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Impacts of land subsidence caused by withdrawal of underground fluids in the United States

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ABSTRACT

Lowering of the land surface of large areas has been a major unintended consequence of groundwater and petroleum withdrawal by humans. Approximately 26,000 km^2 of land in the United States has been permanently lowered. The decrease of land-surface elevation, known as land subsidence, typically occurs at rates measured in centimeters per year. However, the irreversible accumulation of its effects clearly qualifies humans as major geologic agents. Subsidence causes permanent inundation of land, aggravates flooding, changes topographic gradients, ruptures the land surface, and reduces the capacity of aquifers to store water. This paper reviews the mechanism, occurrence and history, impacts, and efforts by society to control land subsidence caused by underground fluid withdrawal in the United States.

Keywords: subsidence, groundwater, aquifer mechanics, earth fissure, aquifer-system compaction.

INTRODUCTION

In 1918, part of the Goose Creek oil field, a small field in southeast Texas, began to disappear slowly beneath the waters of Galveston Bay (Pratt and Johnson, 1926). Although initially an inconvenience to the oil-field operator, the partial submergence of the field eventually prompted the state of Texas to sue for title to the oil. Under Texas law, submerged land and its mineral rights belong to the state. The suit was adjudicated in favor of the defendant on the grounds that the subsidence was an Act of Man, not an Act of God. Although the physical impact of the subsidence at the time was small and localized, it was an ominous foreboding of the capability of humans to modify the landscape by withdrawing underground fluids such as groundwater and petroleum. In ensuing years, as additional oil fields were developed and the capability to pump large quantities of groundwater was enhanced with the introduction of the turbine pump, land subsidence became common in the United States. The elevation of more than 26,000 km^2 of land is estimated to have been permanently decreased by withdrawal of underground fluids (National Research Council, 1991). This paper reviews the mechanism of land subsidence, its occurrence and history, impacts, and efforts by society to control this phenomenon in the United States. It also speculates about potential long-term consequences and the legacy of subsidence for future generations.

MECHANISM

Land subsidence associated with withdrawal of underground fluids from porous granular media is caused by a decrease in the

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volume of the reservoir system. As fluids are withdrawn from porous media, pore-fluid pressures decrease. Because deformation of porous media is controlled by effective stress—the difference between the total stress and pore-fluid pressure—a decrease in pore-fluid pressure causes a decrease of pore volume. This phenomenon is known to hydrologists as compaction (Poland et al., 1972). When effective stress exceeds the yield strength of the granular skeleton of the media, the compaction is permanent and irreversible.

All aquifer systems deform to some extent in response to water-level change. The seasonal cycle of recharge and discharge from unconsolidated heterogeneous aquifer systems typically causes minor elastic (recoverable) expansion and compression (Riley, 1969; Poland and Ireland, 1988; Heywood, 1997) and respective uplift and subsidence (on the order of millimeters to centimeters) of the land surface (Amelung et al., 1999; Hoffmann et al., 2001; Bawden et al., 2001; Lu and Danskin, 2001; Heywood et al., 2002).

In confined aquifer systems, the water supplied to a pumping well is initially derived from deformation of the aquifer system, i.e., expansion of water and compression of the granular skeleton or matrix (Jacob, 1940). In fact, water and matrix compressibilities and porosity determine the storativity of the aquifers and the interbedded and confining aquitards in the aquifer system. Depending on the magnitude of the pressure change and stress history of the aquitards, either elastic (recoverable) or inelastic (unrecoverable) compaction occurs as groundwater drains from the fine-grained aquitards into the coarser-grained aquifers. Aquitards both within and bounding the aquifer system are particularly prone to large compaction because of their compressibility. Typically, matrix compressibility (and therefore storativity) of aquitards is several orders of magnitude larger than the compressibility of coarser-grained aquifers, which in turn is typically much larger than water compressibility. Therefore, much of the water from aquitard storage is derived from deformation of the matrix. Accordingly, aquitard storativity and drainage control the compaction of these aquifer systems and account for most of the land subsidence that accompanies groundwater development of these aquifer systems.

In contrast with aquifer systems, deformation in petroleum reservoirs typically involves significant compaction of sandy intervals. Laboratory investigations (Roberts, 1969) and surveys of deformation in oil wells indicate that sands compact at the higher effective stresses typically encountered in oil fields. The compaction involves crushing of sand grains. Allen and Mayuga (1969) estimated that two-thirds of the compaction at the Wilmington oil field in southern California occurred in reservoir sands; the remainder was in shales.

The effective stress at which deformation in a porous media undergoes the transition from primarily elastic to permanent compaction is known as the preconsolidation stress. This concept was originally proposed by geotechnical engineers to describe the volumetric response of soil to changes of effective stress (Casagrande, 1936). As long as water-level declines remain suffi-

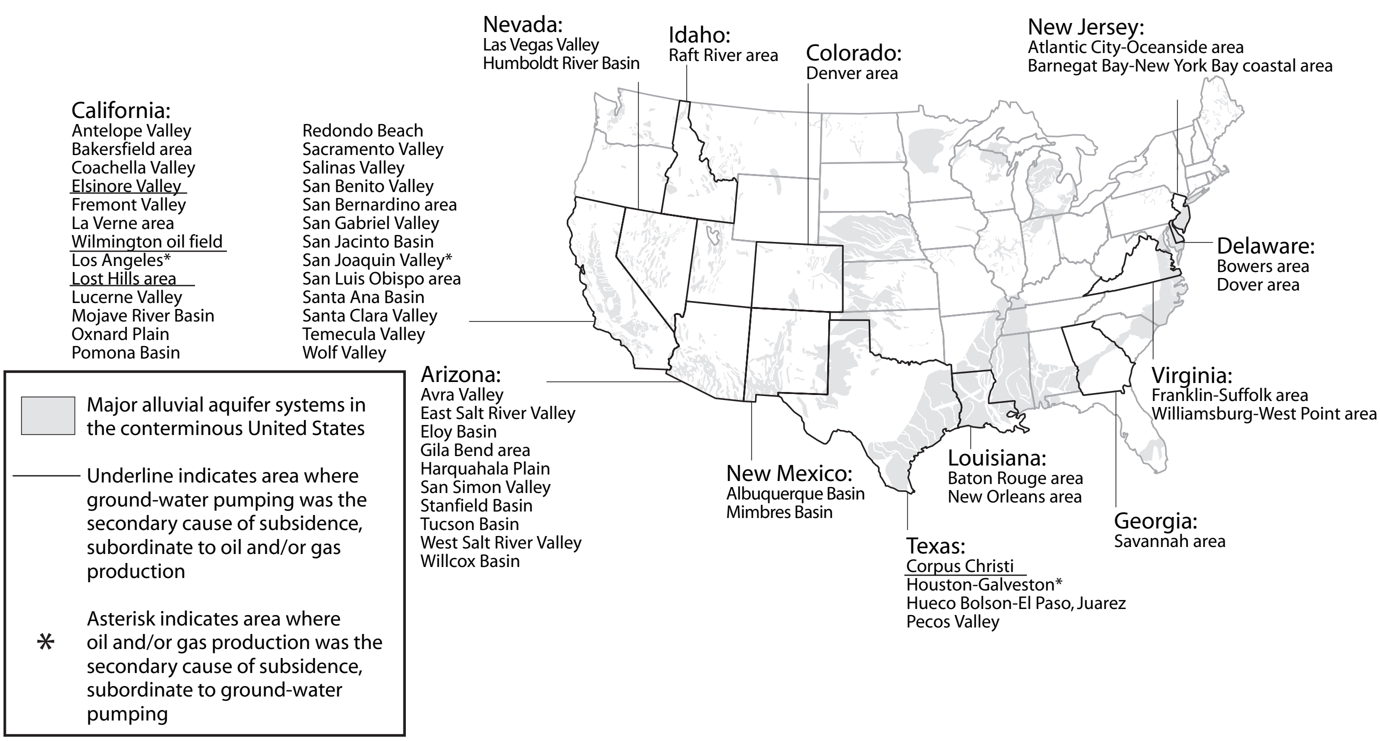

Figure 1. Land-subsidence areas in the contiguous United States (from Galloway et al., 1999).

ciently small that the effective stress does not exceed the preconsolidation stress, compaction will be small. Once effective stress exceeds the preconsolidation stress, however, the compressibility of the aquifer system increases dramatically, typically by a factor of 20–100 (Riley, 1998), and the resulting compaction is largely permanent. Holzer (1981) showed that many aquifer systems in subsidence areas prior to groundwater development had natural preconsolidation stresses that typically required water levels to decline more than 30 m before significant subsidence could begin. Riley (1969) documented that human-induced water-level declines further increase the preconsolidation stress of an aquifer system. By plotting compaction versus changes of effective stress (i.e., water-level decline), he demonstrated that seasonal water-level decline and the resulting compaction incrementally increase the preconsolidation stress of the aquifer system. Thus, if water levels fully recover in a previously developed aquifer and then decline again, significant compaction and subsidence will not reinitiate until the new preconsolidation stress is exceeded.

Compaction of an aquifer system is not instantaneous and may take years and even centuries to complete. The delay is caused by the time required for drainage of fine-grained beds in aquifer systems to reach equilibrium. When an unconsolidated heterogeneous aquifer system is developed as a groundwater resource, most of the produced groundwater is derived initially from storage in the aquifers, the more permeable interbeds, and the outer portions of thicker and confining aquitards. After pumping has lowered heads in the aquifers, vertical gradients of head are established between the aquifers and the interior portions of the thicker or less permeable aquitards, and groundwater is induced to flow from the aquitards to the aquifers. The theory of hydrodynamic consolidation (Terzaghi, 1925), which was developed in soil engineering, is widely used to describe this delay in drainage of the compressible aquitards (Riley, 1969; Helm, 1975, 1976). This theory also accounts for the observed residual compaction of the aquitards that may occur long after drawdown in the aquifers has essentially stabilized.

Pore water released from storage by compaction potentially is a large nonrenewable resource. It is not replaced if water levels subsequently recover because compaction at stresses greater than the preconsolidation stress are irreversible. This water can be a significant percentage of the total pumpage. For example, Lofgren (1975) estimated that 40% of the water pumped from the middle of the Arvin-Maricopa subsidence bowl in the southern San Joaquin Valley, California, was derived from permanent compaction of the aquifer system. This water is known as "water of compaction."

Occurrences of Land Subsidence in the United States

Withdrawal of underground fluids from clastic sediments has permanently lowered the elevation of ~26,000 km^2 of land in the contiguous United States (Fig. 1). This is about equal to the area of the state of Massachusetts, and clearly qualifies humans as major geologic agents. Most of the subsidence has been caused by withdrawal of groundwater and is concentrated in the San Joaquin Valley of central California and the greater Houston area of southeast Texas (Figs. 2 and 3). The largest subsidence area is in the San Joaquin Valley. Nearly half of the valley, more than 13,000 km^2, has subsided at least 0.3 m (Poland et al., 1975). However, at least 45 areas in 12 states in the United States have experienced land subsidence (Galloway et al., 1999). Most of these areas are in the southwestern United States, particularly in sedimentary basins in Arizona and California.

Maximum magnitudes of subsidence in the United States are as impressive as the total area of subsided land. Maximum measured subsidence is 9 m, which occurred in the San Joaquin Valley from 1925 to 1977 (Ireland et al., 1984). The location where this subsidence occurred is shown in the photograph in Figure 4. Placards on the telephone pole indicate the former elevation of

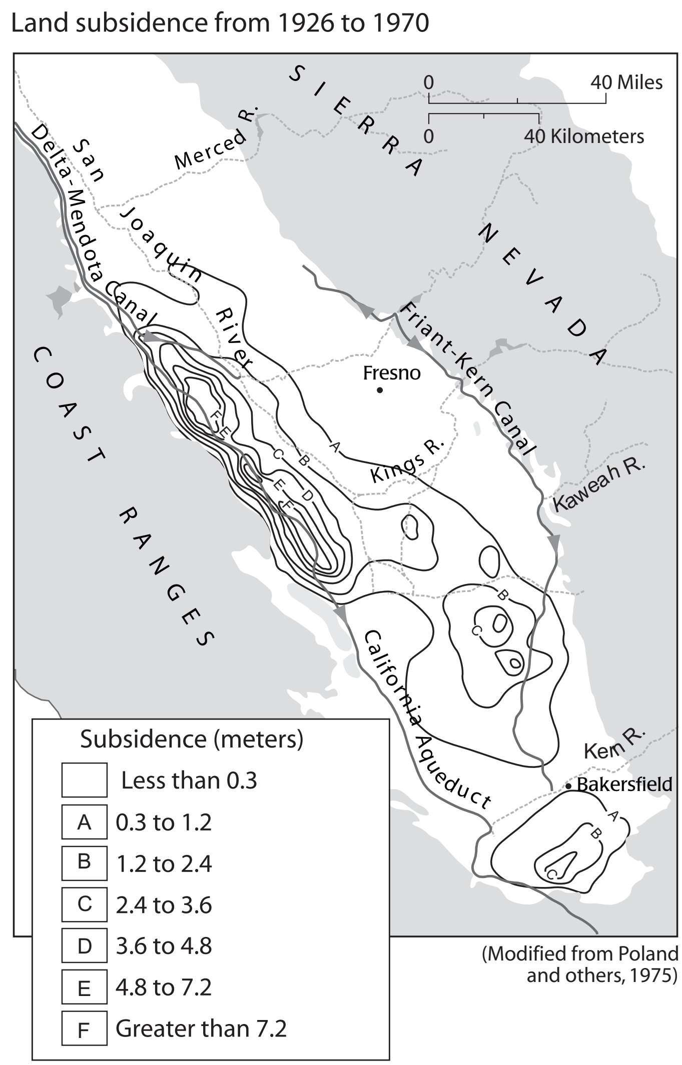

Figure 2. Map of San Joaquin Valley, California, subsidence, 1926–1970 (modified from Poland et al., 1975).

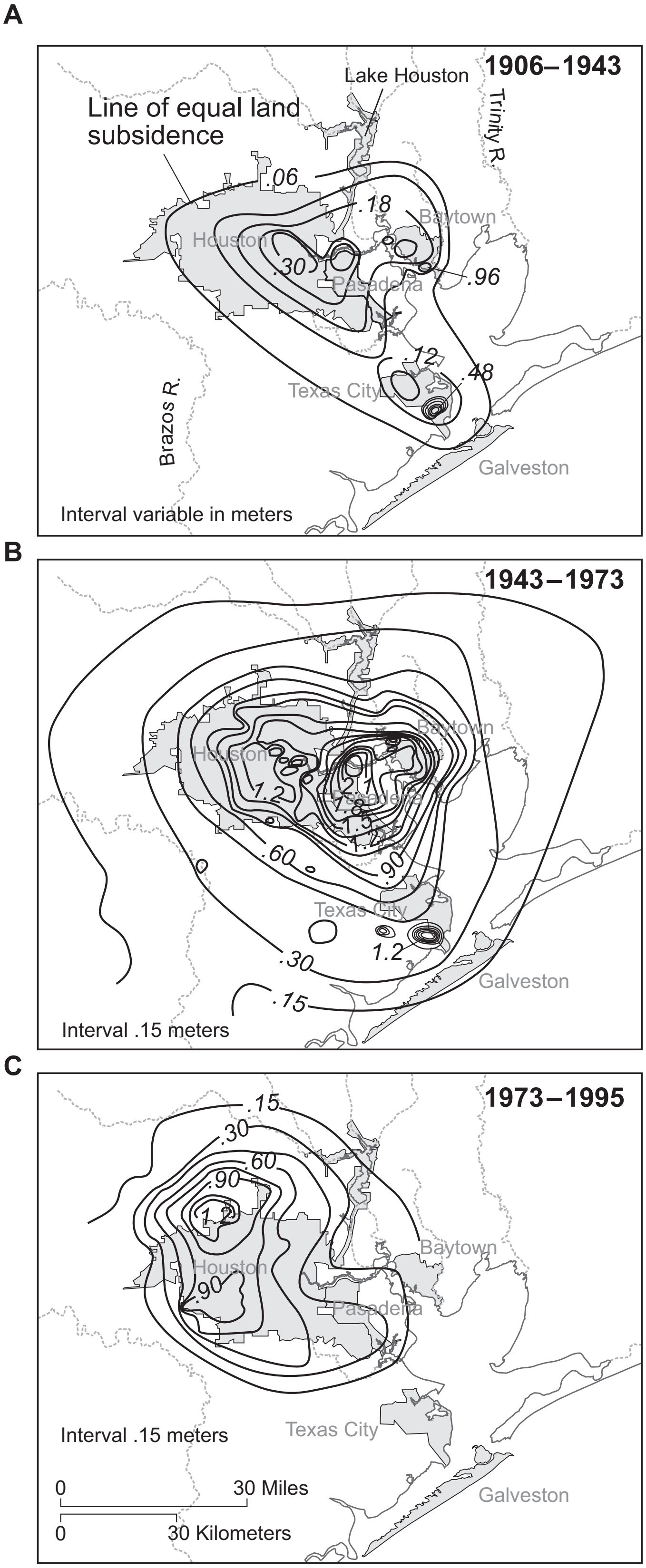

Figure 3. Map of subsidence in the greater Houston, Texas, metropolitan region. A: 1906–1943. B: 1943–1973. C: 1973–1995 (modified from Galloway et al., 1999).

the land surface. This value slightly exceeds the maximum subsidence of 8.8 m measured at the Wilmington oil field in Long Beach, California (Mayuga, 1970).

Land subsidence caused by groundwater withdrawal typically is associated with aquifer systems that consist of unconsolidated to semiconsolidated deposits of late Cenozoic age (Poland and Davis, 1969). In general, subsidence in areas underlain by these deposits can be anticipated where water-level declines are greater than ~30 m, which cause the preconsolidation stress to be exceeded (Holzer, 1981). Where the preconsolidation stress is not exceeded, subsidence remains small and recoverable. Preconsolidation of aquifer systems also explains why subsidence did not become ubiquitous until the twentieth century. It was not until the modern high-capacity turbine pump was introduced that humans could cause large regional water-level declines.

Figure 4. Approximate point of maximum subsidence in the San Joaquin Valley, California. Land surface subsided ~9 m from 1925 to 1977 due to aquifer-system compaction. Signs on the telephone pole indicate the former elevations of the land surface in 1925 and 1955. Photograph by Richard Ireland.

The first recognized subsidence caused by groundwater withdrawal in the United States was in the Santa Clara Valley in California (Tolman and Poland, 1940). In the first half of the twentieth century, the valley was intensively cultivated and relied heavily on groundwater. After World War II, from 1945 to 1970, rapid population growth changed the local economy from agricultural to industrial and urban. The history of subsidence in the Santa Clara Valley is closely related to the major factors that affected the demand on the groundwater system: population growth, changing land use, and importation of surface water (Ingebritsen and Jones, 1999). Most of the subsidence occurred in the northern part of the valley adjacent to San Francisco Bay. The maximum subsidence is near downtown San Jose, where more than 4 m of subsidence occurred between 1910 and 1995. About 65% of it occurred from 1934 to 1967 (Fig. 5). In total, ~44 km^2 of land adjacent to the bay subsided ~0.5–2.5 m, placing it at risk at high tide. Fowler (1981) estimated that direct costs of the subsidence were more than $131,100,000 in 1979 dollars ($332,000,000 in 2003 dollars). He included the cost of constructing levees around the southern end of San Francisco Bay and the bayward ends of stream channels, maintaining salt-pond levees, raising grades for railroads and roads, enlarging or replacing bridges, increasing the capacity of sewers and adding sewage pumping stations, and constructing and operating storm-drainage pumping stations. He also estimated that 1000 wells were damaged or destroyed from 1960 to 1965.

The largest urban area in the United States affected by land subsidence is the greater Houston, Texas, metropolitan region. Despite widespread petroleum production, most of the subsidence is caused by groundwater withdrawal (Holzer and Bluntzer, 1984). Groundwater was developed by the 1940s in Houston to meet a growing public and industrial water demand, especially near Galveston Bay and the Houston Ship Channel. By 1979, subsidence had locally exceeded 3 m, and more than 8000 km^2 of land had subsided at least 0.3 m. Figure 3 shows the subsidence patterns from 1906 to 1995, which indicate that the recent subsidence has shifted spatially from near the bay to inland areas north and west of Houston (Coplin and Galloway, 1999; Stork and Sneed, 2002; Galloway et al., 2003).

Subsidence is also widespread in the intermontane valleys of south-central Arizona, although it is not as contiguous as the subsidence in the San Joaquin Valley and the greater Houston metropolitan region. Subsidence first became apparent during the 1940s in areas where large quantities of groundwater had been pumped to irrigate crops (Carpenter, 1999). Affected areas also include metropolitan Phoenix and Tucson as well as adjacent agricultural areas (Fig. 6). By 1980, groundwater levels had declined at least 30 m in the subsidence-affected areas, and locally had declined 100–150 m. By 1992, maximum subsidence was ~6 m at Luke Air Force Base, ~30 km west of Phoenix (Schumann, 1994).

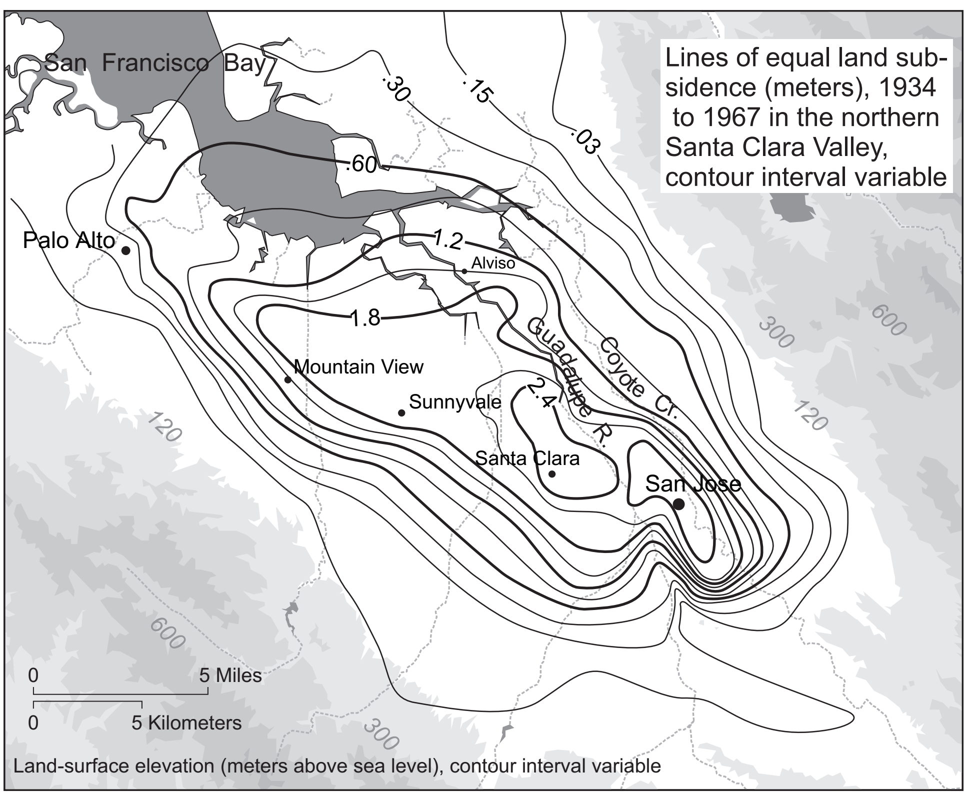

Figure 5. Map of subsidence in the Santa Clara Valley, California, 1934–1967 (modified from Poland and Ireland, 1988).

IMPACTS OF LAND SUBSIDENCE

Loss of Elevation

Flooding caused by loss of elevation and changes of topographic gradients are the most costly impacts of land subsidence. Not surprisingly, flooding is most severe where land subsides adjacent to water bodies, particularly in coastal regions. This causes either permanent submergence or more frequent flooding. Changes of topographic gradients occur where loss of elevation is not uniform.

The most pernicious aspect of flooding associated with land subsidence is the permanent inundation of land near water bodies. Typically, this impact is most severe in coastal regions where small amounts of subsidence may cause the elevation of low-lying land to fall below sea level. Because these regions also are commonly subject to tidal surges, loss of land-surface elevation may increase the frequency and magnitude of intermittent coastal flooding of low-lying coastal land. The most conspicuous examples of coastal subsidence in the United States are in Long Beach, California, the greater Houston, Texas, metropolitan region, and Santa Clara Valley, California.

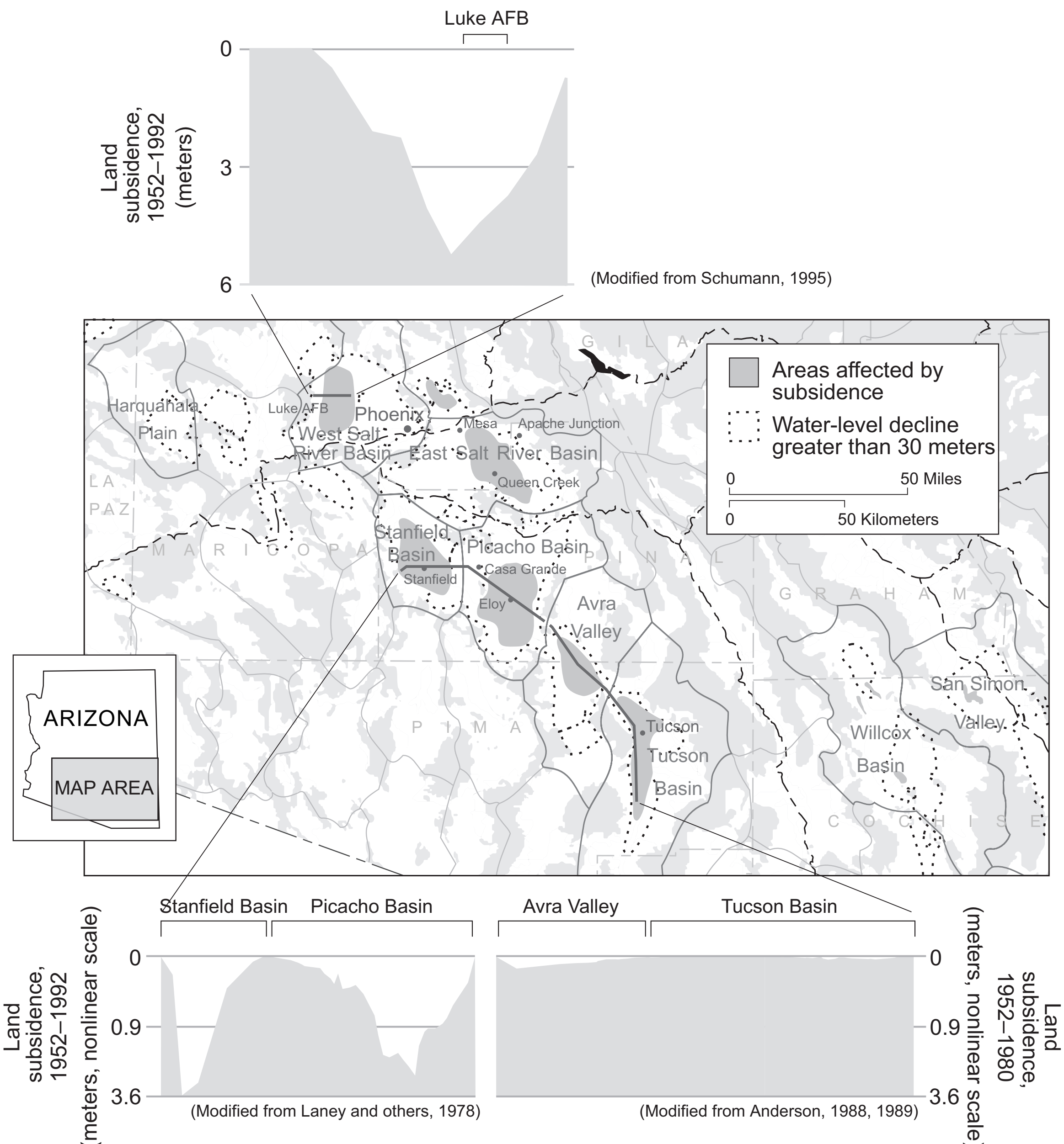

Figure 6. Map of areas of subsidence and groundwater-level decline in south-central Arizona.

In Long Beach, California, oil and gas production from the Wilmington oil field caused more than 50 km^2 of land to subside. Maximum subsidence was 8.8 m. Subsidence affected ~64 km of waterfront and endangered port and U.S. Navy facilities. If remedial measures had not been taken, ~13 km^2 of urban real estate would have been inundated.

In the greater Houston metropolitan region, more than 80 km^2 of low-lying coastal land has been permanently inundated, which has forced houses to be abandoned (Fig. 7). In addition, low-lying parts of the coastal region are now potentially subject to more frequent and severe flooding during high tides and storm surges associated with tropical storms and hurricanes.

In the Santa Clara Valley, as previously noted, ~44 km^2 of coastal land was lowered and would have been inundated by San Francisco Bay if levees had not been constructed to protect the land (Fig. 8). As in the greater Houston area, some areas in the Santa Clara Valley around the southern end of the bay, which are not protected by dikes, are now subject to intermittent flooding because of elevation loss.

Although subsidence-caused flooding in the three coastal regions described above is relatively well documented, contributions of subsidence to inland flooding are suspected but poorly documented. Concerns are based on observed alterations of topographic gradients, particularly along stream channels. Fremont Valley in southern California perhaps offers the most unambiguous example of inland flooding caused by subsidence. Subsidence caused by groundwater withdrawal has been documented by Pampeyan et al. (1988). The flooding occurs around the margins of Koehn Lake, a playa or intermittent lake in the northeastern part of the valley. The flooding occurs because differential subsidence has tilted the playa. Now when surface water ponds on the playa, it also floods the area southwest of the playa (Fig. 9). As with coastal flooding, flooding of the southwestern shore of Koehn Lake is a permanent hazard.

The design of the California Aqueduct in the San Joaquin Valley is a well-documented example of the impact of changes of topographic gradients. Awareness of the large magnitudes of subsidence near the proposed route of the aqueduct prompted studies of potential differential subsidence along alternative routes. Estimated costs of design modifications and rehabilitation resulting from subsidence caused by groundwater withdrawal were \$13 million (\$23 million in 2003 dollars) (Prokopovich and Marriott, 1983). Ironically, many years after completion of the aqueduct, satellite-based synthetic aperture radar interferometry detected substantial subsidence at the Belridge oil field that narrowly missed the aqueduct (Fielding et al., 1998).

Finally, as noted in the "Mechanism" section, compaction and the resulting loss of elevation may take long periods of time to complete because fine-grained layers drain slowly. Analyses of records from vertical extensometers—instrumented wells that continuously monitor compaction and water levels in aquifer systems—reveal that compaction may take decades if not centuries to complete where compressibilities are large and permeabilities are small. Thus, even if water levels stop declining in a subsiding region, the subsidence may continue for many years (for example, Riley, 1998; Sneed and Galloway, 2000). While best documented in aquifer systems, delayed compaction may also be important in petroleum reservoirs (Baú et al., 1999).

Figure 7. Abandoned house in the Brownswood subdivision in Baytown, Texas, in the Houston metropolitan region. Pumping of groundwater caused land to subside below Galveston Bay. Photograph by Charles W. Kreitler, 1975.

Ground Failure

During the 1960s, many geoscientists became intrigued by an earthquake sequence at the Rocky Mountain Arsenal northeast of Denver, Colorado (Evans, 1966). Injection of contaminated wastewater into a deep disposal well had activated faults. The experience suggested a potential method to control earthquakes; fluids could be either pumped from or injected into fault zones to modify effective stresses (Pakiser et al., 1969). Ironically, humans unwittingly had already begun an aseismic fault experiment in the greater Houston subsidence area of southeast Texas. Pumping of groundwater there was causing offsets on what ultimately would be more than 86 faults at the land surface with a cumulative length of more than 240 km. These faults, which grow by aseismic creep, have wracked and destroyed many houses, buildings, and buried utilities (Fig. 10). Today, surface faults are associated with land subsidence in at least five areas in the United States. The density of faults varies greatly from area to area, but is highest in the greater Houston, Texas, and Fremont Valley, California, subsidence areas (e.g., see Holzer, 1984).

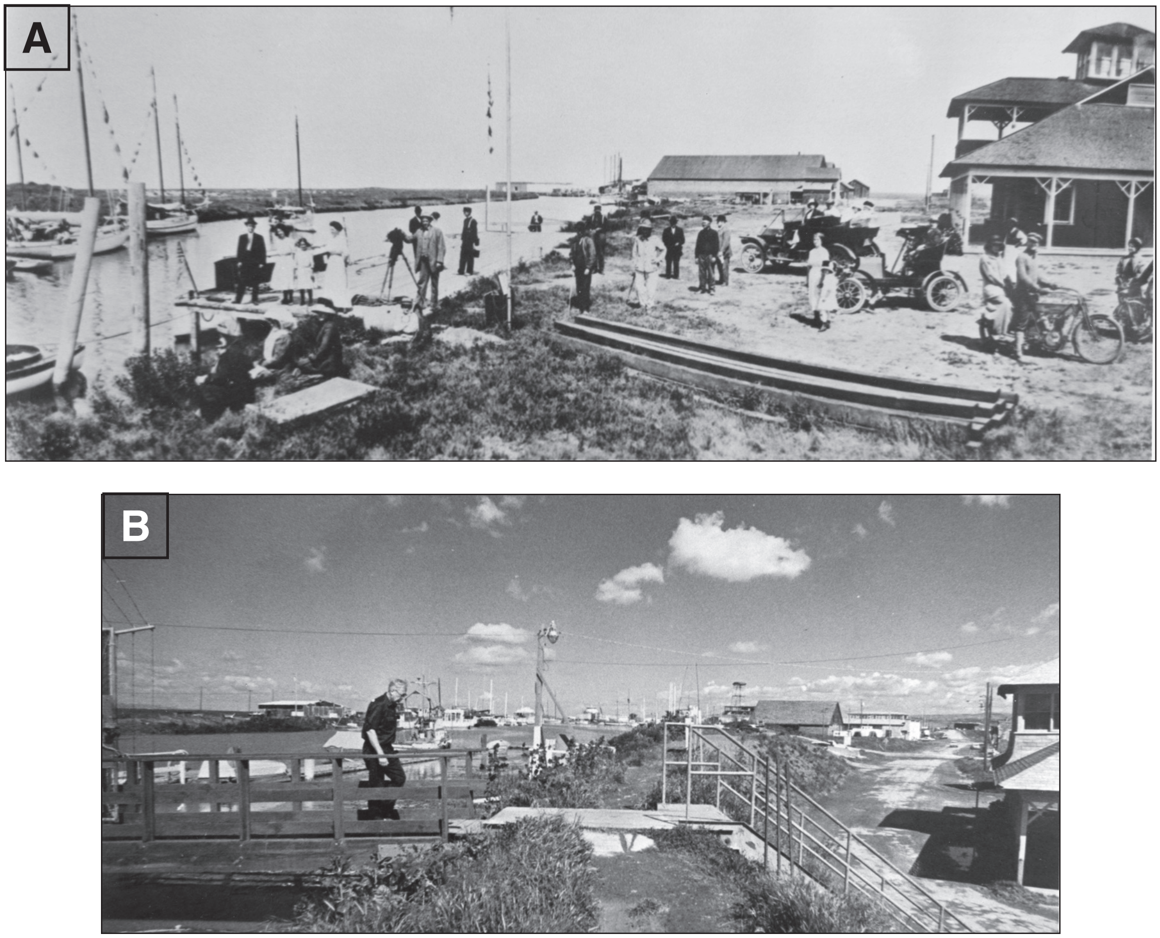

Figure 8. Alviso Yacht Club, Santa Clara Valley, California, in 1914 (A) and 1976 (B). Approximately 2 m of subsidence occurred at this site from 1934 to 1967. Photographs from archives of Alviso Yacht Club.

Figure 9. Local flooding of shore of Koehn Lake playa, Fremont Valley, California. Differential subsidence of playa caused by pumping of groundwater displaced ponded water to the left. Merged by John Evans from two photographs by Thomas L. Holzer, March 1978.

Scarps formed by these faults resemble those caused by tectonism, and the two can be confused, particularly because both typically form along preexisting geologic faults. Scarps commonly are more than 1 km long and 0.5 m high. The longest reported scarp is 16.7 km (Verbeek et al., 1979). Scarps range from discrete shear failures to narrow, visually detectable flexures. They grow in height by creep. Observed creep rates in the Houston area range from 4 to 27 mm/yr, which is typical of these faults. The fastest observed creep rate is 60 mm/yr on the Picacho fault in central Arizona (Holzer, 1984). Neither sudden offset nor seismicity is observed on these faults. Detailed monitoring of differential vertical displacements across a few faults reveals that creep rates of individual faults vary with seasonal fluctuations of water level. In addition, long-term changes in creep rate, including its cessation when water-level declines stop, have been reported (Holzer and Gabrysch, 1987). Only dip-slip displacements have been observed. The sense of faulting is high-angle and normal on the basis of measured ratios of horizontal to vertical displacement and field evidence.

In addition to surface faults, earth fissures—large tension cracks—are commonly associated with subsidence caused by groundwater withdrawal (Holzer, 1984). Field studies indicate the tension is caused by bending of the surface layer resulting from localized differential subsidence (Jachens and Holzer, 1982; Holzer, 2000), although others have speculated on theoretical grounds that the tension is caused by horizontal strains in the aquifer (Sheng et al., 2003). Fissure zones are commonly hundreds of meters long, but may attain lengths as great as 3.5 km (Holzer, 1980). Fissures typically are enlarged by erosion into wide, deep gullies; gully widths of 1–2 m and depths of 2–3 m are commonplace (Fig. 11). Much of the eroded material is transported down into the fissure. Because the inferred crack openings are only a few centimeters, this suggests the cracking extends to great depth. The deepest reported open depth is 25 m (Johnson, 1980). Like surface faults, tension cracks open by slow creep (Holzer, 2000). As a result, they may undergo repeated episodes of erosional enlargement.

Earth fissures occur in at least 18 unconsolidated sedimentary basins in 12 areas in the western United States. The density of fissures varies greatly between areas. In some places only a few

Figure 10. House wracked by surface faulting in Baytown, Texas, near Houston. Faulting here is manifested by flexure of land surface. Photograph by Thomas L. Holzer, October 1983.

Figure 11. Earth fissure associated with land subsidence caused by pumping of groundwater in Fremont Valley, California. Photograph by Thomas L. Holzer, March 1978.

isolated fissures have formed, whereas elsewhere, many fissures occur. Four distinct hazards are posed by fissures: (1) ground displacements associated with their formation, (2) deep, steep-walled gullies by postfissure erosion, (3) interception of surface runoff, and (4) erosion of land near the fissure. Although horizontal displacements across fissures during their formation are small, they are sufficient to damage rigid engineered structures. In addition, differential vertical displacements in narrow zones near fissures may affect structures whose operation is sensitive to small tilts. Gullies associated with fissures are commonly large enough to trap and injure livestock and other animals as well as pose a potential hazard to people. Fissures also serve as conduits for large quantities of water. Consequently, they are potential hazards to water-conveyance structures such as canals. Because of their depth, fissures can also serve as conduits or preferential flow paths for contaminants from the surface into shallow aquifers. Finally, fissures can be sinks for a large volume of sediments. Their formation may locally trigger severe erosion and create badlands topography near the fissure (Fig. 12).

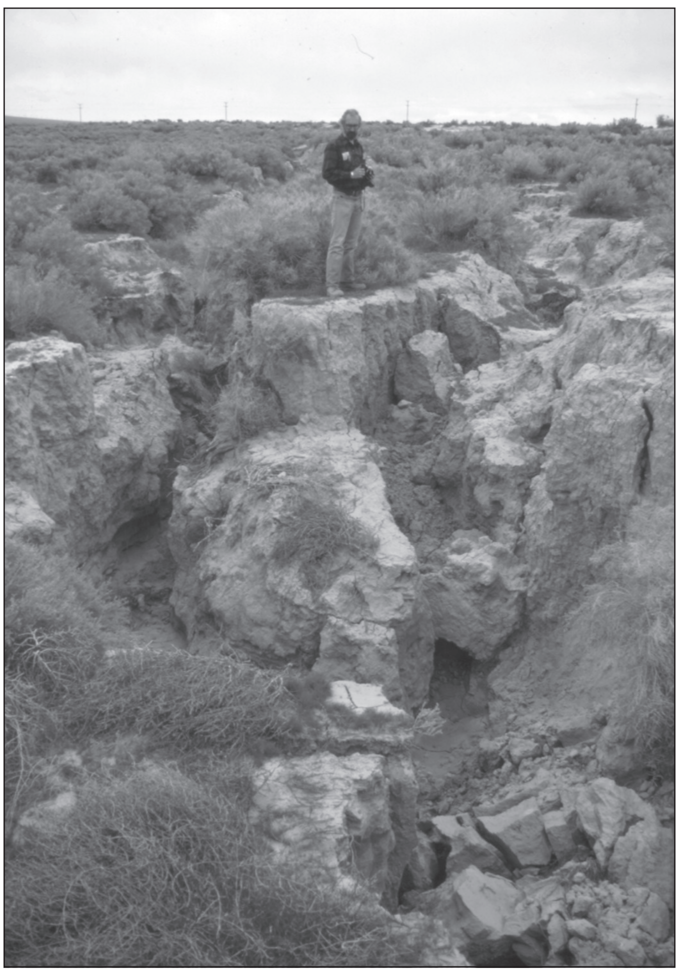

Figure 12. Erosion adjacent to earth fissure in Fremont Valley, California. Photograph by Thomas L. Holzer, March 1983.

Although groundwater withdrawal is the most pervasive cause of ground failure, the most spectacular and costly single incident was caused by petroleum withdrawal. On December 14, 1963, the dam of the Baldwin Hills Reservoir in Los Angeles, California, failed by piping along a fault on which movement had been induced by petroleum withdrawal (Castle and Yerkes, 1976). The catastrophic release of 946,000 m^3 of water killed five people, damaged or destroyed 277 houses, and caused property damage of $12 million in addition to the loss of the reservoir (Hamilton and Meehan, 1971).

Reduction of Aquifer Storage

An inevitable consequence of land subsidence is the permanent, albeit modest, reduction of the capacity of aquifer systems to store groundwater. As noted in the "Mechanism" section, land subsidence is predominantly caused by irreversible compaction of the aquifer system. An implication of this irreversibility is that the capacity of the aquifer system to store groundwater is reduced—pore space is lost forever once water levels have declined in an aquifer system and it has compacted. Thus, if groundwater levels recover to former levels, the volume of water that can reenter the pore space will be smaller than the volume that was originally stored in the aquifer.

If water levels recover in an aquifer system that has compacted, and then the aquifer is pumped again at similar rates, water-level drawdown will be more rapid than during the first cycle of water-level decline. This effect was widely observed during a drought in 1976–1977 in subsidence areas in the San Joaquin Valley, California (Ireland et al., 1984). The heavy pumping and long-term drawdown that caused the subsidence ended in the 1960s when surface water became available. This allowed water levels in the aquifer system to recover by the time of drought. When heavy pumping resumed during the drought, water levels declined 10–20 times as rapidly as when groundwater was pumped for the first time from the aquifer system.

Potential Long-Term Crustal Deformation

While most investigations of land subsidence properly focus on loss of elevation associated with aquifer compaction, Holzer (1979) proposed that there may be a millennia-long legacy associated with land subsidence that would qualify humans as agents of crustal deformation. The hypothesis was based on the discovery of a 6 cm upward displacement of the crust in the general area where land subsidence was occurring. The discovery was possible because the aquifer system in central Arizona consists of sedimentary basins that are partially surrounded by outcrops of bedrock. Holzer noted that the elevation measured at benchmarks on outcrops had not remained fixed. In fact, benchmarks on bedrock outcrops in the middle of the region containing the subsiding basins indicated the bedrock had risen as groundwater was removed by pumping and subsequent evapotranspiration by irrigated crops. He concluded that the uplift was caused by elastic expansion of Earth's crust in response to the removal of 43.5×10^{12} kg of groundwater from central Arizona. (This mass is comparable to the mass of surface water impounded by dams in large water reservoirs where comparable, but downward, crustal displacements have been detected.) Holzer (1979) speculated that large areas of subsidence may experience isostatic uplift over the subsequent several thousand years because the mass of water associated with the reduction of pore volume causing the land subsidence is permanently removed. He estimated that isostatic uplift would equal ~30% of the average subsidence if complete isostatic compensation were to occur.

SOCIETAL RESPONSE

Institutional mechanisms to control land subsidence have been developed and applied in three urban areas in the United States where its impacts became intolerable. These areas are Long Beach, California; the greater Houston, Texas, metropolitan region; and the Santa Clara Valley, California (Holzer, 1989).

In 1958, the state of California passed the California Subsidence Act to control the subsidence caused by production of oil and gas from the Wilmington oil field in Long Beach, California. The act empowers the State Oil and Gas Supervisor to unitize an oil field, i.e., place it under a single operator, in order to repressure reservoirs and thereby ameliorate subsidence in areas prone to inundation. Although compliance with the law was voluntary at the Wilmington oil field, threat of its implementation prompted operators to cooperate and inject fluids into reservoirs to maintain pressures. A collateral benefit of the cooperation of the oil-field operators was that productivity of the oil field improved. Today, operators of the Wilmington oil field continue to monitor and maintain reservoir pressures at levels that prevent resumption of subsidence.

In response to the flooding problem and accompanying pressure from citizens in the greater Houston area, the state of Texas authorized the formation of the Harris-Galveston Coastal Subsidence District in 1975 with authority to regulate pumping of groundwater through a permitting process. The objective of awarding permits, according to the district's charter, is to reduce groundwater withdrawal to an amount that will restore and maintain the artesian pressure in the aquifer sufficient to arrest land subsidence (Holzer, 1989). Actions by the district have significantly reduced pumping in the coastal region and allowed water levels to recover and subsidence to stop. Withdrawals are now concentrated inland where subsidence is less consequential.

Although subsidence in the Santa Clara Valley, California, increased the flood hazard along the margins of San Francisco Bay and damaged many water wells, these problems did not prompt an effort to stop it. Control of subsidence was a collateral benefit of the effort to reduce the regional groundwater overdraft. In 1929, the Santa Clara Valley Water Conservation District was chartered under California State law to mitigate the overdraft. The district initiated recharge efforts and imported surface water. Today, the threat of subsidence is considered in the overall management of the valley's water resources.

OTHER ANTHROPOGENIC CAUSES OF SUBSIDENCE

Although this paper emphasizes land subsidence in the United States caused by withdrawal of underground fluids from porous granular media, humans have also caused widespread and significant elevation loss by other processes. As measured by area affected, mining of coal and minerals, drainage of organic soils, and diversion of sediment from marshes in the delta of the Mississippi River are the most significant. Collectively, the impacts from these processes rival those from withdrawal of underground fluids. The National Research Council (1991) estimates that ~8000 and 9400 km^2 of land, respectively, have subsided because of mining and drainage of organic soils. While the mining subsidence is widespread and mostly associated with coal extraction, the organic soil subsidence is concentrated in two areas, the Florida Everglades and the San Joaquin–Sacramento River delta, California (National Research Council, 1991; Galloway et al., 1999). The ongoing submergence of land in coastal Louisiana, however, is one of the most dramatic and challenging subsidence problems in the United States. The diversion of sediment from the marshlands in the Mississippi River delta has contributed to a phenomenon known as "land loss" (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Authority, 1998). In excess of 104 km^2 of Louisiana coastal marshlands has disappeared annually on average over the past 50 yr—about one acre every 20 minutes. Although the cause of this land loss is complex, major contributors include ongoing natural subsidence of the delta, rising sea level, and diversion of replenishing sediment (Burkett et al., 2003). Formerly, sediment from the Mississippi River was deposited in the marshlands during flood stages and compensated for the loss of elevation caused predominantly by natural subsidence. However, retention of sediment behind upstream dams on the river and diversion of the remaining sediment directly into the Gulf of Mexico because of levees that confine the river have stopped most of this compensation. As a result, a vast coastal ecosystem in southern Louisiana is endangered by the inability of the marshes to maintain their surface elevation.

CONCLUSIONS

Withdrawal of groundwater and petroleum by humans has had a major impact on the landscape and aquifer systems. Subsidence has caused permanent inundation of land, aggravated flooding, changed topographic gradients, ruptured the land surface, and reduced aquifer storage. In the United States, ~26,000 km^2 of land has subsided. Although land subsidence typically occurs at rates measured in centimeters per year, the irreversible accumulation of its effects clearly qualifies humans as major geologic agents.

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