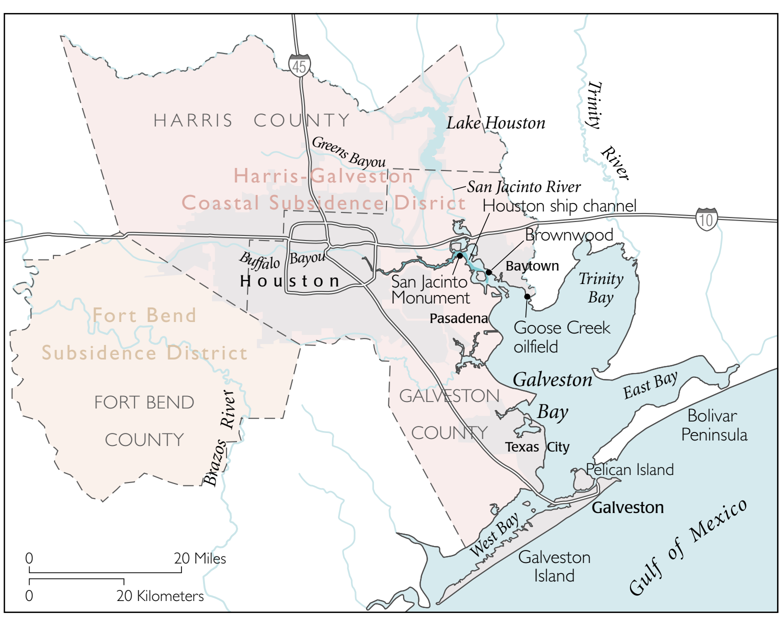
part of the remaining area must now be protected from the Bay by dikes that trap local rain water, which must then be removed by pumps. At many localities in the Houston area, ground-water pumpage and subsidence have also induced fault movement, leading to visible fracturing, surface offsets, and associated property damage.

Growing awareness of subsidence-related problems on the part of community and business leaders prompted the 1975 Texas legislature to create the Harris-Galveston Coastal Subsidence District, "… for the purpose of ending subsidence which contributes to, or precipitates, flooding, inundation, and overflow of any area within the District …." This unique District was authorized to issue (or refuse) well permits, promote water conservation and education, and promote conversion from ground-water to surface-water supplies. It has largely succeeded in its primary objective of arresting subsidence in the coastal plain east of Houston. However, subsidence has accelerated in fast-growing inland areas north and west of Houston, which still rely on ground water and, partly as a result, the Fort Bend Subsidence District was created by the legislature in 1989.

THE FLAT, HUMID GULF COAST IS PRONE TO FLOODING

The Houston-Galveston Bay area includes a large bay-estuary-lagoon system consisting of the Trinity, Galveston, East, and West Bays, which are separated from the Gulf of Mexico by Pelican Island, Galveston Island, and the Bolivar Peninsula. Tidal exchange occurs between the Gulf and bay system through the barrier-island and peninsula complex.

The Houston climate is subtropical; temperatures range from 45° to 93° Fahrenheit and on average about 47 inches of rain falls each year. The humid coastal plain slopes gently towards the Gulf at a rate of about 1 foot per mile. Two major rivers, the Trinity and San Jacinto, and many smaller ones traverse the plain before discharging into estuarine areas of the bay system. Another large river, the Brazos, crosses the Fort Bend Subsidence District and discharges directly into Galveston Bay. The same warm waters of the Gulf of Mexico that attract recreational and commercial fishermen, and other aquatic enthusiasts, are conducive to hurricanes and tropical storms. The Texas coast is subject to a hurricane or tropical storm about once every 2 years (McGowen and others, 1977). Storm tides associated with hurricanes have reached nearly 15 feet in Galveston . The flat-lying region is particularly prone to flooding from both riverine and coastal sources, and the rivers, their reservoirs, and



Galveston Bay near Goose Creek

an extensive system of bayous and manmade canals are managed as part of an extensive flood-control system.

Land subsidence contributes to flooding

Land subsidence in the Houston-Galveston area has increased the frequency and severity of flooding. Near the coast, the net result of land subsidence is an apparent increase in sea level, or a relative sea-level rise: the net effect of global sea-level rise and regional land subsidence in the coastal zone. The sea level is in fact rising due to regional and global processes, both natural and human-induced. The combined effects of the actual sea-level rise and natural consolidation of the sediments along the Texas Gulf coast yield a relative sea-level rise from natural causes that locally may exceed 0.08 inches per year (Paine, 1993). Global warming is contributing to the present-day sea level rise and is expected to result in a sea-level increase of nearly 4 inches by the year 2050 (Titus and Narayanan, 1995). However, during the 20th century human-induced subsidence has been by far the dominant cause of relative sea-level rise along the Texas Gulf Coast, exceeding 1 inch per year throughout much of the affected area. This subsidence has resulted principally from extraction of ground water, and to a lesser extent oil and gas, from subsurface reservoirs. Subsidence caused by oil and gas production is largely restricted to the field of production, as contrasted to the regional-scale subsidence typically caused by ground-water pumpage.

HOUSTON'S GROWTH WAS BASED ON OIL AND GAS INDUSTRIES

Since 1897, when the population was about 25,000, the Houston area has experienced rapid growth, spurred on by the discovery of oil and establishment of the Port of Houston. In 1907 the first successful oil well was drilled, marking the beginning of the petrochemical industry that provided the economic base on which the Houston area was built and still stands. In 1925 Houston became a deep-water port when the U.S. Army Corps of Engineers completed dredging the Houston Ship Channel across Galveston Bay, up the lower reaches of the San Jacinto River, and along Buffalo Bayou to Hous-

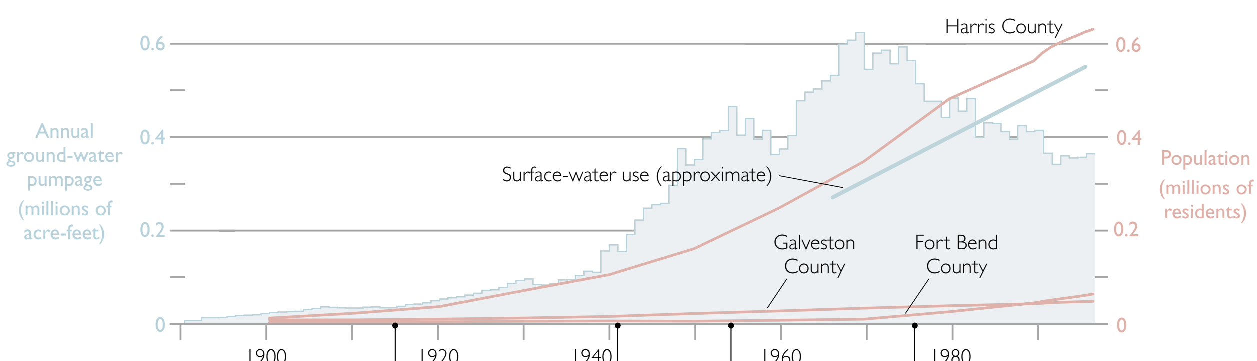
Homes at Greens Bayou were flooded during a storm in June 1989.

(Harris-Galveston Coastal Subsidence District)

Houston (downtown can be seen top center) owes much of its development to the Houston ship channel, which is flanked by petrochemical industries and shipping facilities.

(Harris-Galveston Coastal Subsidence District)

ton. Easy access to the Gulf via the ship channel, and the discovery of additional oilfields, triggered major industrial development along the ship channel in Baytown-La Porte, Pasadena, Texas City, and Houston. The region and industry have continued to grow, and the Houston-Galveston area currently has a population of about 3 million people that is projected to grow to 4.5 million by the year 2010. Nearly half of all U.S. petrochemical production occurs in the greater Houston area. The Port of Houston is the second largest port (by tonnage shipment) in the nation, eighth largest in the world, and handles more commodities for Mexico than all Mexican ports combined. Subsidence to the east of Houston has recently been arrested by substituting imported surface water supplies for much of the ground-water pumpage, but fast growing areas to the west and north, which still depend largely on ground water, are actively subsiding.



Following the opening of the Houston Ship Channel in 1915, large water-consuming oil refineries were constructed.

Industries were established in the early 1940s to support the war effort, and after World War II industry and population continued to grow.

Surface water from Lake Houston became available in 1954, and ground-water pumpage was temporarily reduced.

Water from Lake Livingston was first delivered to the Ethyl Corporation in late 1976 and most of the industrial conversion to surface water occurred in 1977.

(Compiled from Jorgenson, 1961; Gabrysch, 1987; and Houston-Galveston Coastal Subsidence District, 1996)

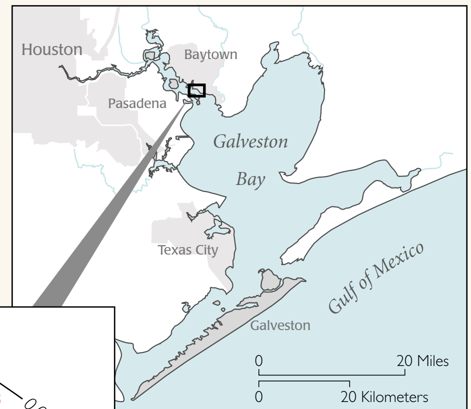
Goose Creek oil field

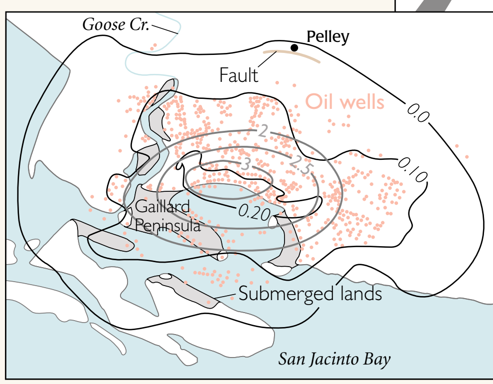
Prolific oil production produced the region's first major subsidence

Most subsidence in the Houston area has been caused by ground-water withdrawal, but the earliest subsidence was caused by oil production. In fact, the subsidence of the Goose Creek oil field on Galveston (San Jacinto) Bay was the first subsidence attributed to subsurface-fluid withdrawal to be described in the scientific literature. A dispute over the legal status of the land submerged by subsidence caused Texas courts to formally recognize the process.

"In 1917 a prolific oil field was developed near the mouth of Goose Creek, and during 1918 and subsequent years, millions of barrels of oil were removed from beneath its surface. Beginning in 1918 it became apparent that the Gaillard Peninsula, near the center of the field, and other nearby low land was becoming submerged. Elevated plank roadways or walks were built from the mainland to the derricks. Derrick floors had to be raised. Vegetation was flooded and killed, and finally all of the peninsula disappeared beneath the water… The maximum measured subsidence is now more than 3 feet and the area affected is 2½ miles long by 1½ miles wide… Outside this area no change in elevation can be detected…."

—Pratt and Johnson, 1926





Between 1918 and 1926 subsidence was measured around Goose Creek oilfield. Lines of equal subsidence (feet) for an 8-year period are shown in grey lines—for a 1-year period, in black lines.

"There can be no doubt, …that the contours show correctly the essential fact that a local 'dishing' of the earth's surface has occurred in the Goose Creek region, the central area of greatest subsidence corresponding approximately with the center of the oil field."

—Pratt and Johnson, 1926

"Submerged land in Texas belongs to the state and only the state can grant oil and gas leases on submerged lands. Consequently, when Gaillard Peninsula became submerged, the state claimed title to it and sought not only to dispossess the fee owner and the oil and gas lessee, but also to recover from them the value of the oil and gas removed from the premises subsequent to the time when the land became submerged. The question was taken into court and finally a decision was rendered in favor of the defendants, that is, the claim of the state of Texas was denied, and the present owners continue in possession. The basis for the decision was the court's acceptance that the subsidence at Goose Creek (which the defendants admitted) was caused by an act of man, namely, the removal of large volumes of oil, gas, water, and sand from beneath the surface."

— Pratt and Johnson, 1926

Pratt and Johnson (1926) also noted that the subsided volume, calculated based on the difference between current and initial topography, amounted to about 20 per cent of the produced volume of oil, gas, water, and sand.

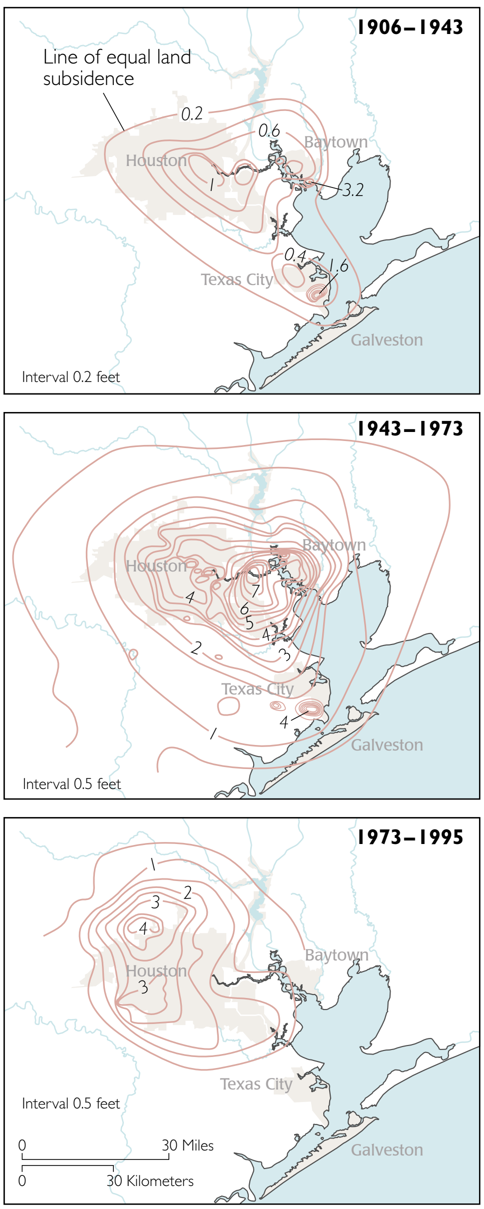
FAULTING FOLLOWED SUBSIDENCE

"…cracks appeared in the ground running beneath houses, across streets, and through lawns and gardens…. recurrent movement along them resulted in dropping the surface of the ground on the side toward the oil field… The movements were accompanied by slight earthquakes which shook the houses, displaced dishes, spilled water, and disturbed the inhabitants generally."

—Pratt and Johnson, 1926

This photograph taken about 1926 shows a 'fault fissure' in Pelley, one-half mile north of the oil fields. To the left of the fault, the ground had dropped about 16 inches.

Subsidence trends reflect patterns of resource development that shifted inland from coastal oil and gas extraction to ground-water extraction for municipal and industrial supplies.



(Harris-Galveston Coastal Subsidence District)

Subsidence trends are related to patterns of ground-water and oil-and-gas extraction

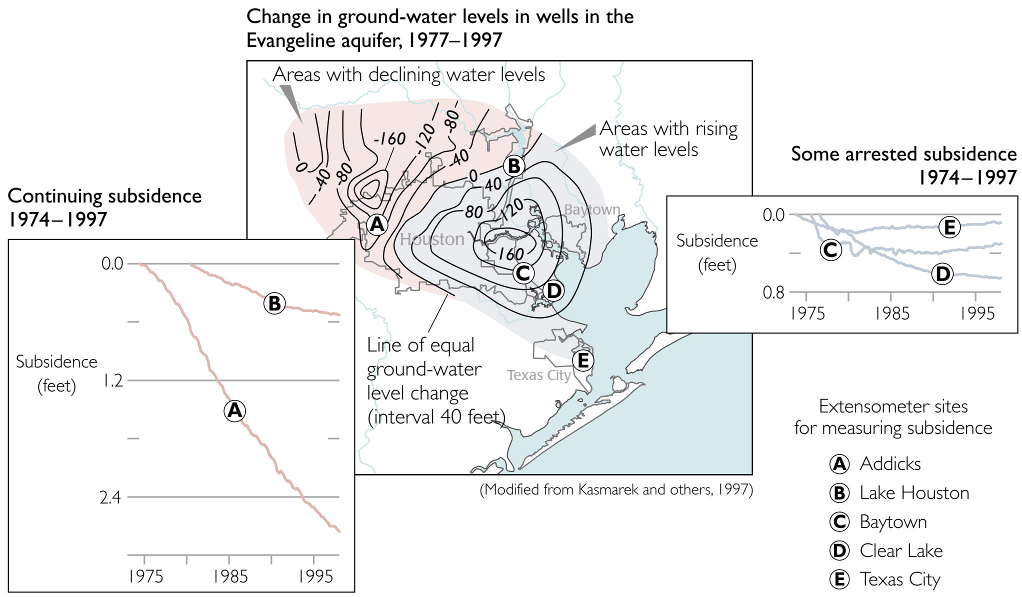
Land subsidence first occurred in the early 1900s in areas where ground water, oil, and gas were extracted and has continued throughout the 20th century due primarily to ground-water pumpage. The patterns of subsidence in the Houston area closely follow the temporal and spatial patterns of subsurface fluid extraction.

Prior to the early 1940s there was localized subsidence caused chiefly by the removal of oil and gas along with the attendant brine, ground water and sand in oilfields such as Goose Creek. Near Texas City the withdrawal of ground water for public supply and industry caused more than 1.6 feet of subsidence between 1906 and 1943. This period also marked the beginning of a slow but steady development of ground-water resources that constituted the sole water supply for industries and communities around the Ship Channel, including Houston. By 1937 ground-water levels were falling in a growing set of gradually coalescing cones of depression centered on the areas of heavy use. Until 1942, essentially all water demand in Houston was supplied by local ground water. By 1943 subsidence had begun to affect a large part of the Houston area although the amounts were generally less than 1 foot.

A period of rapid growth in the development of ground-water resources was driven by the expansion of the petrochemical industry and other allied industries in the early 1940s through the late 1970s. By the mid-1970s, 6 or more feet of subsidence had occurred throughout an area along the Ship Channel between Bayport and Houston, as a result of declining ground-water levels associated with the rapid industrial expansion. During this time, subsidence problems took on crisis proportions, prompting the creation of the Harris-Galveston Coastal Subsidence District. By 1979 up to 10 feet of subsidence had occurred, and almost 3,200 square miles had subsided more than 1 foot.

In the 1940s upstream reservoirs and canals allowed the first deliveries of surface water to Galveston, Pasadena, and Texas City, but ground water remained the primary source until the 1970s. The city of Galveston began converting to surface water supplied from Lake Houston in 1973, and in the late 1970s the cities of Pasadena and Texas City converted to surface water from Lake Livingston, a reservoir on the Trinity River.

Since the late 1970s subsidence has largely been arrested along the Ship Channel and in the Baytown-LaPorte and Pasadena areas due to a reduction in ground-water pumpage made possible by the conversion from ground-water to surface-water supplies. By 1995, total annual ground-water pumpage in the Houston area had declined to only 60 percent of peak amounts pumped during the late 1960s; within the jurisdiction of the Harris-Galveston Coastal Subsidence District, ground-water pumpage constituted only 25 percent of peak amounts. However, as subsidence in the coastal area was stabilizing, The Harris-Galveston Coastal Subsidence District has arrested subsidence along the western margins of Galveston Bay by substituting imported water for ground water. A new challenge is to manage ground-water use north and west of Houston where water levels are declining and subsidence is increasing.



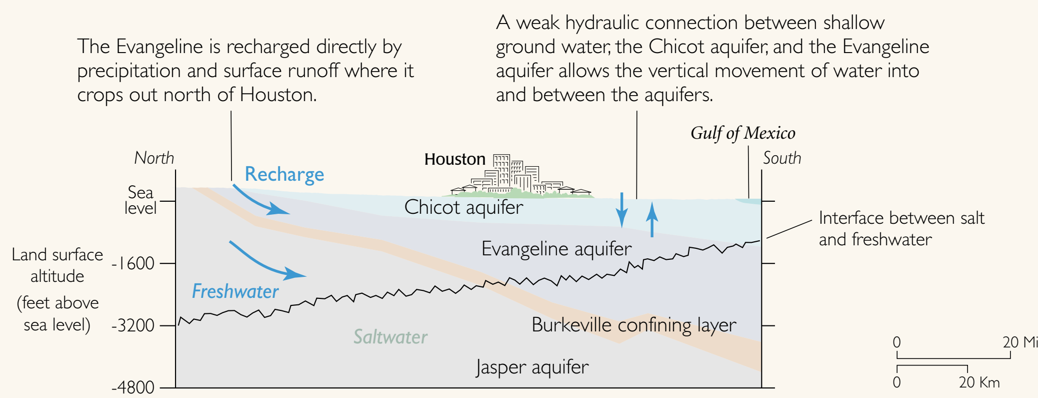
(Modified from Kasmarek and others, 1997)

subsidence inland—north and west of Houston—was accelerating. In this region ground-water levels have declined more than 100 feet in the Evangeline aquifer between 1977 and 1997, and more than 2.5 feet of subsidence was measured near Addicks between 1973 and 1996.

Texas Gulf Coast Aquifer System

The Evangeline aquifer is the principal source of freshwater

Most of the ground water pumped in the Houston-Galveston area comes from the Chicot and Evangeline aquifers—part of a vast coastal aquifer system that extends throughout the margin of the coastal plain of Texas and Louisiana into Florida. Most of the supply wells are completed in the upper 1,000 to 2,000 feet of the aquifers, where freshwater is available. Saltwater, originally in the aquifers and subsequently flushed by freshwater following sea-level recession, now encroaches on deeper portions of the aquifers. An interface between the saltwater and the overlying freshwater slopes landward from the Galveston coast. Historically, saltwater encroachment in both aquifers has been exacerbated by lowered ground-water levels, especially near the coast. Ground-water quality, levels, and aquifer-system compaction are being closely monitored to minimize any detrimental effects related to overdrafting the ground-water supply.



Subsidence increases the frequency and intensity of flooding

In 1983 Brownwood was flooded after hurricane Alicia produced a storm surge up to 11 feet.

(Harris-Galveston Coastal Subsidence District)

Located along a low-lying coast that is subject to tropical storms, the Houston area is naturally vulnerable to flooding. In coastal areas, subsidence has increased the amount of land subject to the threat of tidal inundation. Flooding by tidal surges and heavy rains accompanying hurricanes may block evacuation routes many hours before the storms move inland, endangering inhabitants of islands and other coastal communities. The increased incidence of flooding in coastal areas eventually led to the growing public awareness of subsidence and its costs.

The fate of the Brownwood subdivision of Baytown affords a particularly dramatic example of the dangers of coastal subsidence. Brownwood was constructed, beginning in 1938, as an upper-income subdivision on wooded lots along Galveston Bay (Holzschuh, 1991). At that time the area was generally 10 feet or less above sea level. By 1978 more than 8 feet of subsidence had occurred.

"The subdivision is on a small peninsula bordered by three bays. [It] is a community of about 500 single-unit family houses. Because of subsidence, a perimeter road was elevated in 1974 to allow ingress and egress during periods of normal high tide [about 16 inches], and to provide some protection during unusual high tide. Pumps were installed to remove excess rainfall from inside the leveed area. Because of subsidence after the roadway was elevated, tides of about [4 feet] will cause flow over the road. The United States Army Corps of Engineers studied methods to protect the subdivision from flooding. The cost of a levee system was estimated to be about $70 million. In 1974, the Army Corps estimated that it would cost about $16 million to purchase 442 homes, relocate 1,550 people, and convert [750 acres] of the peninsula into a park. This proposed solution was approved by the Congress of the United States and provided necessary funding. However, the project required that a local sponsor (the City of Baytown) should approve the project, provide 20 per cent of the funds ($3 million) and agree to maintain the park. By the time the first election to fund the project was held on 23 July 1979, the cost estimate had increased to $37.6 million, of which the local share was $7.6 million. The proposal was defeated, and two days later 12 inches of rain fell on Brownwood causing the flooding of 187 homes. Another bond election was held on 9 January 1980 and again the proposal was defeated. Accepting the residents' decision, Baytown officials began planning the sale of $3.5 million worth of bonds to finance the first stage of a fifteen-year, $6.5-million programme to upgrade utilities in the subdivision. Meanwhile, those who own the houses generally also owe mortgages and cannot afford to purchase other homes. Although they continue to live in the subdivision many have to evacuate their homes about three times each year."

—Gabrysch, 1983

Water from Galveston Bay inundated subsiding land and flooded homes in Baytown (1960).

The year that article was published, Hurricane Alicia struck a final blow to Brownwood. All homes in the subdivision were abandoned. Today, most of the subdivision is a swampy area well-suited for waterfowl; egrets and scarlet ibis are often seen.

An abandoned house in the Brownwood subdivision

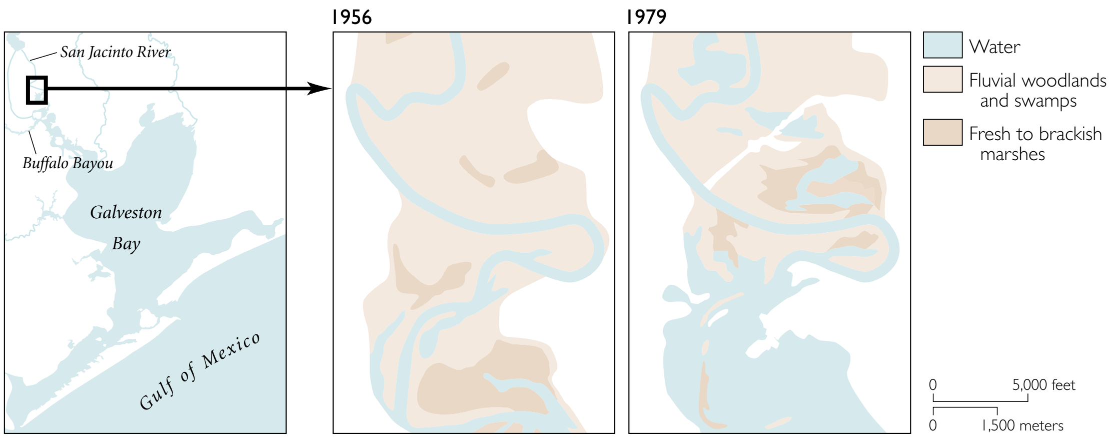
Subsidence also exposes inland areas to increased risks of flooding and erosion by altering natural and engineered drainageways (open channels and pipelines) that depend on gravity-driven flow of storm-runoff and sewerage. Differential subsidence, depending on where it occurs with respect to the location of drainageways, may either reduce or enhance preexisting gradients. Gradient reductions decrease the rate of drainage and thereby increase the chance of flooding by storm-water runoff. Gradient reversals may result in ponding or backflow of sewage and stormwater runoff. In some areas, the drainage gradients may be enhanced and the rate of drainage may be increased. In terms of flooding risk, this may have a beneficial effect locally but an adverse effect downstream. For open channels, the changing gradients alter streamflow characteristics leading to potentially damaging consequences of channel erosion and sediment deposition.

Wetlands are being lost to subsidence

Galveston Bay is one of the most significant bay ecosystems in the Nation. The estuary is Texas' leading bay fishery and supports vibrant recreation and tourism industries. Sixty-one percent of the Bay's 232 miles of shoreline is composed of highly productive fringing wetlands but, mainly because of subsidence, more than 26,000 acres of emergent wetlands have been converted to open water and barren flats (White and others, 1993). Subsidence has also contributed to a significant loss of submerged aquatic vegetation (mostly seagrass) since the 1950s. Some bay shorelines have become more susceptible to erosion by wave action due to loss of fringing wetlands. At the same time, the reduction in sediment inflows to the bay system resulting from construction of reservoirs along tributary rivers slows the natural rebuilding of shorelines. Because of the combined and interrelated effects of relative sea-level rise, loss of wetlands, and reduced sediment supply, the shoreline is eroding at an average rate of 2.4 feet per year (Paine and Morton, 1986). As the water level rises, marsh along the shoreline is drowned. When residential, commercial, or industrial development is located near the shoreline, the potential for the landward migration of marshes is eliminated. The result is a reduction in wetland habitats, which provide the foundation for commercial and recreational fisheries.

The most extensive changes in wetlands have occurred along the lower reaches of the San Jacinto River near its confluence with Buffalo Bayou. This area had subsided by 3 feet or more by 1978, resulting in submergence and changes in wetland environments that progressed inland along the axis of the stream valley. Open water displaced riverine woodlands and swamps. Trends along the lower reaches of other rivers, bayous, and creeks have been similar, resulting in an increase in the extent of open water, loss of inland marshes

Wetlands were lost to inundation resulting from subsidence in the lower reaches of the San Jacinto River.



(White and others, 1993)

Coastal subsidence allows shorelines to move landward causing the demise of some coastal woodlands.

(Galveston Bay Information Center, TAMUG)

and woodlands and, in some areas, the development of new marshes inland from the encroaching waters.

The health and productivity of the bay ecosystem depends on the presence of key habitats like salt marshes, but also on the mix of river and bay water. Many species of fish, wildlife, aquatic plants, and shellfish in Galveston Bay depend on adequate freshwater inflows for survival. The estuary is adapted to highly variable inflows of freshwater. For instance, oysters prefer somewhat salty water, but need occasional surges of freshwater. The volume, timing, and quality of freshwater inflows to the estuary are key factors.

The increasing demand for surface-water supplies, motivated in recent years by efforts to mitigate land subsidence, has led to construction of reservoirs and diversions that have reduced the sediments and nutrients transported to the bay system (Galveston Bay National Estuary Program, 1995). Controlled releases from surface impoundments such as Lake Livingston and Lake Houston have changed the natural freshwater inputs to the bay system; the high flows are lower, the low flows are higher, and peak flows are delayed by about 1 month. As a result, the amount of mineral sediment being delivered by streams to the wetlands has been reduced, limiting some of the natural accretion of wetlands.

Normally, the process of wetland accretion is self-regulated through negative feedback between the elevation of the wetland and relative sea level. When wetland elevations are in balance relative to mean sea level, periodic and frequent tidal inundations mobilize sediment and nutrients in the wetland in a way that favors vegetative growth and a balance between sediment deposition and erosion. Subsidence may upset this balance by submerging the wetland. The drowned wetland cannot support the same floral community, loses its ability to trap sediment as before, and is virtually unregulated by relative sea-level changes. These changes impact the natural processes in the bay and related ecosystems, which evolved with the rhythm of the unregulated streams and rivers.

Subsidence activates faults

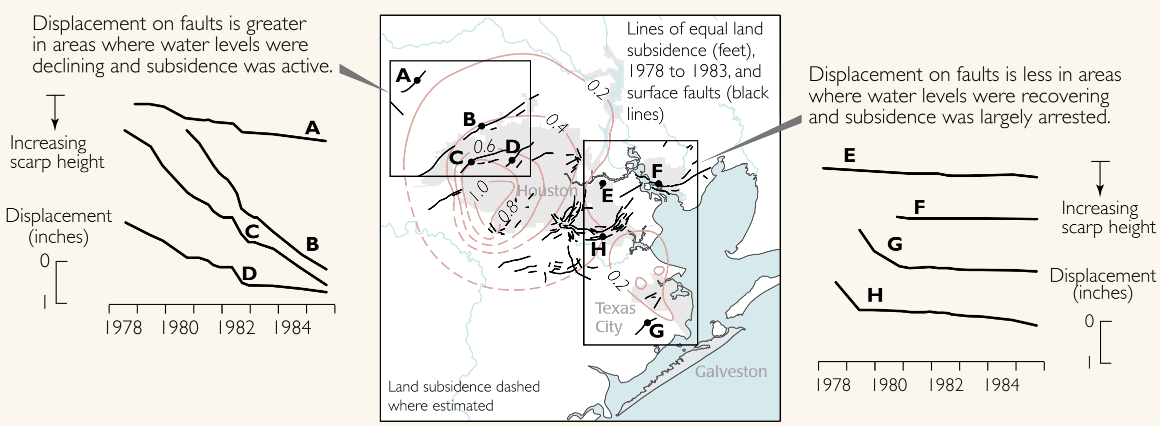
Fault creep related to water-level declines

(Holzer and Gabrysch, circa 1987)

A house in Baytown near Brownwood was damaged by fault creep.

Many faults exist in the Houston-Galveston area, both regional-scale "down-to-the-coast" faults that represent slow sliding of the land mass towards the Gulf of Mexico and local structures associated with oil fields (see sidebar on the Goose Creek oil field) (Holzshuh, 1991). Since the late 1930s, 86 active faults with an aggregate scarp length of about 150 miles have offset the land surface and damaged buildings and highways in the metropolitan area (Holzer and Gabrysch, 1987). The scarps typically grow by seismic creep at rates of up to 1 inch per year (Holzer, 1984). Monitoring of fault creep, water levels, and land subsidence has demonstrated a clear cause-and-effect relation. The fault movement is caused by water-level decline and associated subsidence. In the 1970s, a period of water-level recovery began in the eastern part of the Houston area, due to delivery of imported surface water and associated reduction of ground-water pumpage. Fault creep stopped or slowed in the area of water-level recovery, but continued unabated in the area of ongoing water-level decline.

Vertical displacements at eight selected fault-monitoring sites in the Houston area show a pattern related to water-level declines and land subsidence.



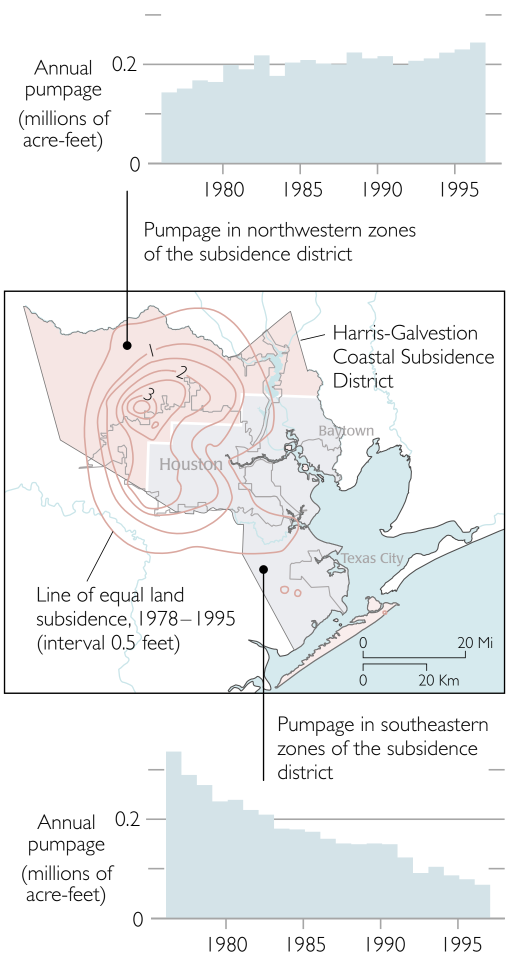
(Holzer and Gabrysch, 1987)

SUBSIDENCE IS ACTIVELY MANAGED

Public awareness of subsidence and its causes increased along with the frequency of coastal flooding. In the late 1960s groups of citizens began to work for a reduction in ground-water use. State legislators became educated about the problem, and in May 1975 the Texas Legislature passed a law creating the Harris-Galveston Coastal Subsidence District, the first district of its kind in the United States. The unprecedented Subsidence District was authorized as a regulatory agency, with the power to restrict ground-water withdrawal by annually issuing or denying permits for large-diameter wells, but was forbidden to own property such as water-supply and conveyance facilities.

Increasing ground-water pumpage landward, west and north of Houston, has caused additional, ongoing subsidence.

In areas to the east and south of Houston, regulatory action by the Harris-Galveston Coastal Subsidence District has reduced ground-water pumpage, thus dramatically slowing subsidence.



(Harris-Galveston Coastal Subsidence District)

The initial (1976) Subsidence District plan recognized the critical situation in the coastal areas and was designed to have an immediate impact there. Surface water from the recently completed Lake Livingston reservoir on the Trinity River was used to convert industry along the Houston Ship Channel from ground water to surface water. Subsidence in the Baytown-Pasadena area soon slowed dramatically. Earlier imports of surface water from Lake Houston on the San Jacinto River, to the east side of Houston, had locally and temporarily halted water-level declines, but were insufficient to keep pace with the growing demand. The additional water supplied from Lake Livingston was sufficient to significantly reduce ground-water use and ultimately did lead to a recovery of water levels over a large area.

In the eastern part of the greater Houston region, near the bay system, subsidence has been controlled by conversion from groundwater to imported surface-water. However, subsidence is accelerating to the west, where ground-water use has increased. Thus, the area of active subsidence has shifted from the low-lying, tide-affected areas towards higher elevations inland.

A devastating flood in 1984 on Brays Bayou, a major watershed in southwest Houston, renewed concern about the effects of subsidence in inland areas. It was recognized that flood control and subsidence control should be coordinated to minimize flood damages. During the 1989 legislative session, the Fort Bend Subsidence District was created to manage and control subsidence in Fort Bend County.

In 1992, the Harris-Galveston Coastal Subsidence District adopted a regulatory action plan to reduce ground-water pumpage by 80 percent no later than the year 2020. Due to the high cost of constructing distribution lines westward across the metropolitan area, the plan was to be implemented in phases, allowing time to design, finance, and construct surface-water importation facilities. The two subsidence districts will cooperate to ensure coordinated planning of the conversion from ground water to surface water.

The direct and indirect costs of subsidence

The low elevation, proximity to bays and the Gulf of Mexico, dense population, and large capital investment make it likely that the Houston-Galveston area has been more significantly impacted by subsidence than any other metropolitan area in the United States. The actual economic cost of subsidence is hard to quantify, and most published estimates are necessarily vague. For example, Gabrysch (1983) stated that "many millions of dollars" have been spent reclaiming land submerged by tidal water, elevating structures such as buildings, wharves and roadways, and constructing levees to protect against tidal inundation; further, "millions of dollars" are spent on repairing damage due to fault movement. One conservative estimate for the period 1969 to 1974 placed the average annual cost to property owners at more than $31,000,000 in 1975 dollars (Jones, 1976) or about $90,000,000 in 1998 dollars.

After the completion of Lake Houston in 1954, water distribution lines were constructed to convey surface water from Lake Houston to the Pasadena industrial area in order to supplement local ground-water supplies.

(Harris-Galveston Coastal Subsidence District)

The costs of such subsidence-related phenomena as the loss of wetlands are even more difficult to assess than property losses. Although some estimates could be made based on the changing value of commercial and recreational fisheries, it would be difficult to distinguish the influence of subsidence from that of other factors. Similarly, some fraction of the ongoing cost of flood prevention and flood-damage repair could fairly be attributed to subsidence.

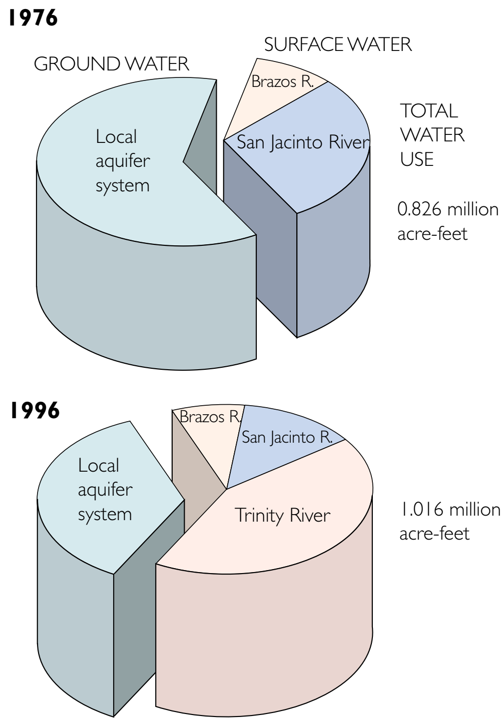
The most definitive published subsidence-damage estimates have to do with the costs of relocating dock facilities, constructing hurricane levees, and rectifying drainage problems at refineries along the Houston Ship Channel. For two refineries alone, the estimated total cost was $120,000,000 in 1976 dollars (Holzschuh, 1991), or about $340,000,000 in 1998 dollars. If these estimates are correct, it seems reasonable to suggest that subsidence-related damage to industrial infrastructure alone may run into the billions of dollars.

USGS hydrologist measures water levels at an extensometer site, which also serves as a Continuous Operating Reference Station equipped with a GPS antenna and receiver to continuously monitor land subsidence.

Ongoing monitoring will help managers plan for the future

Ongoing patterns of subsidence in the Houston area are carefully monitored. Compaction of subsurface material is measured continuously using 13 borehole extensometers (wells equipped with compaction monitors) at 11 sites throughout the region. Piezometers completed to different depths are used to simultaneously monitor water levels. The decreasing subsidence rates observed at sites in the eastern part of the region are a direct result of reducing local ground-water withdrawals through conversion to imported surface-water supplies. In contrast, measurements from the western part of the region reveal continuing subsidence.

A network of 82 bench marks distributed throughout the two subsidence districts was installed in 1987 for determination of elevation changes using the Global Positioning System (GPS). The bench marks were resurveyed using GPS in 1995. The results of the measurements are the basis for the subsidence measured during the 1987 to 1995 period. Continuous Operating Reference Stations (CORS), used to continuously monitor the elevation of three extensometers with GPS, are being maintained by the Harris-Galveston Coastal Subsidence District under the direction of the National Geodetic Survey (NGS). One of the CORS sites is in the NGS Na-



As a percentage of the total, ground-water use has dropped significantly, but total water use is rising.

tional Network. In addition to the fixed locations, portable GPS receivers mounted in trailers are used wherever subsidence measurements are needed. Each portable receiver can operate at up to four different sites each month. GPS is expected to be more cost-effective for monitoring subsidence in the Houston area than constructing additional extensometers or surveying benchmarks using more traditional leveling techniques.

Some controversy attends efforts to gradually achieve conversion to surface water on the north and west sides of Houston, mainly because the imported surface water is expected to cost about twice as much as the ground water that is currently used. Various local municipalities are contesting the timing and apportioning of costs (Houston Chronicle, 27 August 1997, "That sinking feeling hits northwest Houston").

Given the continuing rapid growth of Houston, there is also some long-term concern about securing sufficient surface-water supplies. State and local governments are already at work seeking to ensure that there will be enough water for the expected future population. The primary strategies aim to promote water conservation and acquire supplies from East Texas reservoirs. In addition to the concerns of East Texas communities about water being exported to Houston, such water transfers have ecological effects on the coast and on the waterways through which the water is moved.

The price of water is expected to gradually increase as population and economic growth increase demand. Many farmers will find it difficult to pay higher prices. This may lead to land-use changes in rural communities as farmers find new crops, turn to ranching, or give way to suburban development. Small businesses that support farms will be particularly vulnerable to these changes.

Houston's continuing rapid growth means that subsidence must continue to be vigilantly monitored and managed. However, the region is better-positioned to deal with future problems than many other subsidence-affected areas, for several reasons: a raised public consciousness, the existence of well-established subsidence districts with appropriate regulatory authority, and the knowledge base provided by abundant historical data and ongoing monitoring.

Galveston at sunset

(Harris-Galveston Coastal Subsidence District)

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).

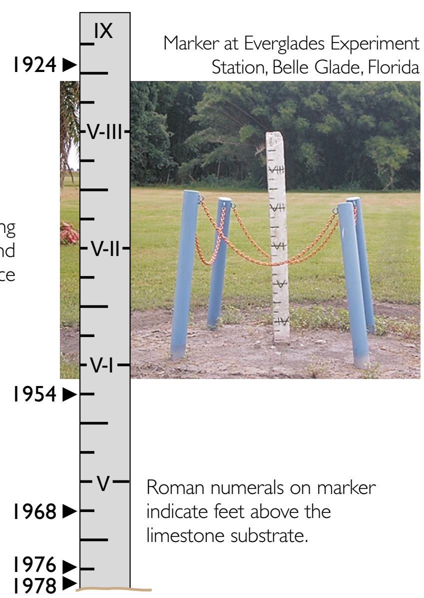
Most organic soils occur in the northern contiguous 48 States and Alaska.

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.



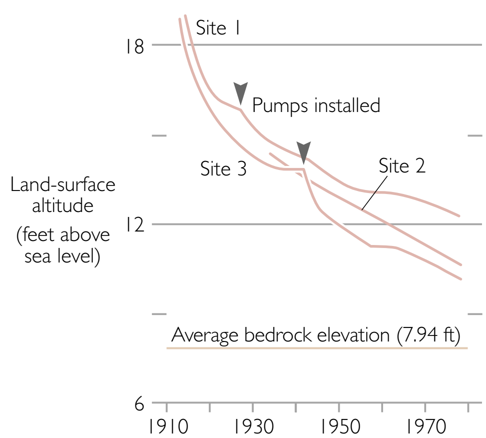
The biochemical origin of much organic-soil subsidence was established by 1930 through laboratory experiments with Florida peat that balanced the loss of dry soil weight with rates of carbon-dioxide production (Waksman and Stevens, 1929; Waksman and Purvis, 1932). This early laboratory work also suggested 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.

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)

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).