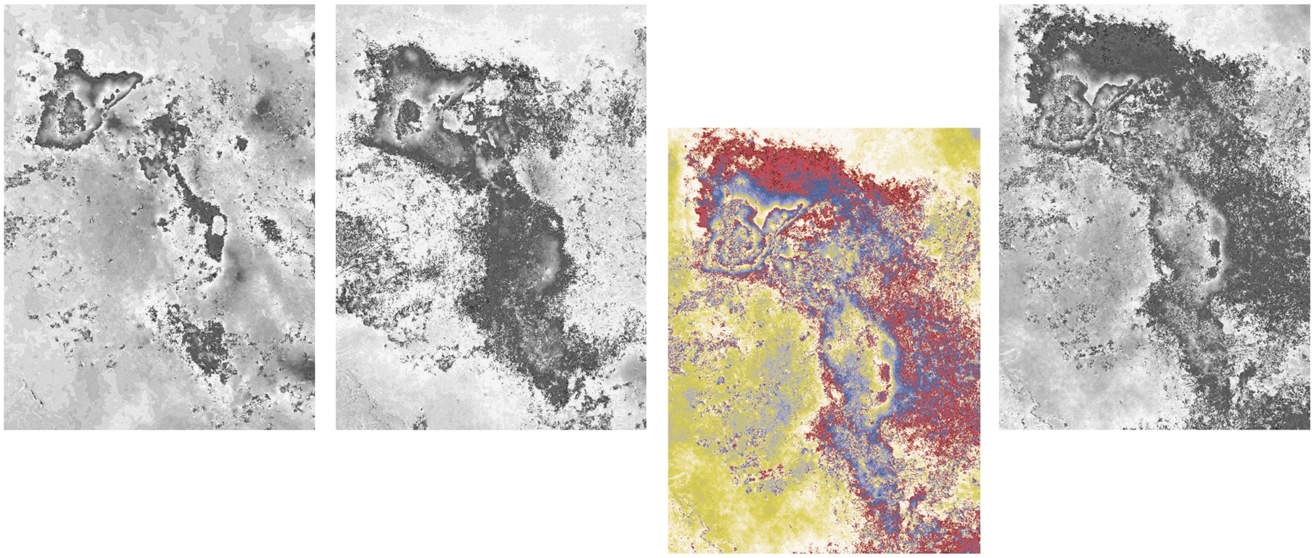
Land Subsidence in the United States



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LAND SUBSIDENCE IN THE UNITED STATES

EDITED BY

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Foreword

Sacramento/San Joaquin River Delta

From the San Francisco Bay/Delta to the Florida Everglades and from upstate New York to Houston, people are dealing with a common problem in these diverse locations—land subsidence due to the withdrawal of ground water or the application of water at the land surface. These locations illustrate that subsidence is not an isolated problem: an area of more than 15,000 square miles in 45 States experience land subsidence. Using these locations and others as case studies, this report focuses on three principal processes causing land subsidence: the compaction of aquifer systems, the oxidation of organic soils, and the collapse of cavities in carbonate and evaporite rocks. The impacts of land subsidence, past and present, are illustrated, and most importantly, so is the value of science in effectively limiting damages from land subsidence.

An important aspect of the USGS mission is to provide information that describes the Earth, its resources, and the processes that govern the availability and quality of those resources. With reports such as this Circular, the USGS seeks to broaden public understanding of land subsidence as an Earth process, and the serious impacts that subsidence can cause if those impacts are not understood, anticipated, and properly managed. By applying scientific understanding and engineering approaches to problems of land subsidence, our society will have solutions that can mitigate or eliminate the negative impacts of subsidence while allowing continued beneficial uses of water. It is our hope that this information will be helpful for concerned citizens, landowners, water users, water managers, and officials responsible for public investments and regulation of land and water use.

For some readers, this report will be an end in itself in providing an understanding of the phenomena of land subsidence that satisfies their need to act as informed citizens or decision makers, or simply to satisfy their curiosity about an important Earth process. For other readers, we hope this report will be a gateway to the rich scientific literature on the subject of subsidence and strategies for the control of subsidence, through the references provided.

Scientific understanding is critical to the formulation of balanced decisions about the management of land and water resources. This Circular coupled with ongoing data collection, basic research, and applications of that research to specific subsidence problems, constitute the USGS contribution toward wise management of land subsidence as a part of effective and publicly beneficial land- and water-management strategies.

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We are also especially grateful to the many key colleagues and cooperators who generously lent their expertise to review technical and nontechnical aspects of each of the case studies: Behzad Ahmadi, Tom Iwamura, and Cheryl Wessling (Santa Clara Valley Water District), and Eric Reichard (U.S. Geological Survey) for Santa Clara Valley, California; Gil Bertoldi (U.S. Geological Survey, retired), George Davis (U.S. Geological Survey, retired) and Harvey Swanson (California Division of Water Resources, retired) for San Joaquin Valley, California; Robert Gabrysch (U.S. Geological Survey, retired), and Ron Neighbors (Harris-Galveston Coastal Subsidence District) for Houston-Galveston, Texas; John Bell (Nevada Bureau of Mines and Geology), Gary Dixon (U.S. Geological Survey), and Michael Johnson (Las Vegas Valley Water District) for Las Vegas Valley, Nevada; Stan Leake (U.S. Geological Survey), and Herb Schumann (U.S. Geological Survey, retired) for Southern Arizona; Margit Aramburu (Delta Protection Commission), Lauren Hastings (U.S. Geological Survey), and M. Mirmazaheri (California Department of Water Resources) for the Sacramento-San Joaquin River Delta, California; Jud Harvey (U.S. Geological Survey), Carol Kendall (U.S. Geological Survey), and Jayantha Obeysekera (South Florida Water Management District) for the Florida Everglades; Jim Borchers (U.S. Geological Survey), Kathy Sanford (New York State Department of Environmental Conservation) and Richard Young (State University New York—Geneseo) for the Retsof Salt Mine Collapse, New York; and Mark Barcelo (Southwest Florida Water Management District), Craig Hutchinson (U.S. Geological Survey), William L. Wilson (Subsurface Evaluations Inc.), and Dan Yobbi (U.S. Geological Survey) for West-Central Florida. We are also grateful to our U.S. Geological Survey colleagues, Charles Heywood and Steven Phillips, for thorough and thoughtful reviews of the final chapter, Role of Science. Finally we thank Michelle Sneed (U.S. Geological Survey) for her final read-through of the Circular and for her constructive comments.

Cover-collapse sinkhole, West-Central Florida

Contents

Conversions

This Circular uses English units. To determine metric values use the conversion factors listed below.

MEASUREMENT	MULTIPLY	BY	TO OBTAIN
Length	inch	25.4	millimeter
	foot	0.3048	meter
	mile	1.609	kilometer
Area	square foot	0.09290	square meter
	square mile	2.590	square kilometer
	acre	0.4047	hectare
Volume	acre foot	1233	cubic meter
	cubic foot	0.02832	cubic meter
	gallon	3.785	liter
Mass	ounce	28.35	gram
	pound	0.4536	kilogram
	ton (short)	0.9072	megagram
Temperature	degree Fahrenheit	$\frac{°F-32}{1.8}$	degree Celsius

Vertical Datum

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929." "Mean sea level" is not used with reference to any particular vertical datum; where used, the phrase means the average surface of the ocean as determined by calibration of measurements at tidal stations.

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.

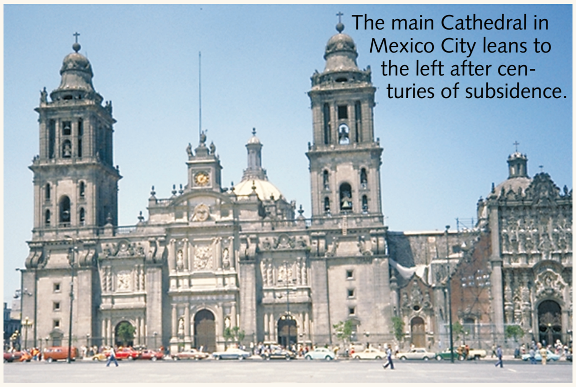
We explore the role of underground water in human-induced land subsidence through illustrative case histories. Extraction and drainage of ground water play direct roles in land subsidence by causing the compaction of susceptible aquifer systems and the dewatering of organic soils. The catastrophic formation 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.

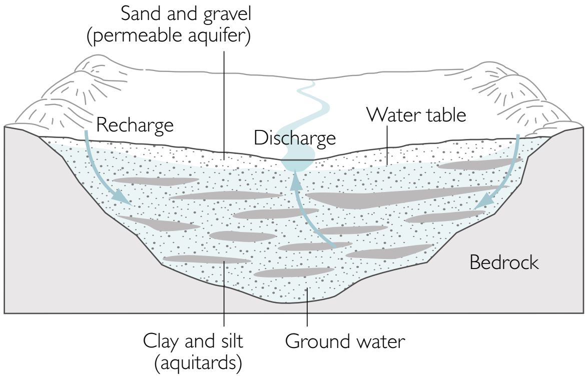
also be triggered by ground-water-level declines caused by pumping, or by infiltration from reservoir impoundments, surface-water diversions, or storm runoff channels. The case histories illustrate the three basic mechanisms by which human influence on ground water causes land subsidence—compaction of 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.

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.

Cover collapse sinkhole in Winter Park, Florida, 1981

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.