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Documenting the Multiple Facets of a Subsiding Landscape from Coastal Cities and Wetlands to the Continental Shelf

Open-File Report 2022–1064

U.S. Department of the Interior
U.S. Geological Survey

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By James Flocks, Eileen McGraw, John Barras, Julie Bernier, Mike Bradley, Devin Galloway, James Landmeyer, W. Scott McBride, Christopher Smith, Kathryn Smith, Christopher Swarzenski, and Lauren Toth

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic decimeter (dm^3)	0.2642	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per year (m/yr)	3.281	foot per year ft/yr)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)

Abbreviations

BE	barometric efficiency
CFWSC	Caribbean Florida Water Science Center
CORS	Continually Operating Research Station
CRMS	Coastwide Reference Monitoring System
DOI	Department of the Interior
GIS	geographic information systems
GPS	global positioning system
HRSP	high resolution seismic profiling
InSAR	Interferometric Synthetic Aperture Radar
lidar	light detection and ranging
LMGWSC	Lower Mississippi-Gulf Water Science Center
m MSL	meters below mean sea level
NWIS	National Water and Information System
OKIWSC	Ohio-Kentucky-Indiana Water Science Center
SAWSC	South Atlantic Water Science Center
SER	Southeast Region
SFT	Subsidence Flex Team
SLR	sea-level rise
SPCMSC	St. Petersburg Coastal and Marine Science Center
UFA	Upper Floridan aquifer
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USGS	U.S. Geological Survey
WARC	Wetland and Aquatic Research Center

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Abstract

Land subsidence is a settling, sinking, or collapse of the land surface. In the southeastern United States, subsidence is frequently observed as sinkhole collapse in karst environments, wetland degradation and loss in coastal and other low-lying areas, and inundation of coastal urban communities. Human activities such as fluid extraction, mining, and overburden alteration can cause or exacerbate subsidence, which can result in damage to infrastructure and resources. Subsidence is a hazard that takes place throughout the United States; however, a systematic approach to recognize and develop informed responses to the drivers of subsidence has not yet been fully established. To address this problem, the U.S. Geological Survey (USGS) Southeast Region (SER) funded the gathering of a team of interdisciplinary USGS scientists to promote scientific collaboration. Southeast Region scientists welcomed scientists from other regions (see table 1.1 in Appendix 1) in September 2018 at the St. Petersburg Coastal and Marine Science Center (SPCMSC) in Florida for the first workshop of the Subsidence Flex Team (SFT) (see Appendix 2 for agenda). The SFT set out to review subsidence-related research and technology and develop a unifying framework for describing the processes and hazards associated with land subsidence. A more comprehensive understanding of subsidence hazards could help to inform regional vulnerability assessments that would prove invaluable to the public, community developers, policy makers, and resource managers in both inland and coastal states. The SFT analyzed USGS strengths and weaknesses to identify existing infrastructure and capabilities that could be leveraged to create a comprehensive and far-reaching subsidence-monitoring and mitigation program. Over the course of the 2-day workshop, interdisciplinary understandings of the processes and hazards related to subsidence were explored through individual presentations and group discussion. With all perspectives considered, the SFT recommended that subsidence-related research develop scientific approaches and metrics by which the subsidence component can be isolated and quantified in order to protect both the environment and human infrastructure from harm.

Introduction

Definition of Subsidence

Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to subsurface movement of earth materials (Galloway and others, 1999). Subsurface movement is the mass flux of material through chemical and (or) physical processes. Presenting itself in a variety of forms, subsidence occurs both naturally and through human activity. Land subsidence has been observed throughout human history; however, research aimed at understanding the causes, types, and related hazards of subsidence did not begin in earnest within the United States until the early 20th century (Meinzer, 1939). Dramatic impacts of subsidence were first formally documented in the Santa Clara Valley in Northern California (Tolman and Poland, 1940), which highlighted the impact of groundwater withdrawal on subsidence. Shortly thereafter, a counteractive and restorative program was effectively implemented to halt groundwater withdrawal in the valley until subsidence was fully stopped in 1969 (Galloway and others, 1999). Owing to high rates of land subsidence in southeast Texas, citizen-driven campaigns during the 1960s called for the decrease in groundwater extraction. By May 1975, Texas state legislators took interest in mitigating the effects of land subsidence and passed a law appointing the Harris-Galveston Coastal Subsidence District (Zilkoski and others, 2003). The first of its kind, the Subsidence District controlled the distribution of permits for large-diameter wells in order to oversee and regulate the amount of groundwater pumped annually. In 1976, the Subsidence District developed a plan that recognized the immediate need for subsidence mitigation in coastal areas, and demand on groundwater was mitigated by using surface water from nearby lakes instead. This change caused groundwater levels to rebound in the region and mitigation processes continued.

More recently, subsidence-related research and expertise has expanded through both groundwater and structural studies. The Subsidence Flex Team (SFT) identified various working groups, conferences, and publications related to subsidence issues (table 1). For example, the U. S. Geological Survey (USGS) maintains a Land Subsidence webpage that hosts land subsidence fact sheets and circulars, as well as a Karst Interest Group webpage that houses proceedings from a series of workshops presenting research on karst related issues. International assessments of subsidence science include two workshops and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Working Group on Land Subsidence. Also, coastal vulnerability assessments related to relative sea-level rise (SLR), particularly in the central northern Gulf of Mexico, are outlined in the USGS National Assessment of Coastal Vulnerability to Sea Level Rise webpage.

Table 1. Subsidence-related resources.

Institutions, organizations, & interest groups	Related publication(s)	Link(s)
USGS Water Resources Land Subsidence	Galloway and others (2000)	USGS Land Subsidence Webpage: https://www.usgs.gov/mission-areas/water-resources/science/land-subsidence?qt-science_center_objects=2%23qt-science_center_objects
USGS Subsidence Interest Group	Prince and others (1992) Prince and Leake (1997) Prince and Galloway (2001)	USGS Groundwater Information Website: https://water.usgs.gov/ogw/subsidence.html
USGS Texas Water Science Center Subsidence Overview	Kasmarek and others (2009)	Texas Water Science Center Subsidence Webpage: https://www.usgs.gov/centers/tx-water/science/subsidence-science-texas-overview?qt-science_center_objects=0#qt-science_center_objects
USGS National Assessment of Coastal Vulnerability to Sea Level Rise	Website with Publications Page: https://www.usgs.gov/centers/whcmsc/science/national-assessment-coastal-vulnerability-sea-level-rise?qt-science_center_objects=3#qt-science_center_objects	Assessment Webpage: https://www.usgs.gov/centers/whcmsc/science/national-assessment-coastal?qt-science_center_objects=0#qt-science_center_objects
USGS Wetland and Aquatic Research Center (WARC) – Sea Level Rise	See Link to Website	WARC - Sea Level Rise: https://www.usgs.gov/centers/wetland-and-aquatic-research-center/science/impacts-sea-level-rise-ecosystem-restoration
USGS Karst Interest Group Proceedings	Kuniansky (2005) Kuniansky (2008) Kuniansky (2011)	8th USGS Karst Interest Group Workshop: https://www.usgs.gov/mission-areas/water-resources/karst-interest-group-kig-workshop
InSAR Studies	Lu and Danskin (2001) Sneed and others (2003)	Measuring Land Subsidence from Space: https://pubs.usgs.gov/fs/fs-051-00/
2016 2nd International Workshop on Coastal Subsidence (Venice, Italy)	See Abstracts at Link	2nd International Workshop on Coastal Subsidence: https://ambiente.regione.emilia-romagna.it/it/geologia/geologia/costa/pdf/2ndInternationalworkshoponcoastalsubsidence_rid.pdf
UNESCO Land Subsidence International Initiative	See Resources at Link	UNESCO Land Subsidence International Initiative: https://www.landsubsidence-unesco.org/
Louisiana State University Center for Geoimformatics Louisiana Universities Marine Consortium Florida Department of Environmental Protection (DEP) Geological Survey of Kentucky	See Publications at Link Kolker and others (2011) Schmidt (2005) See Publications at Link	LSU Center for Geoinformatics: http://c4g.lsu.edu/ Louisiana Universities Marine Consortium: https://lumcon.edu/ Florida DEP Website: https://floridadep.gov/ Florida DEP Subsidence Incident Report: https://floridadep.gov/fgs/sinkholes/content/subsidence-incident-reports Kentucky Geological Survey Website: https://www.uky.edu/KGS/

Drivers of Subsidence

Fluid Withdrawal

Groundwater Pumping

As global populations continue to rise, the demand for water and land resources has reached unprecedented levels. Subsidence owing to excessive groundwater pumping accounts for the majority of all subsidence in the United States (Galloway and others, 1999, p. 1). The removal of groundwater from an aquifer system can result in either elastic or inelastic deformation of the aquifer. Groundwater recharge results in the expansion of the aquifer system. Reversible deformation is present in all aquifer systems and is commonly driven by seasonal variations in groundwater withdrawal and surface water recharge rates (Galloway and others, 1999, p. 8–9).

Permanent deformation of aquifer systems occurs when groundwater is pumped out of the system at an extremely high volume, placing unprecedented stress on the system. The visible hazards of aquifer-system compaction owing to excessive groundwater withdrawal, such as infrastructure and environmental damage, are being seen at higher rates within the span of half a century. In the San Joaquin Valley in California, for example, the effects of this form of subsidence are afflicting water-conveyance structures such as the California Aqueduct (Galloway and others, 1999).

Hydrocarbon Extraction

Like groundwater, hydrocarbons, such as oil and gas, reside in the pore spaces and cracks in subsurface reservoirs. When the pore pressure is reduced because of production of oil and natural gas reserves, subsidence can result from compaction and collapse of reservoirs (White and Morton, 1997). These reservoirs can be found in many parts of the world; however, the immense exploitation of oil and natural gas in modern society has resulted in the excessive rates of hydrocarbon extraction. The first sign of land subsidence related to hydrocarbon extraction was observed shortly after the development of the Goose Creek Oil Field near Houston, Texas in 1917. During production, the land subsided around the producing well, activated faults within the region, and caused earthquakes (Pratt and Johnson, 1926; Morton, 2003). Regions rich with hydrocarbon reservoirs have had to take measures to combat subsidence resulting from oil and gas production. For example, in the Houston-Galveston region in Texas, the use of levees, coupled with improved management of reservoirs (such as re-injecting produced water [a by-product of pumping oil and gas to the surface]) and surface-water distribution facilities has been required to prevent subsidence-related flooding, infrastructure damage, and ecosystem loss (Ketelaar, 2009).

Oxidation of In Situ Organic Matter

Organic soils that contain 20 percent or more organic matter and are at least 0.4-m thick are often formed in environments, such as marshes, where poor drainage impedes proper decomposition of plant and animal matter, allowing for accumulation over time. When these soils are drained (for example, for agricultural use), microbial decomposition, or oxidation of the organic material, occurs (Drexler and others, 2009). Oxidation is the process of organic carbon being converted into carbon dioxide and water. Removal of the organic material leads to creation of pore space, which will collapse under load (fig. 1). The Florida Everglades is a notable example of where organic-soil subsidence is occurring at an unsustainable rate and is leading to several associated hazards (Stephens and others, 1984). These risks include unknown sustainability of agricultural production, damage to the infrastructure that transports water to urban areas, and heightened importance on ecosystem restoration efforts (Galloway and others, 1999).

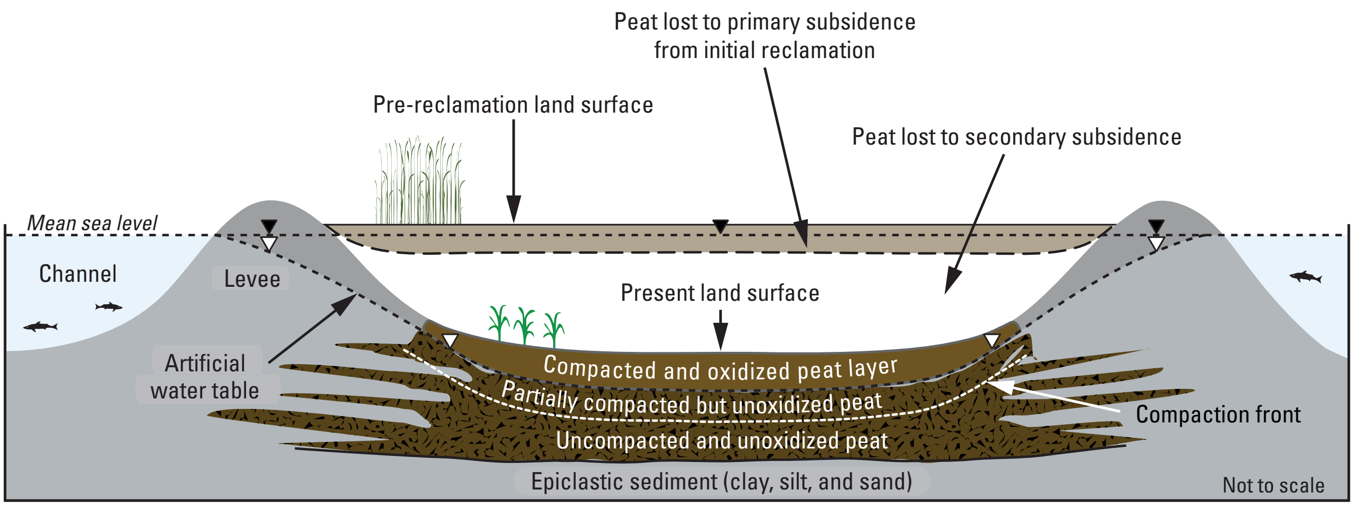


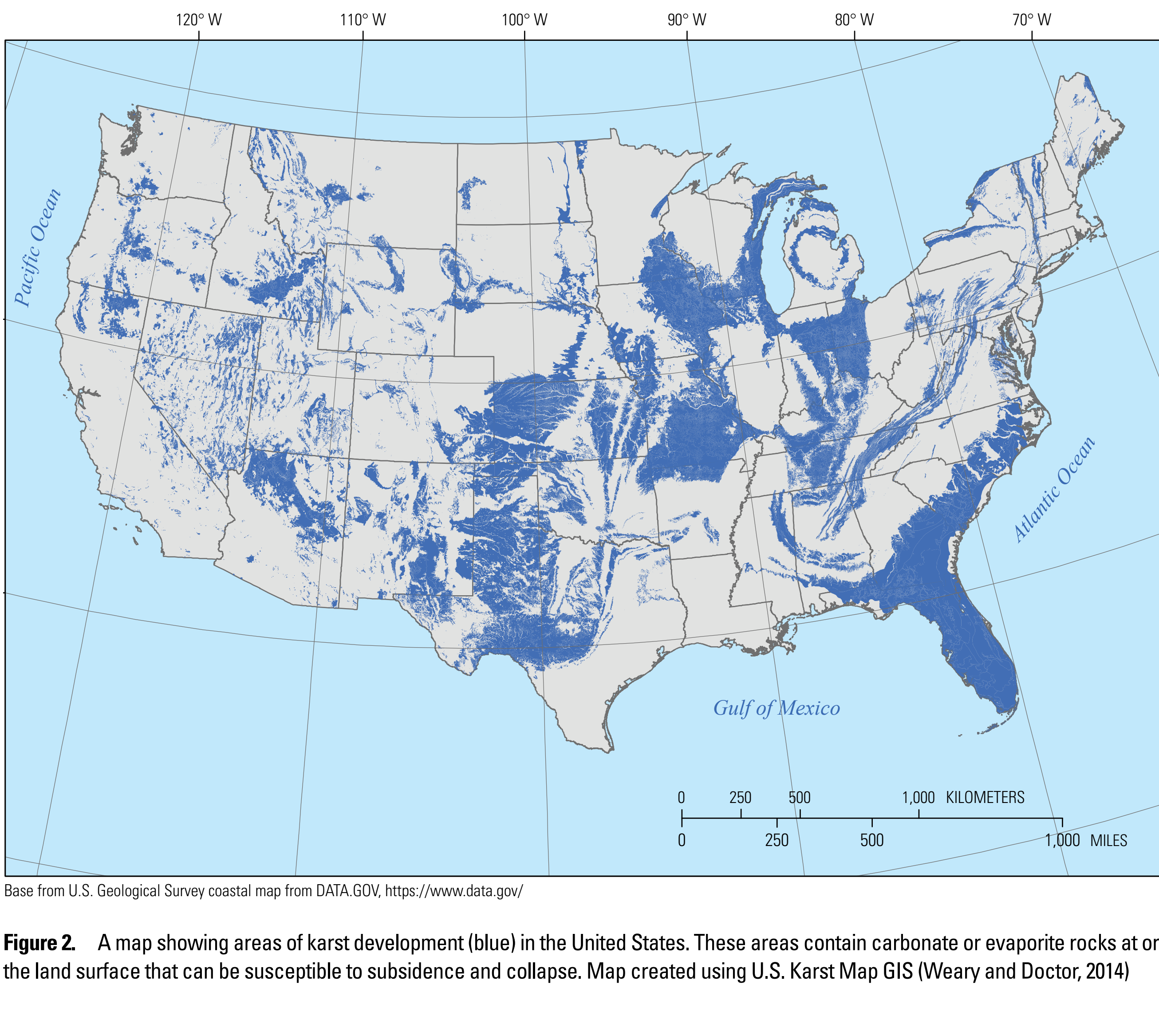
Figure 1. Subsidence owing to oxidation of organic rich soils, such as peat. Figure from https://www.usgs.gov/centers/land-subsidence-in-california/science/decomposition-organic-soils-sacramento-san-joaquin (Drexler and others, 2009).

Land Subsidence Owing to Landscape Alteration (Mining, Impoundment, Surface Modification)

Abandoned mines of all shapes and sizes can be found across the United States. Many of these mines have experienced extensive removal of minerals, mineral fuels, rock aggregate, and other solid and liquid materials, which leaves a risk of surface collapse. Mine subsidence is considered as the vertical and (or) horizontal movement of the ground surface commonly triggered by the removal of support during active mining operations. Underground extraction of coal accounts for most of the mining-related subsidence in the United States (Galloway and others, 1999). The potential risk of subsidence varies at each individual mining site and can only begin to be assessed through analysis of the overlying stratigraphy, removal methods, infrastructure, depth of extraction, thickness of deposit, and topography (Lee and Abel, 1983). The two major forms of subsidence associated with mines are sag subsidence and pit subsidence. Sag subsidence describes the appearance of gentle depressions of the ground surface sometimes spanning as far as several acres. Subsidence pits, or holes, are usually bell-shaped holes of varying diameter and depth. Both forms of subsidence are the result of the weight of overburden overcoming the support of the mine, causing the roof to collapse or cave (Galloway and others, 1999). Other forms of human-induced landscape subsidence include loading during impoundment of water to create reservoirs. In a study of elevation change using global positioning system (GPS) observations at a dam in Malaysia, Tangdamrongsub and others (2019) found that, over the 17-month study period, elevation change was 10–11 milimeters (mm), or 7–8 milimeters per year (mm/yr). The study estimates that the land around the reservoir subsided up to 200 mm following impoundment.

Dissolution and Karst

Perhaps the most obvious type of subsidence is triggered by the dissolution of soluble bedrock, such as carbonate. Carbon dioxide in the atmosphere converts to carbonic acid in rainwater. When acidic rainwater comes in contact with specific rock types—carbonates (limestone and dolomite) and evaporites (gypsum and anhydrite), for example—it can cause the dissolution of the rock substrate, forming subsurface cavities. This process, known as karstification, is pervasive in parts of the United States (fig. 2), and it is most prevalent in the



Base from U.S. Geological Survey coastal map from DATA.GOV, https://www.data.gov/

Figure 2. A map showing areas of karst development (blue) in the United States. These areas contain carbonate or evaporite rocks at or near the land surface that can be susceptible to subsidence and collapse. Map created using U.S. Karst Map GIS (Weary and Doctor, 2014)

southeast region of the United States. Salt and gypsum deposits have high solubilities, resulting in relatively quick formation of cavities, whereas carbonates form cavities very slowly over the span of centuries (Galloway and others, 1999). However, sinkhole collapse can occur very rapidly, causing significant damage to infrastructure (fig. 3). A study by the USGS (Weary, 2015) estimates that karst-related damage in the United States is at least $3 million per year, but likely much higher as no comprehensive national database tracking karst-related damage exists. The Florida Office of Insurance Regulation (FOIR) reported $1.4 billion in claims for sinkhole damage between 2006 and 2010, and this does not include the cost of damages to state roads (Weary, 2015). Owing to increasing population growth in karst-prone areas, these costs are constantly rising. Between 1987 and 1991, FOIR estimated that claims for damage from sinkhole collapse increased by 1,200 percent (Kindinger and Flocks, 2000).

Tectonics

Tectonic subsidence is large-scale adjustments of the Earth's crustal plates in response to extension, loading, and cooling of the plates. Extension occurs as the plates accommodate movement along crustal faults and can result in failure and subsidence along normal and listric faults, common features in the northeastern Gulf of Mexico. A study by Taha and Anderson (2008) found that downward movement along a listric fault in the Brazos River Valley of Texas caused numerous river avulsions throughout the Holocene. In the northern Gulf of Mexico, the Mississippi River Delta responds to glacial isostatic adjustment and lithospheric subsidence owing to the loading of deltaic deposits following late Pleistocene deglaciation through forebulge collapse (Yu and others, 2012). They also measured subsidence through the loading of Holocene deltaic sediments along the Mississippi Delta Plain at a rate of 0.15 mm/yr, in addition to compaction of these sediments through dewatering. This combination of continental/crustal-scale and delta-lobe-scale processes leads to some of the highest rates of land subsidence in the world.

Thermal subsidence occurs as previously heated mantle lithosphere cools and sinks, resulting in gradual subsidence at the surface. Owing to the tectonic evolution of the North American continent, this process is not a contributor to regional subsidence patterns.

Hydrocompaction

Hydrocompaction, also known as hydro-collapse, is a near-surface process that occurs when water infiltrates dry sediment, resulting in granular resettlement and a decrease in volume. Hydrocompaction predominantly takes place in alluvial-fan sediments that are higher than the peak prehistoric water table and in areas where runoff did not reach below the zone impacted by summer dryness owing to evaporation and transpiration (Zisman and West, 2015). Through these processes, the pore spaces within the sediments are solidified, conserving the pre-wetting strength. The scale of subsidence features is determined through several different factors, such as the rate and depth of water infiltration to the sediments and exposure time (Galloway and others, 1999). Another factor that dictates the vulnerability of the soil to hydrocompaction is sediment composition and structure. In most cases, geologically immature sediments with weak structural and chemical bonds, high void ratios, and low densities are the most susceptible to compaction. Soils rich in silt and clay will take the longest to settle compared with loosely packed sands,

Figure 3. Collapse sinkhole that formed over the course of several days in Winter Park, Florida in 1981. The sinkhole consumed many businesses, including a car dealership and a municipal pool. Damage was estimated at $4 million. Photograph from https://www.usgs.gov/media/images/winter-park-florida-sinkhole-1981-3.

which take less time to settle once saturated. When water infiltrates the sediment, weak bonds break easily, allowing for uninhibited compaction of the sediments (Zisman and West, 2015).

Localized hydrocompaction underneath water-filled basins can lead to vertical shear failure, which can result in concentric tensional fissures with the possibility of significant vertical offset on the surface (Galloway and others, 1999). Hazards facing infrastructure owing to hydrocompaction have been documented throughout the U.S., including multiple cases of hydraulic structure damage (Galloway and others, 1999).

Subsidence and Sea Level Rise

The SFT recognizes the intimate relation between subsidence and SLR. Global mean sea level is projected to rise as much as 2 m over the upcoming century (Lindsey, 2018). In many coastal locations, the impacts of rising water levels are already being felt today because of concurrent land subsidence, which results in a relative SLR that exceeds global mean estimates. Recent analysis by Keogh and Törnqvist (2019) indicates that tidal-gauge monitoring systems systematically underestimate rates of inundation relative to regional subsidence rates because they do not adequately capture sediment compaction in the near surface and do not differentiate between rising water levels and land subsidence. Instead, the net change in water level is commonly attributed to SLR without accounting for the role of subsidence. The SFT concluded that although the public is largely aware of the risk that inundation poses to coastal communities, very few recognize that flooding is frequently a consequence of subsidence. For example, the south Florida shelf has a low elevation and a gentle slope, making it highly vulnerable to SLR (Toth and others, 2018). This area of coastline is also subsiding, but the driving processes and rates of land-level change are largely unknown and unquantified. In contrast, regional and local subsidence in coastal Louisiana is widely known to be extremely high, but the physical processes that drive it are complex and more difficult to quantify (Allison and others, 2016). With every centimeter of SLR, the coastal plain of Louisiana faces further risks of inundation and land loss. The contrast of these two areas highlights both the complexity of vertical land movement and the disparity in data and consensus on processes and rates. However, the overall ramification is much the same; subsiding land exacerbates the hazards facing coastal communities owing to SLR. To properly understand current and future rates of relative SLR, both locally and globally, subsidence rates must be known and analyzed as a contributing factor. Spatial and temporal assessments of subsidence risks could be used to better inform USGS assessments of coastal hazards, water availability, and habitat resilience to provide guidance for the management and restoration of natural and urban environments.

Summary of Workshop Presentations

During the workshop, presentations were provided by the scientists to summarize their expertise and current state of knowledge in subsidence-related research. The following section provides general overviews of the individual presentations. The workshop agenda is provided in appendix 2.

"Groundwater and Surface-Water Interactions as Related to Subsidence in West-Central Florida," presented by William Scott McBride (Caribbean-Florida Water Science Center)

The Upper Floridan aquifer (UFA), the largest source of potable water in Florida, is generally a confined aquifer system (fig. 4), but extensive areas in central and northern Florida are unconfined or semi-confined (Kingsbury, 2018). Areas of the UFA lacking extensive confinement are also synonymous with sinkhole development, which is a form of land subsidence (fig. 4). Sinkholes form where the aquifer is unconfined because the soluble carbonate bedrock of the UFA is exposed to chemical weathering. Unconfined areas of the UFA, generally defined as having less than 100 feet of overburden, lack a clay confining unit, whereas in semi-confined areas the clay overburden is thin, discontinuous, or perforated. Sinkholes increase the risk of surface contaminants interacting with groundwater supplies by forming direct conduits to the UFA. The sands and clays of the surficial aquifer, which is congruent with land surface, act as a natural filter of groundwater recharge when sinkholes are not present. Surface-to-groundwater interaction can be monitored by measuring the hydraulic head through paired surface aquifer and UFA wells, and also through the use of geochemical tracers. Geophysical investigations and temperature mapping can also be employed to monitor transmission. Sinkholes form naturally in karst terrains, but the rates of formation can be greatly intensified by human activities, such as over pumping of groundwater. Declines in groundwater levels cause a loss of support to the bedrock roofs over cavities and to surficial materials overlying openings in bedrock, which promotes sinkhole collapse.

"Overview of Land Subsidence Caused by Aquifer-System Compaction Accompanying Exploitation of Groundwater Resources," presented by Devin Galloway (Ohio-Kentucky-Indiana Water Science Center)

Most of the subsidence in the United States is directly due to human exploitation of water resources (Galloway and others, 1999). Areas of concern within the conterminous United States include the San Joaquin Valley of California, Las Vegas, Nevada, and Houston, Texas (fig. 5).

Aquifer-system compaction takes place when groundwater is extracted from beneath the surface through aquitard drainage, and the reduction of fluid pressure on the pores and cracks within the system results in subsidence. Tolman and Poland (1940) describe the aquitard drainage model as the irreversible compression or consolidation of aquitards (interbeds and confining units) during the typically slow process of fluid drainage.

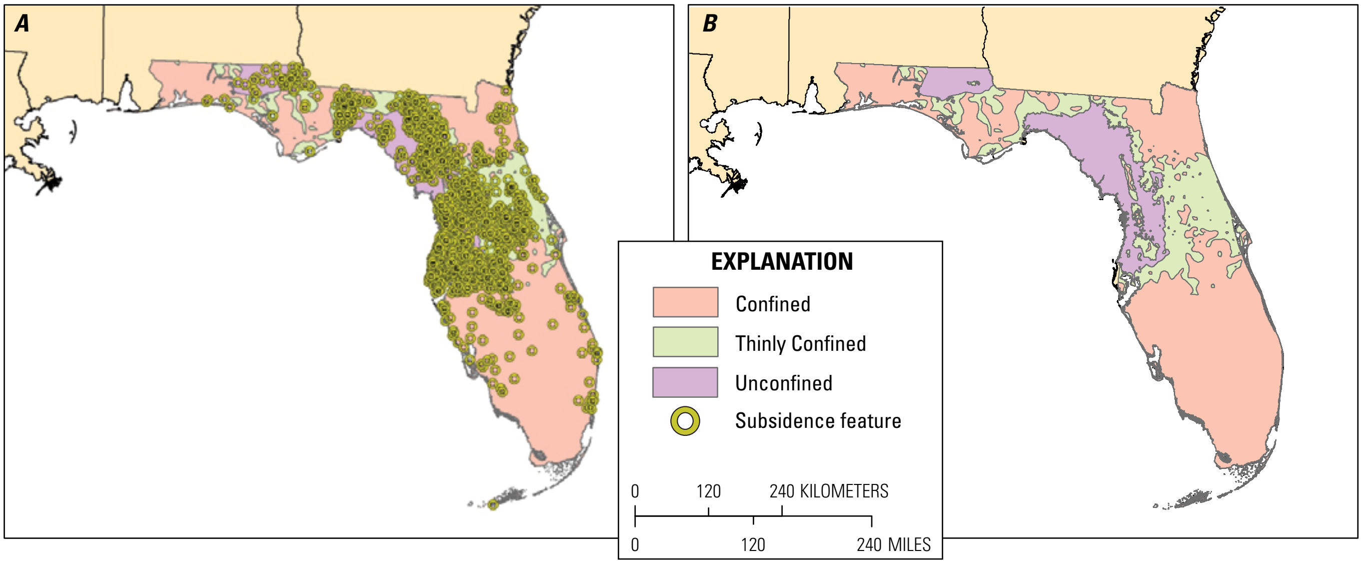


Figure 4. Map showing the correlation between subsidence features (*A*) and level of confinement of the Upper Floridan Acquifer (*B*). Figure modified from Williams and Kuniansky (2015).

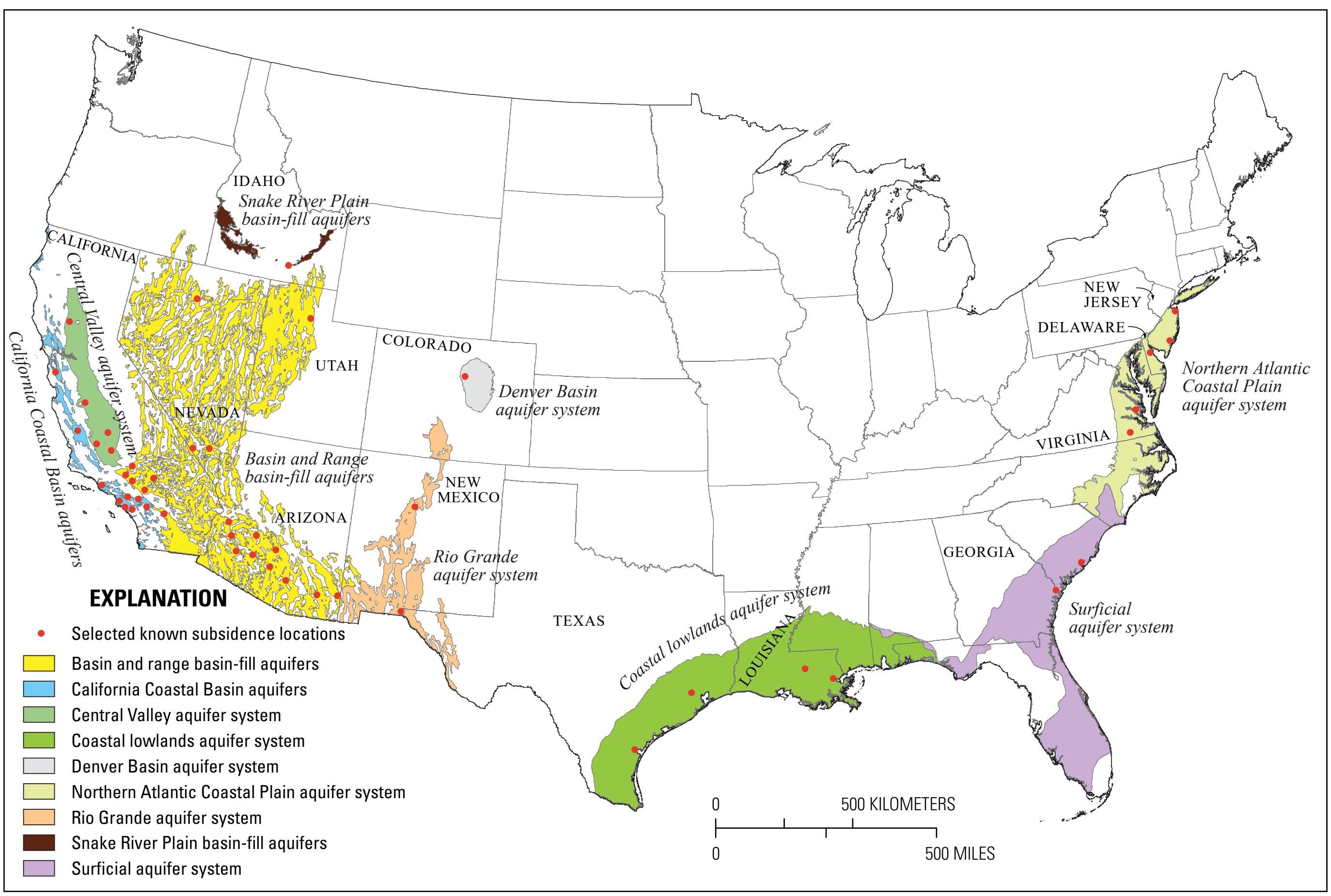


Figure 5. Map of aquifer locations throughout the United States with related subsidence locations. Modified from Galloway and others (2008).

Methods, such as geodetic measurements and analysis of hydrogeologic properties, are used to quantify the change in stress and head of aquifers and aquitard systems. Subsidence mitigation is achievable through reducing groundwater-pumping rates and increasing recharge through artificial and natural means.

"Aquifer Responses to Barometric Pressure: A Proxy for Measuring Changes in Deep Sediments Owing to Subsidence?" presented by James Landmeyer (South Atlantic Water Science Center)

The evaluation of deep subsidence is possible through utilizing metrics currently collected by the USGS, such as barometric pressure. Researchers can temporally measure the barometric efficiency (BE) of a well as a proxy for subsidence by using the equation:

$$BE = \Delta(\text{head})/\Delta(\text{barometric pressure}) \qquad (1)$$

where

BE is the barometric efficiency, in percent,

Δ(head) is the change in water level in a well over a set period of time, and

Δ(barometric pressure) is the maximum change in barometric pressure over the same set period of time.

Correlation between barometric pressure gradients and groundwater levels was observed in wells from Florida, Georgia (fig. 6), and South Carolina, where water levels in the wells responded inversely to the short duration, extreme drop in barometric pressure related to the historic "no name" storm that passed through the southeastern United States in March 1993 (Landmeyer, 1996). The BE is also influenced by the aquifer's extent of confinement, such that the BE is higher with increasing distance from aquifer outcrop areas. Pressure gradients owing to subsidence-related compaction within confined aquifers may also impart an influence on BE. Selected well sites can be analyzed temporally for BE to draw conclusions about the possible role of subsidence owing to compaction in an area.

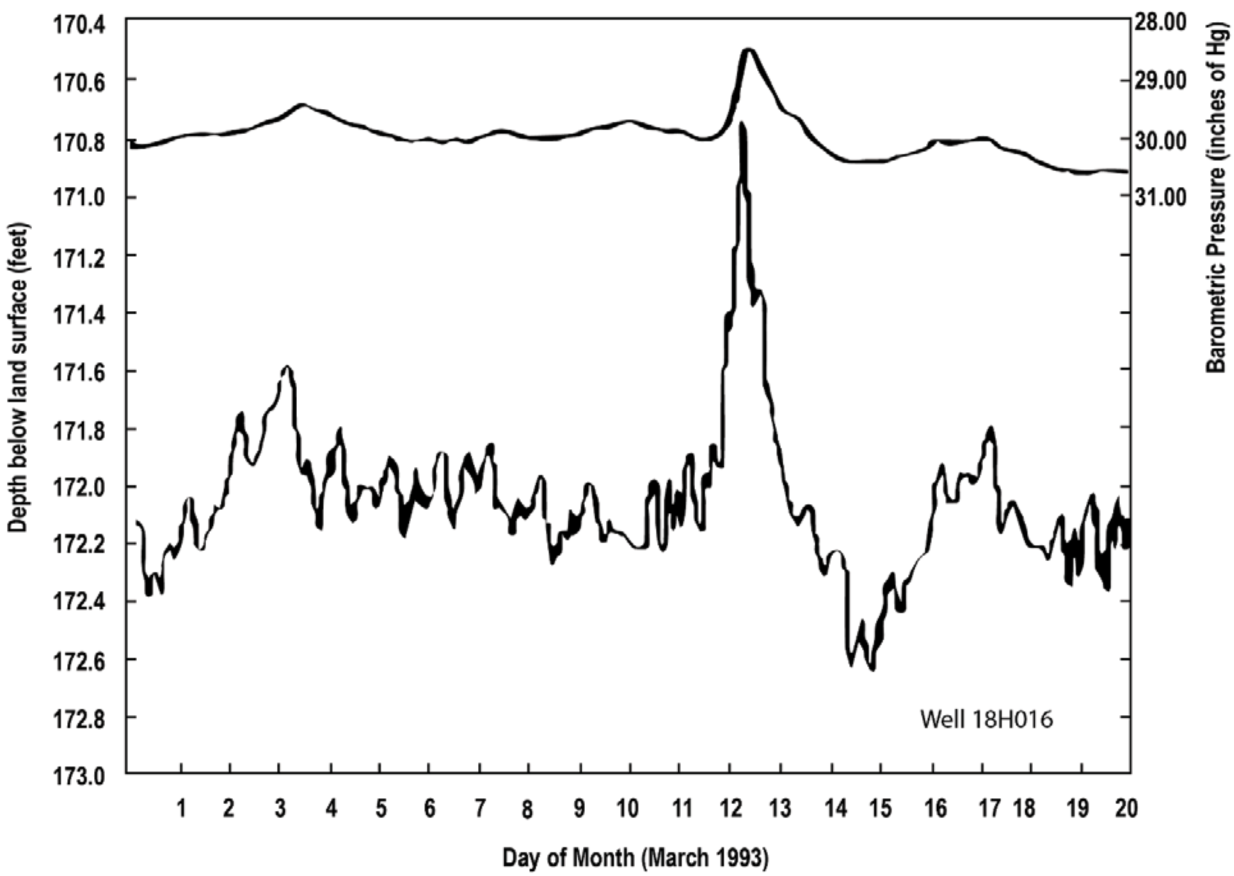


Figure 6. Change in water level (bottom graph) in an Upper Floridan Aquifer well (Georgia) from March 1 to 20, 1993, during the passage of the historic cold front (the "no name" storm) and reduction in barometric pressure (upper graph). Modified from Landmeyer (1996).

“Uncertainties in Measuring Submergence of Coastal Marshes Below Long-Term Water Levels,” presented by Chris Swarzenski (Lower Mississippi-Gulf Water Science Center)

The elevation of marsh environments is the result of counterbalanced rates of subsidence and vertical accretion. Subsidence in these environments is primarily driven by the oxidation of organic materials, resulting in the compaction of sediments, whereas vertical accretion relies on sediment accumulation and root growth (Stagg and others, 2016; Gambolati and others, 2006). During subsidence, decreasing porosity within the sediments reduces hydraulic connectivity and may leach potential toxins from the dewatered clays into the environment. Variations in accretion rates are due to differences in mineral and organic matter content within the substrate. Saltwater marshes have more pore space than freshwater marshes and organic-rich marshes have higher rates of compaction. These factors are unique in each marsh, making it difficult to monitor the drivers of elevation change. However, as SLR rates continue to increase, this information will be crucial in forecasting sustainability of marsh ecosystems.

“Quantifying Wetland-Loss Trends, Processes, and Large-Scale Historical Accommodation Formation in Coastal Louisiana,” presented by Julie Bernier (St. Petersburg Coastal and Marine Science Center)

The primary goals of the USGS Gulf Coast Subsidence Project were to provide a more complete understanding of the physical processes and human impacts contributing to historical wetland loss in coastal Louisiana (fig. 7) and to more precisely constrain the temporal and spatial trends of that loss (Bernier, 2016). Analysis of satellite and aerial imagery shows rapid onset of wetland loss occurred from the mid-1960s to mid-1970s across coastal Louisiana, with peak wetland-loss rates persisting until the mid-1990s at some sites. Comparison with tide-gauge, elevation, and hydrocarbon production data shows close temporal and spatial correlation between wetland loss, subsidence, and hydrocarbon production trends, indicating that hydrocarbon production likely induced accelerated historical subsidence rates in coastal Louisiana. Land-surface subsidence, sediment erosion, and accommodation formation were quantified by comparing water depths, marsh-surface elevations, marsh-sediment thicknesses, and vertical displacement of stratigraphic contacts (fig. 7) across wetland-loss chronic hotspots in the Chenier and Delta Plains. Subsidence occurred and likely initiated historical wetland loss in all “hotspot” study areas. In the Delta-Plain study areas, subsidence was determined to be the primary driver of the observed wetland loss and subsequent development of accommodation space, or areas of future deposition. Local accommodation values, calculated by integrating spatial and vertical measurements of wetland loss, provide estimates of sediment volume necessary for wetland restoration. Because of the lack of extant subsidence rates from interior wetlands in coastal Louisiana, the project proposed leveraging Coastwide Reference Monitoring System (CRMS) stations to install and monitor compaction gauges to better understand the continued role of subsidence and provide data to support future vulnerability assessments. Recently, GPS data from CRMS sites were analyzed to identify short-term (<20 years) subsidence trends at CRMS sites from Barataria Basin (Byrnes and others, 2019). Similar analyses from CRMS sites across the Louisiana coastal plain would be beneficial; additionally, integration with data from proposed compaction gauges would enable quantification of the relative contribution of both shallow and deep subsidence from different geological units.

“Episodic Wetland Loss from Rapid Subsidence and Other Drivers,” presented by John Barras (St. Petersburg Coastal and Marine Science Center)

Remote sensing was a primary tool used for analysis in the USGS Gulf Coast Subsidence Project that took place from 2000 to 2011. Rapid wetland loss was spatially and temporally constrained using satellite and aerial imagery, hydrocarbon production data, tide gauges, benchmark elevations, Continually Operating Reference Station (CORS) elevation stations, and coring and bathymetric surveys. Linear loss of wetlands over time owing to subsidence-related elevation change was punctuated by episodic drivers such as storms and flooding events to generate wetland loss chronic hot spots (Palaseanu-Lovejoy and others, 2013). These hot spots included areas of as much as 80 square kilometers (km^2) that developed over the past half century (Barras, 2009). For this study, special attention was given to using storm-related open-water expansion as an indicator of vulnerability; for example, wetland loss in the Mississippi Delta Plain following Hurricane Katrina. Identifying and quantifying the drivers of subsidence is useful in reconstructing historical wetland loss as a tool for projecting future loss rates.

“Diatoms as Indicators of Sea-Level Change,” presented by Kathryn Smith (St. Petersburg Coastal and Marine Science Center)

The lack of long-term and spatially dense land elevation data is one of the major challenges to understanding the long-term implications and coastal hazards associated with land subsidence. Fossil diatoms are often used as a paleoindicator of sea level, water quality, and climate condition. They are also sensitive to tidal position and can thereby be a useful indicator of land elevation. For example, diatoms collected in surface samples across the Chenier plain in Louisiana were identified by their species and assemblage type (high marsh,

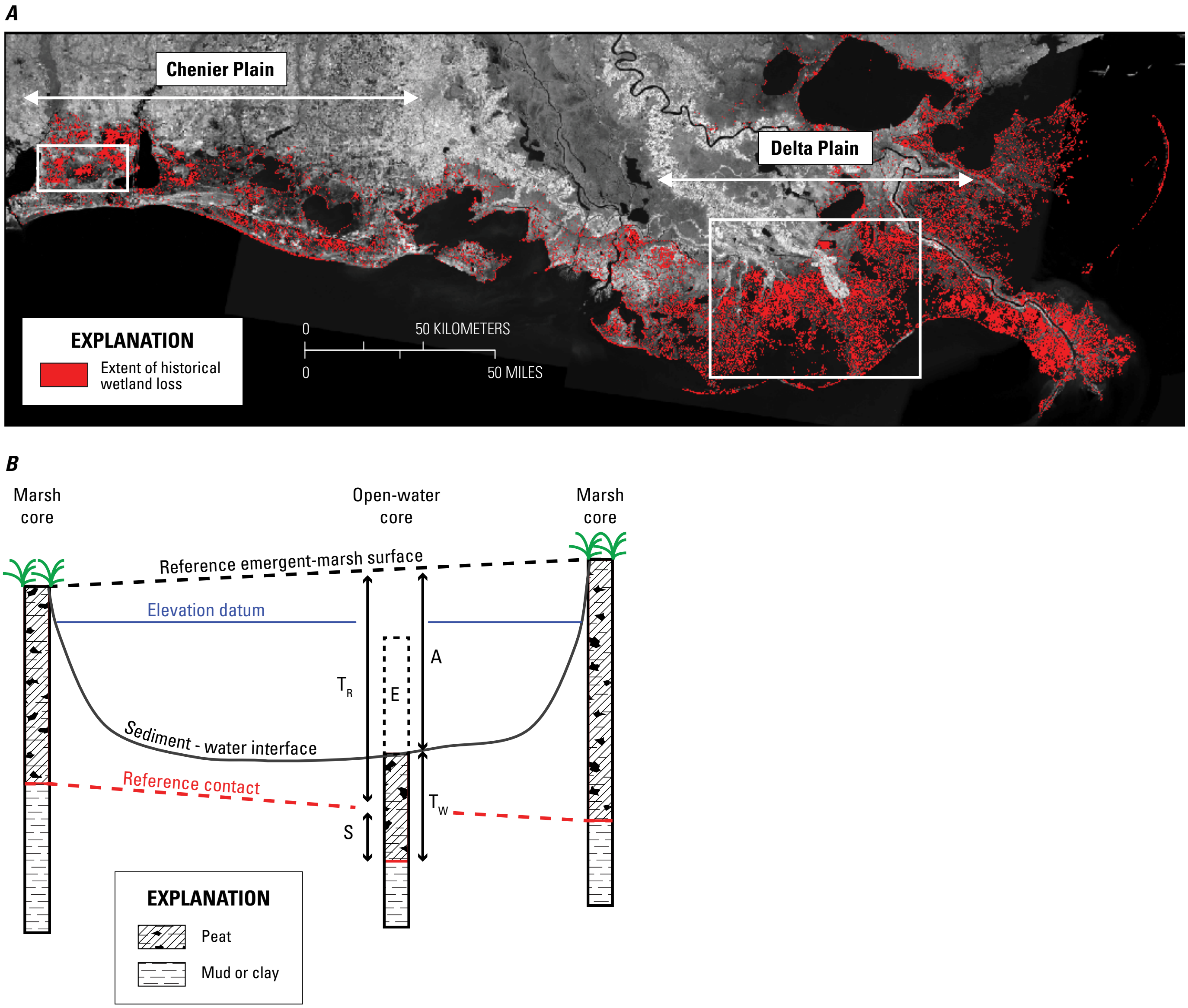


Figure 7. *A* Regional map of coastal Louisiana showing, in red, extent of the historical wetland loss. *B* Conceptual diagram showing the stratigraphic relations used to estimate the subsidence and erosion components contributing to the total one-dimensional accommodation at an open-water core site. Abbreviations: A, 1D accommodation; E, erosion; S, subsidence; TR, reference stratigraphic thickness; TW, stratigraphic thickness in the open-water core. Figure from https://www.usgs.gov/centers/spcmsc/science/subsidence-and-wetland-loss-related-fluid-energy-production-gulf-coast-basin#science.

low marsh, tidal flat). Elevation at the sample sites can be extrapolated downcore to similar assemblages as a proxy for subsidence (fig. 8). Diatoms preserve well within the sediment column and are abundant in coastal areas, therefore previously collected sediment cores held within the USGS and other sediment archives can be analyzed for diatom distribution over time. When linked to land elevation information, the fossil assemblage can provide data in locations where long-term monitoring is nonexistent or future monitoring is difficult to maintain. As global sea level continues to rise, an understanding of the response of coastal environments to changes in land elevation in the past is critically important to informing coastal managers how land subsidence will impact future infrastructure and habitats.

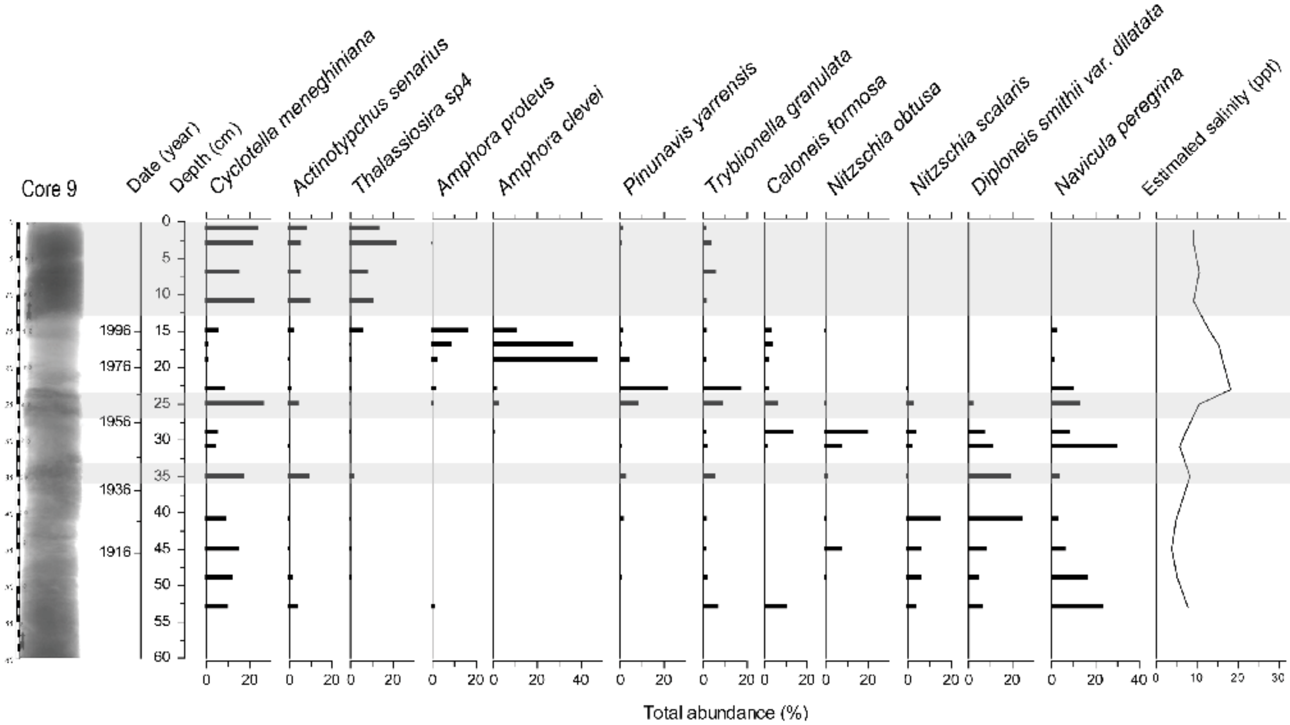


Figure 8. Downcore diatom assemblage abundance with estimated age of deposition and salinity. From Smith (2012).

"Did Subsidence Contribute to Differential Rates of Relative Sea-Level Rise in South Florida?" presented by Lauren Toth (St. Petersburg Coastal and Marine Science Center)

In Florida, the contribution of subsidence and its drivers to relative SLR represents a fundamental knowledge gap that must be addressed to forecast the rates and magnitude of future SLR. Anomalously high rates of SLR in south Florida suggested by both Holocene geological reconstructions and historical data imply that subsidence might play a significant role in regional inundation. This trend is consistent with the observed southwest tilt of the Florida Platform (fig. 9). Further studies are necessary to determine whether active tectonic (for example, faulting or epeirogenic movement) or erosional processes (for example, differential weathering of carbonate rock) contribute to this tilt.

"Gains or Losses: Uncertainty in Episodic Sediment Loading on Marsh Elevations," presented by Christopher Smith (St. Petersburg Coastal and Marine Science Center)

The susceptibility of coastal salt marshes to SLR may be influenced by elevation loss owing to sediment loading. During an episodic event, such as a hurricane, sediment removal can result in elevation loss; this loss reduces the ability of the salt marsh to recover. The Pearl River Bay-Head Delta in Louisiana was relatively unaffected by Hurricane Katrina, as accretion rates since the storm kept pace with SLR and no depression was observed on the marsh surface (McCloskey and others, 2018). On the other hand, Dauphin Island in Alabama experienced a storm surge-induced washover of sand across the marsh platform. The sediment loading that took place during this storm surge resulted in the compression of the marsh surface and overall lowering of elevation.

"GIS Techniques in Mapping Sinkholes at a Regional Scale," presented by Michael Bradley (Lower Mississippi-Gulf Water Science Center)

Geographic information systems (GIS) are an invaluable tool for understanding the regional occurrence, density, and characteristics of regional variability to better identify anomalous features, such as sinkholes. Information about groundwater hydrology, regional variability, economic impact, contaminant transport, and flooding can be gained using GIS techniques (Taylor and Nelson, 2008). The fill tool in ArcGIS is used to automate the delineation of depressions for infrastructure-hazard assessment. Automated methods can process large regions while taking advantage of light detection and ranging- (lidar) derived topographic data. However, false positives often result from using automated GIS techniques, and thus the overall process can be labor intensive. Regardless, GIS is a practical and necessary tool for monitoring land change, of which subsidence is a significant contributor, and it can contribute to USGS development of geologic hazard maps.

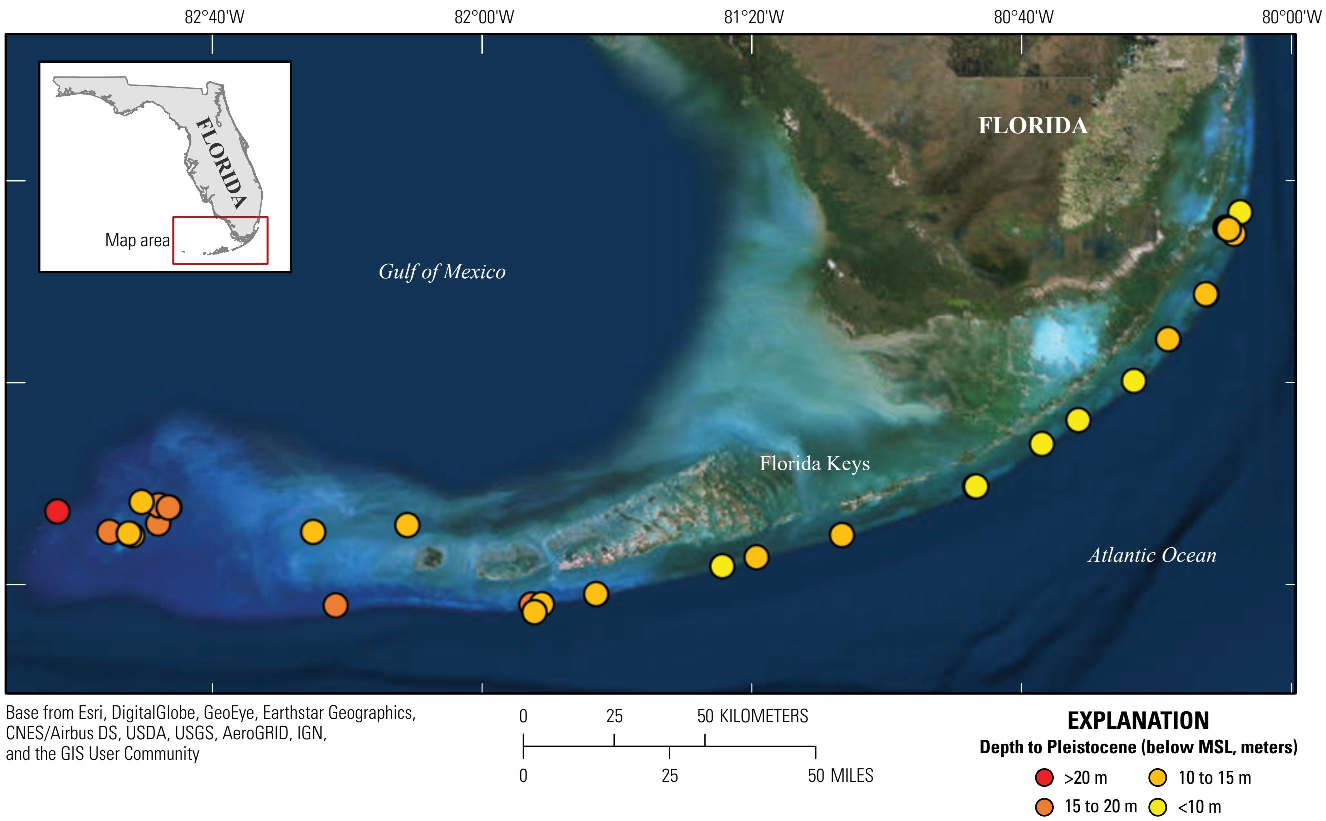


Figure 9. Map showing depth to the Pleistocene bedrock of the Florida Keys reef tract in meters below mean sea level (m MSL) based on reef cores. Note the apparently southwest tilt of the south Florida platform. Modified from Toth and others (2018).

"Tools to Measure Relative Compaction Rates in Deltaic Sediments and Detect Subsurface Collapse Features in Karst," presented by James Flocks (St. Petersburg Coastal and Marine Science Center)

Rates of land subsidence vary greatly across coastal systems and consist of many mechanisms: compaction of deltaic sediments, growth faulting, fluid withdrawal, sediment loading, and isostatic adjustment. In deltaic environments, the stratigraphy is highly variable in lithology and texture, leading to differential rates of subsidence, both spatially and vertically, owing to lithologic-specific compaction and loading. Despite recognition as an important component to differential subsidence rates, the relative contribution of these deposits remains unknown. Current techniques of measuring subsidence (geodetic surveys, surface elevation tables, lidar, satellite imagery, tide-gauge data, age-date measurements of peat deposits) cannot isolate the relative contribution of subsidence owing to sediment compaction in subsurface deposits (Keogh and Törnqvist, 2019). By characterizing the stratigraphy through borehole drilling, key lithologic units can be identified. These lithologic units can be targeted with gauges that are repeatedly measured over decades with high precision to monitor changes in elevation between the gauges, which provides a proxy for differential compaction. These compaction gauges are composed of ring magnets fitted around the borehole and attached to the substrate using steel strings (fig. 10).

In karst terrain, land subsidence is due to the dissolution of carbonate rock in the subsurface, sometimes leading to catastrophic collapse in the form of sinkholes. Subsurface dissolution features are difficult to detect because of spatial variability in stratigraphy and the wide range in dimension of these features. High resolution seismic profiling (HRSP) has proven adequate in imaging subsurface karst features in coastal and lacustrine settings (Flocks, and others, 2001). Subsurface dissolution features in HRSP appear as chaotic signal returns within horizontal reflectors, while concave reflectors can represent subsidence of stratigraphy overlying deeper dissolution or collapse features. Identifying karst-related features in the subsurface is important in mitigating potential hazards to infrastructure and characterizing fluid migration pathways between aquifers and surface water bodies.

Key Findings

Subsidence is a naturally occurring process that can be intensified through human activities such as fluid extraction, mining, and overburden alteration. These concerns formed the basis for organizing the SFT to review our current

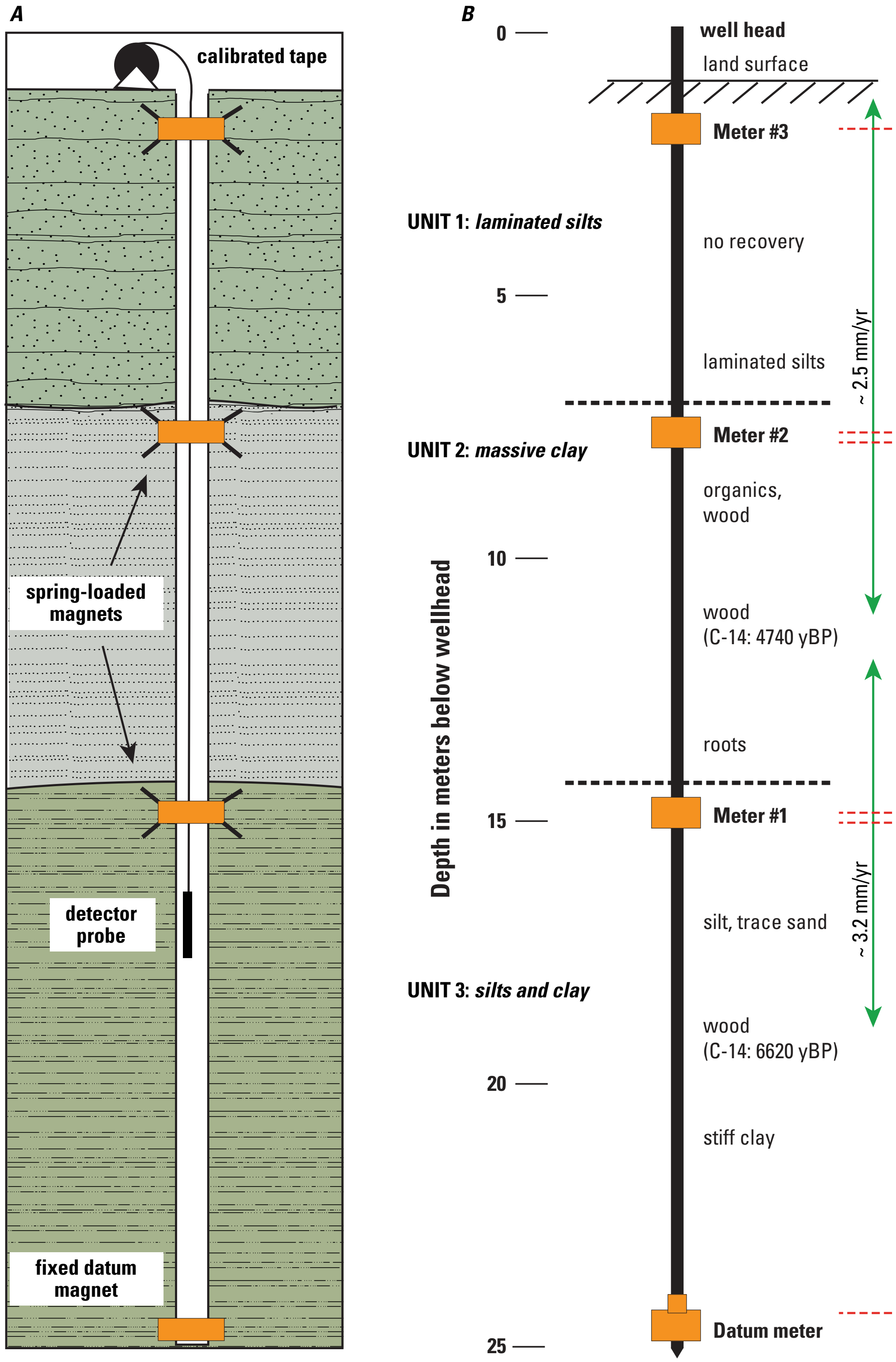


Figure 10. *A* Schematic of a borehole with compaction gauges installed. The magnet rings with steel springs are installed following drilling and attached to the substrate. Depth to the magnet rings is repeatedly measured with high precision using a probe and tape measure or a digital wire-out system. *B* Lithologic descriptions from borehole samples identify three units in the substrate. Carbon dating from wood samples identifies two ages from which variable rates of subsidence can be inferred (green arrows). Since the recovered wood samples are not at the lithologic horizons, the differential rates of subsidence do not correspond to compaction within the lithologic units (red dashed lines). Using the lithologic interpretation, compaction gauges installed near the lithologic horizons can be repeatedly measured to quantify rates of compaction for each identified unit.

understanding of subsidence-related phenomena. Several key findings were identified by the SFT after the presentations and in-depth group discussions by team members:

- Hazards associated with subsidence, such as surface-water inundation, sinkhole formation, infrastructure damage, and loss of critical habitat such as wetland loss, are a significant threat across a diverse range of landscapes throughout the world. Subsidence is frequently observed in all SER states as well as most other U.S. states and territories.

- Subsidence affects both inland and coastal communities through many different processes. Subsidence that takes places near the coast is often a driver of local relative SLR. Whereas global networks exist that quantify and monitor rising sea level, the relative contribution of subsidence to past and present sea-level variability represents a fundamental knowledge gap.

- There is a lack of a unifying framework that describes the processes driving land subsidence and its impact to environments and coastal communities through a comprehensive subsidence-monitoring and assessment program, with the intent of providing Federal and state agencies, as well as the public, with high-quality long-term data, historic and real-time maps of subsidence-related hazards.

Knowledge Gaps

The processes that drive subsidence are diverse. Because of the wide range in the scale of subsidence-related features, as well as the typically long time periods necessary for their evolution, a comprehensive assessment of subsidence-related hazards is difficult to develop. Unlike other natural disasters, such as earthquakes and hurricanes, no comprehensive database exists that tracks subsidence-related impacts. Research has been further hindered by the fact that data on subsidence is typically only collected as a byproduct of other focused studies, such as groundwater or SLR assessments, rather than being a focus of study unto itself. Global networks have been established to quantify and monitor rising water levels; however, the relative contribution of subsidence and its drivers to past and present sea-level variability represents a fundamental knowledge gap. The spatial and temporal variability of subsidence-related events requires systematic monitoring in order for predictive modeling to account for associated hazards (Shirzaei and others, 2020). An approach to quantify the rates and drivers of subsidence is needed to accurately forecast coastal vulnerability to SLR. This approach could include a national elevation-monitoring network that is integrated with subsidence-reporting tools and modeling capabilities. This information would help inform management decisions that affect coastal communities and infrastructure.

The Potential Role of USGS in Subsidence-Related Research

The USGS has the expertise to address the knowledge gaps present in both research and community outreach related to land subsidence. The SER, with its extensive coastline, dense coastal population centers, and economically valuable infrastructure and wetlands, is especially vulnerable to coastline changes. The USGS is a leader in coastal hazard assessments and karst studies for the Nation. By leveraging and adapting existing monitoring networks and programs, the development of a subsidence research and assessment program can be an achievable goal for the USGS within the next few years. Nationwide, the USGS has a diverse staff of researchers with a variety of specialties and research interests, many of which are directly or indirectly related to land subsidence and (or) its associated hazards. This network of USGS researchers can leverage their wide range of expertise to develop a regional and temporal synthesis of subsidence processes and related hazards. The USGS has a long history of fostering agency partnerships within the Department of the Interior (DOI) and with other Federal and state agencies to provide high quality and long-term monitoring data that is publicly available. Not only are large datasets able to be stored and managed by the USGS for perpetuity, but researchers can also transfer research science to applied science through the development of technology or vulnerability assessments, which can be used by local or state agencies. USGS researchers also have the capability to incorporate new technologies and (or) improve current systems for research efficiency. This combination of a wide breadth of expertise, legacy of monitoring capability, and balance of research and applied science provides the USGS with the opportunity to develop a comprehensive subsidence research program within the DOI.

Nonetheless, there are gaps in USGS capabilities that prevent development of a proper subsidence research program. Currently, no cohesive working group exists that brings together all past and present subsidence-related research efforts. Integrating work between the Water Science Centers and Mission Areas could help to develop a subsidence monitoring network, perhaps through permanent working groups at the DOI level. Additional meetings with other SER Flex-team efforts, such as the SLR working group, would help integrate related research topics. To advance subsidence issues to a higher level of consideration, connections could be established between other research networks. For example, subsidence is directly related to SLR hazards such as inundation and storm surge vulnerability, aquifer drainage systems, karst environments, and coastal wetland sustainability. A better understanding of how these systems affect and are affected by subsidence could help create a comprehensive subsidence research network. A large obstacle facing the implementation of a nationwide subsidence research network stems from the inconsistencies in the nature and intensity of subsidence in different regions. In addition to USGS datasets being publicly accessible, a unifying framework of information could provide a consistent transfer of knowledge to the public, as well as to local and state-wide decision makers and resource managers. Scientific research aligned with urban issues at the local level could engage land managers and the public. These goals can be accomplished through the development of a communication template that can be distributed across regions, as well as the distribution of public-friendly and media-digestible products.

To achieve a USGS subsidence research network that can translate findings into region-specific risk assessments, existing monitoring systems such as the USGS National Water Information System (NWIS) and the Coastwide Reference Monitoring System (CRMS) could be leveraged to measure subsidence rates; however, to provide far-reaching subsidence assessments for the Nation, additional monitoring sites would be useful. A national network of experts could analyze the subsidence data and create hazard-risk assessments. This line of research would allow the dominant processes driving subsidence in each region to be identified and mapped, and the contribution of subsidence to SLR in coastal areas to be quantified. A national subsidence monitoring system would allow hazard thresholds for specific areas to be identified, and impacts on water quality, hydraulic connectivity, urban inundation, and infrastructure to be assessed on a local level and communicated directly to the stakeholders.

The SFT concluded that USGS communication strategies could be expanded in order to better educate the public on subsidence and its associated hazards. One method that was discussed was to quantify subsidence through the lens of economics. Using historical data on infrastructure and ecosystem damage resulting from land-loss and inundation, region-based vulnerability to sinkholes, and projected rates of SLR in coastal areas, it would be possible to provide the public and community decision makers with an economic understanding of the hazards at large owing to subsidence in a given area. As subsidence occurs in different forms throughout the Nation, one way to achieve a greater public understanding of subsidence risks would be to develop accessible and easy-to-understand economic risk information related to the regional threat.

Goals for Future Efforts

The SFT concluded the workshop by brainstorming what the USGS could be doing with respect to subsidence in the SER and nationwide. There was an underlying agreement among participating scientists that systematically monitoring subsidence would be a beneficial goal. The USGS has the capability to develop and maintain a nationwide network to monitor, assess, and model subsidence-related processes. The SFT discussed the development of a program analogous to the USGS's earthquake and volcano monitoring programs. Existing monitoring networks such as CRMS, well networks, NWIS, and tidal networks could be augmented with compaction meters and gravity sensors to quantify ongoing subsidence rates and determine total magnitude of subsidence that has occurred historically. For example, GPS monitoring at selected CRMS station sites could be conducted by identifying numerous sites per hydrologic basin along coast-to-inland transects in both healthy and degraded wetlands to quantify subsidence rates. In addition, remote sensing technologies such as Interferometric Synthetic Aperture Radar (InSAR) could be utilized for operational subsidence monitoring and analysis.

Nevertheless, data collection and analysis only provide the raw materials needed to elevate subsidence and its related hazards to that of national importance. A more location-specific, in-depth understanding of the causes and effects of subsidence could inform development and resource management decisions. A potential approach would be a pilot monitoring project in a publicly visible place, such as a National Park, to both bring attention to the issues and to coordinate with other agencies.

It was noted by the SFT that most management actions related to subsidence issues focus on groundwater sustainability and not necessarily on subsidence mitigation (for example, Coachella Valley Water District, 2002). In coastal areas, this lack of understanding about subsidence processes makes it impossible to accurately project the local impacts of global SLR, which is exacerbated by subsidence in many places. A recent study by Shirzaei and others (2020) describes various techniques used to monitor subsidence and modeling capabilities to project potential hazards to infrastructure. Employing these methods into a nation-wide architecture would reduce public exposure to subsidence-related risk. The USGS has the responsibility to inform and protect the public from natural hazards through expanding technologies and subsidence related to research.

Conclusion

With all perspectives considered, the SFT recommends that subsidence-related research should continute to expand in scope to be successful in mitigating damage to both the environment and human infrastructure. Many communities within the SER and the nation are experiencing the consequences of subsidence hazards such as coastal flooding, wetland loss, and sinkhole collapse. A comprehensive assessment of the issues will provide a consistent framework of information for public awareness and land management. As subsidence near the coast is often a driver of local relative SLR, and global mean water levels are projected to continue rising, it is important to better understand the role of subsidence within communities. A comprehensive monitoring and assessment program, organized at the national level in collaboration with regional stakeholders with a goal of long-term support and consistent communication, would prove invaluable to decision makers in protecting our natural environments and human infrastructure from subsidence-related hazards.

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Appendixes

Appendix 1. Table

Table 1.1. 2018 Subsidence Flex Team Members

[CFWSC, Caribbean Florida Water Science Center; LMGWSC, Lower Mississippi-Gulf Water Science Center; OKIWSC, Ohio-Kentucky-Indiana Water Science Center; SAWSC, South Atlantic Water Science Center; SPCMSC, St. Petersburg Coastal and Marine Science Center]

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Appendix 2. Agenda

Documenting the multiple facets of a subsiding landscape from coastal cities and wetlands to the continental shelf, September 26–27, 2018, SPCMSC

Day 1 (Wednesday Sept. 26)

Convene: 9:00am
Introduction (Jim Flocks, Eileen McGraw)
Round table Intro

9:30am Flex-Team workshop reviews
John Stamm (**call-in**): Summarize SLR Workshop
Chris Smith: Summarize carbon/saltwater intrusion workshop

10:00am Presentations (organized by general theme)

Hydrology

Scott McBride: Groundwater and Surface-Water Interactions as Related to Subsidence in West-Central Florida

Devin Galloway: Overview of Land Subsidence Caused by Aquifer-System Compaction Accompanying Exploitation of Groundwater Resources

James Landmeyer: Aquifer Responses to Barometric Pressure: A Proxy for Measuring Changes in Deep Sediments Due to Subsidence?

Break (15 minutes)

Landscape Change and Sea Level Rise

Chris Swarzenski: Uncertainties in Measuring Submergence of Coastal Marshes Below Long-Term Water Levels

Julie Bernier: Quantifying Wetland-Loss Trends, Processes, and Large-Scale Historical Accommodation Formation in Coastal Louisiana

John Barras: Episodic Wetland Loss from Rapid Subsidence and Other Drivers

Kathryn Smith: Diatoms as Indicators of Sea-Level Change

Lauren Toth: Subsidence and Local-Scale Variability in Relative Sea-Level Rise in South Florida

12:00pm Lunch (provided)

1:00pm Presentations (continued)

Measurement and detection

Christopher Smith: Gains or Losses: Uncertainty in Episodic Sediment Loading on Marsh Elevations

Michael Bradley: GIS Techniques in Sinkhole Delineation

Jim Flocks: Tools to Measure Relative Compaction Rates in Deltaic Sediments and Detect Subsurface Collapse Features in Karst

Break (15 minutes)

2:00pm Discussion (group)

Summaries of presentations
Connections between presentations
Current USGS research strengths and weaknesses
What other entities do (list of known experts)
What is not being done
Review agenda for Day 2 and revise if needed based on Day 1 accomplishments

Adjourn: 5:30pm

Day 2 (Thursday, September 27)

Convene: 9:00am

Refresh Day 1 analysis of knowns and unknowns
(Eileen McGraw)

Synthesis: How to cross-collaborate research efforts (group)
Hazards and Landscape change connections

Identifying potential funding streams for collaborative research. List of asks for region, Science Centers, and Mission Areas (group)

List potential products where team can participate in proposals, publications, or other venues (group)

Lunch (provided)

1:15pm Nick Aumen call-in: Getting the word out and further charge

Develop a science strategy to strengthen the role of the Natural Hazards Mission Area in subsidence related issues (group)

What is needed to express the importance of subsidence-related research to the Region? (group)

Consolidate notes from Workshop, develop ideas for a fact sheet and white paper (group)

Adjourn: 5:00pm

For more information concerning the research in this report, contact the
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