PART III

Collapsing Cavities

Sudden and unexpected collapse of the land surface into subsurface cavities is arguably the most hazardous type of subsidence. Such catastrophic subsidence is most commonly triggered by ground-water-level declines caused by pumping, or by diversion of surface runoff or ground-water flow through susceptible rocks. Though the collapse features tend to be highly localized, they can introduce contaminants to the aquifer system and, thereby, have lasting regional impacts. Collapse features tend to be associated with specific rock types having hydrogeologic properties that render them susceptible to the formation of cavities. Human activities can facilitate the formation of subsurface cavities in these susceptible materials and trigger their collapse, as well as the collapse of preexisting subsurface cavities.

In terms of land area affected, underground mining accounts for about 20 percent of the total land subsidence in the United States, and most of this fraction is associated with underground mining for coal. Subsidence over underground coal workings develops as a gradual downwarping of the overburden into mine voids and is generally unrelated to subsurface water conditions. Underground salt and gypsum mines are also subject to downwarping of the overburden, but these evaporite minerals are also susceptible to rapid and extensive dissolution by water. Salt and gypsum are, respectively, almost 7,500 and 150 times more soluble than limestone, the rocktype often associated with catastrophic sinkhole formation and the distinctively weathered landscapes collectively known as karst. Here, we consider only the collapse of cavities that form in soluble rocks such as salt, gypsum, and limestone.

This sinkhole in Kansas was formed by collapsed evaporite rocks.

Formation of subsurface cavities by dissolution requires: 1) bedrock composed in large part of soluble minerals; 2) a water source that is unsaturated with respect to these minerals and, therefore, can dissolve them; 3) an energy source in the form of a hydraulic gradient to move the water through the rock; and 4) an outlet for the escaping, mineralized water. Once a through-flowing passage develops in the soluble rock, erosion and further dissolution enlarges the pas-

In western Kansas dissolution of gypsum and salt beds several hundred feet below the surface caused the sudden formation of the Meade Sink in March 1879. The hole was about 60 feet deep and 610 feet in diameter and filled with saltwater. Today the sink has partly filled with sediment and is usually dry.

(Kansas Geological Survey)

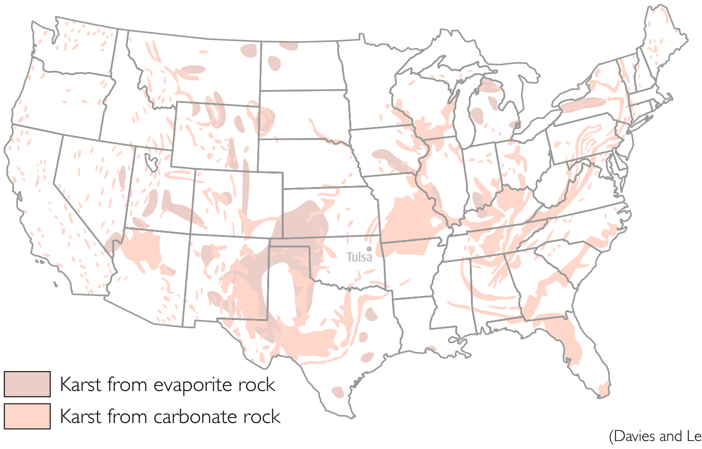
sage, further enhancing the throughflow. Once established, subsurface cavities may provide habitat for populations of species specially adapted to cave environments—a cave ecosystem. The interaction between these biological communities and the mineral substrate of the host cavities may further enhance mineral dissolution and cavity enlargement through the production of acid metabolites.

EVAPORITE ROCKS CAN FORM CAVITIES WITHIN DAYS

Evaporites are sediments deposited from natural waters that have been concentrated as a result of evaporation. Evaporite rocks such as salt and gypsum underlie about 35 to 40 percent of the contiguous United States. Natural solution-related subsidence has occurred in each of the major salt basins (Ege, 1984), perhaps most notably in the Permian basin of Texas, New Mexico, Oklahoma, and Kansas and the smaller Holbrook basin of northeast Arizona. Although evaporites underlie most of the Michigan-Appalachian and Gulf Coast basins, naturally forming collapse features are much less common in these areas. Human-induced collapse cavities are relatively uncommon in gypsum deposits, and more likely to develop above salt deposits, where they are associated with both purposeful and accidental dissolution of salt.

Salt and gypsum underlie about 40 percent of the contiguous United States.

(Martinez and others, 1998)



(Davies and Legrand, 1972)

Carbonate karst landscapes comprise about 40 percent of the contiguous United States east of Tulsa, Oklahoma.

CARBONATE ROCKS FORM CAVITIES OVER CENTURIES

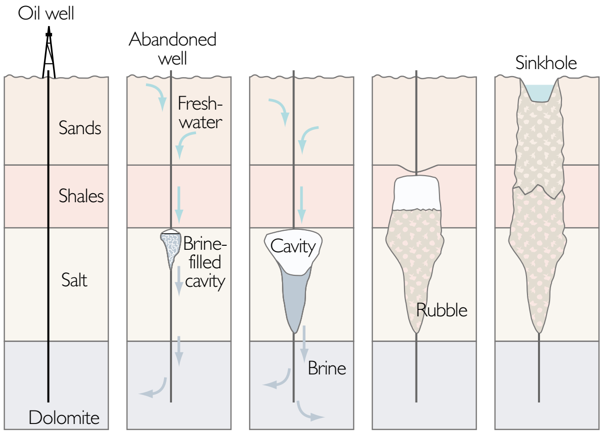
Natural cavities in carbonates (limestone and dolomite) develop by the same processes that form cavities in evaporite rocks, albeit much more slowly. The high solubilities of salt and gypsum permit cavities to form in days to years, whereas cavity formation in carbonate bedrock is a very slow process 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.

Both dissolution and erosional processes play roles in the maturation of karst in carbonates; if not for a balance between mechanical erosion and dissolution, the distinctive landscapes could not persist. The high strength of carbonate rocks confers resistance to mechanical failure despite progressive weakening by chemical dissolution. The potential for dissolution is controlled by the amount of water available and also by the level of saturation of that water with respect to calcium carbonate. Where the potential for dissolution is low, mechanical erosion dominates the morphology of carbonates. For example, in the arid Southwest, limestone exposures tend to erode as cliffs rather than form karst.

These karst towers in Puerto Rico are hills of limestone surrounded by nearly flat alluvial plains cultivated with pineapple.

Carbonate karst landscapes comprise about 40 percent of the contiguous United States east of the longitude of Tulsa, Oklahoma (White and others, 1995). In these more humid landscapes, surface and subsurface drainage pathways converge in discrete conduits formed in the carbonate bedrock. Sinkholes, swallows (where streams disappear into the subsurface), and springs are linked to form an interconnected surface and subsurface drainage network. Thus, karst aquifer systems are directly affected by variabilities in timing and magnitude of surface runoff. Surface runoff carries all the components of streamflow into the conduit flow system, including suspended sediment, dissolved contaminants, immiscible fluids, and micro- and macrobiological agents. The slower infiltration of surface water through porous soil and rock to the water table, which helps to protect ground water from surficial contamination in most areas, is short-circuited in karst landscapes.

An accidental sinkhole: Freshwater from shallow aquifers flowed down an abandoned oil well and dissolved the salt in an underlying formation. A large brine-filled cavity formed and eventually the roof collapsed. Through successive collapses the cavity migrated upward until it formed a sinkhole.



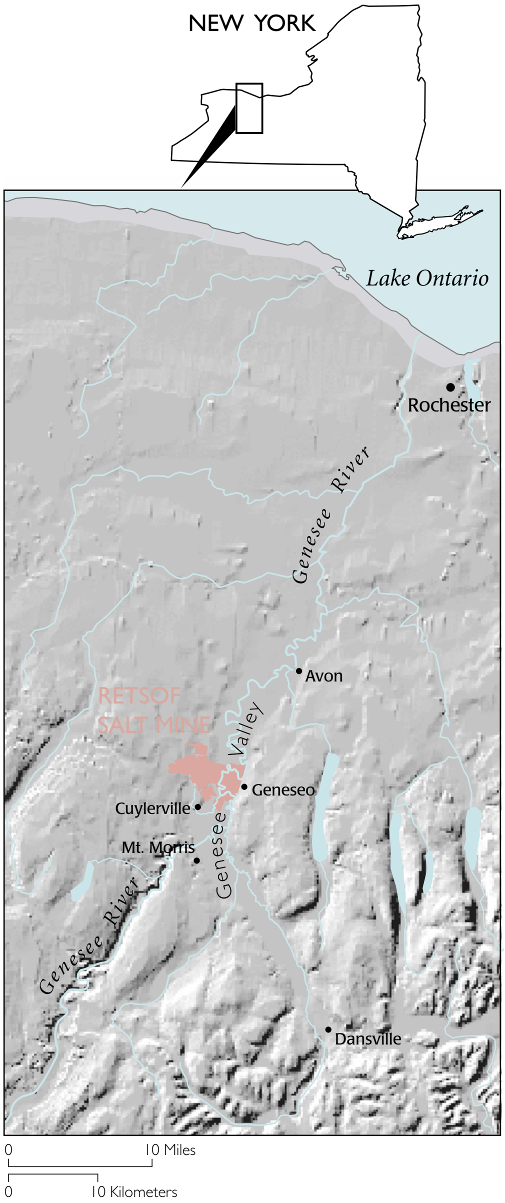
HUMAN ACTIVITY EXACERBATES FORMATION AND OCCURRENCE OF SINKHOLES

The intimate connection between surface hydrologic processes and karst aquifer systems underscores problems related to our land- and water-resources practices in karst landscapes. Human activities tend to accelerate the progress of karstification. Our practice of redirecting surface drainage away from engineered structures and developed lands refocuses higher intensity runoff onto other, generally undeveloped, land surfaces. In karst terrane this increases both mechanical and chemical erosion of susceptible carbonates and evaporites and often accelerates the formation of new sinkholes and the failure of preexisting sinkholes. Exploitation of ground water causes long-term lowering and seasonal and daily cycling of ground-water levels that may destabilize cavities. Lower water tables reduce fluid-pressure support of cavities, sometimes causing drying and ravelling of loose, unconsolidated overburden deposits through preexisting sinkholes and sometimes causing their catastrophic collapse.

Here we will consider two examples where humans have helped to create collapse features in soluble rocks—the Retsof Salt Mine in Genesee Valley, New York and the mantled karst of west-central Florida. In the Genesee Valley the catastrophic collapse and eventual flooding of an underground salt mine threatened the water resources and economic future of a rural New York community. In west-central Florida, where sinkholes naturally dot the landscape, new sinkholes related to land and water-resources development threaten public safety and one of the most productive aquifers in the world, the Floridan Aquifer System.

THE RETSOF SALT MINE COLLAPSE

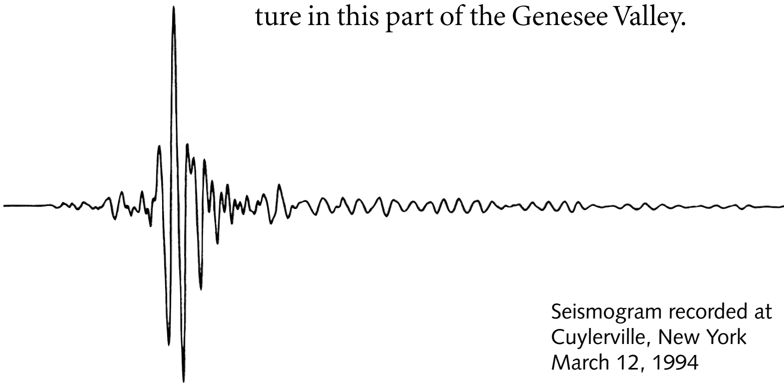
Widespread subsidence occurred after a mine collapse in the Genesee Valley, New York



On March 12, 1994, at 5:43 a.m. (local time), an apparent earthquake of magnitude 3.6 centered near Cuylerville, New York, woke residents and registered on seismographs 300 miles away. Prompted by a call placed from a local resident, the USGS National Earthquake Information Center confirmed that a seismic event had occurred near Cuylerville and immediately notified State emergency services offices in New York who, in turn, notified the Livingston County Sheriff's Department. The Sheriff's Department contacted the Retsof Mine, which, except for some limited subsurface maintenance activity, had suspended active mining that weekend.

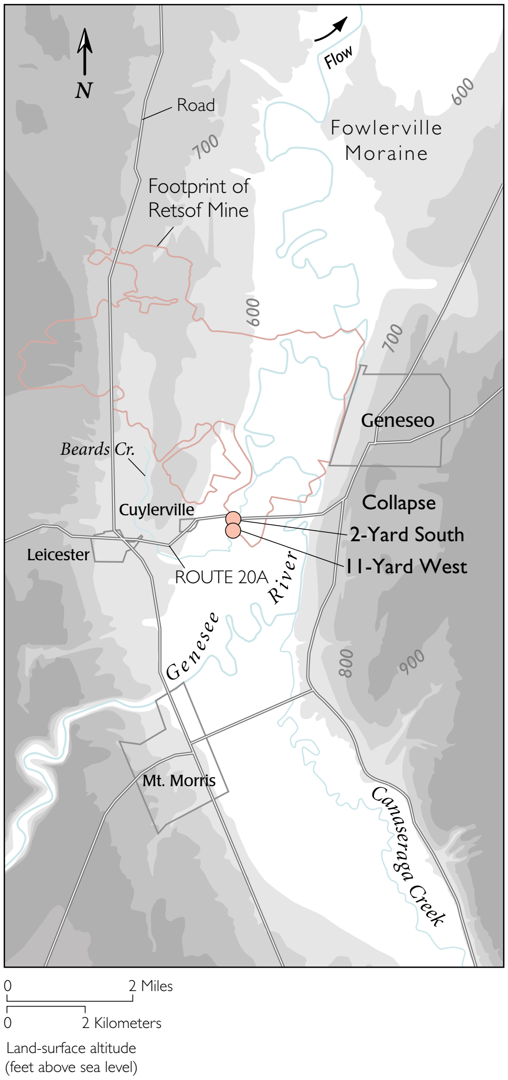
Mine officials discovered that a 500- by 500-foot section of shale roof rock some 1,200 feet below land surface had collapsed in a part of the mine known as room 2-Yard South. Mine officials detected methane and hydrogen sulfide gases, and ground water was flowing into the mine from the roof collapse area at nearly 5,000 gallons per minute.

This collapse began a series of events that would eventually lead to the further collapse and complete flooding of the mine, large declines in local ground-water levels, degradation of potable ground-water supplies, land subsidence, release of natural gases (methane and hydrogen sulfide) to the atmosphere, and other detrimental effects on the cultural resources and infrastructure in this part of the Genesee Valley.



Seismogram recorded at
Cuylerville, New York
March 12, 1994

William M. Kappel, Richard M. Yager, and
Todd S. Miller
U.S. Geological Survey, Ithaca, New York



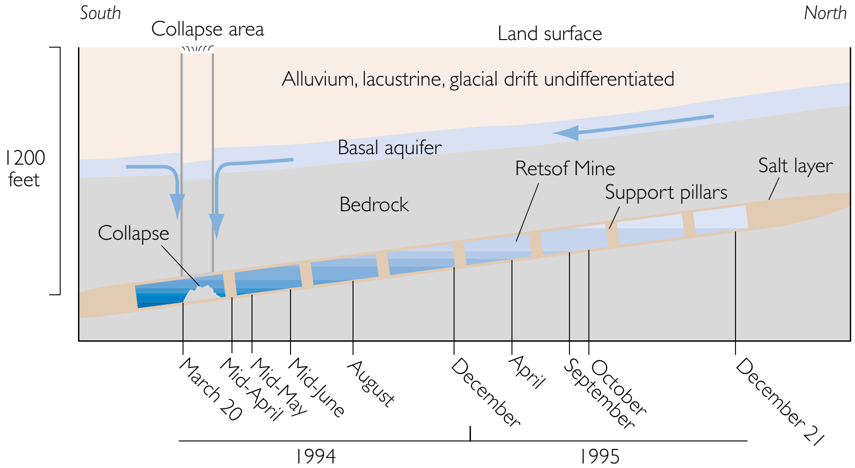
SALT MINING HAS A LONG HISTORY IN THE GENESEE VALLEY

Salt mining (both salt-solution and rock-salt mining) began in the Genesee Valley in the early 1880s, and in 1884 the Empire Salt Company excavated a shaft to extract rock salt from seams 900 feet below land surface. In 1885 the Empire Salt Company was renamed the Retsof Mine Company and the Village of Retsof was founded near the mine shaft. During the next 110 years, the mine grew to become the largest salt-producing mine in the United States and the second largest in the world. Before the initial collapse in March 1994, the mine encompassed an underground area of more than 6,000 acres, and the mine footprint (outer edge of mined area) extended over an area of nearly 10 square miles.

At the time of the collapse, the Retsof Mine was owned by Akzo-Nobel Salt Incorporated (ANSI), and, during the winter of 1993–94, operated at full capacity to meet demands for road salt throughout the northeastern United States. Prior to its closure, the Retsof Mine played a major role in the Livingston County economy, providing more than 325 jobs with an annual payroll in excess of $11 million and estimated annual gross sales of more than $70 million (NYSDEC, 1997). During the 17 months following the collapse, mining operations shifted to the northern, high end of the mine in a race to salvage mineable salt before the mine flooded. The Retsof Mine ceased operations on September 2, 1995, and by December, 21 months after the initial collapse, the mine was completely flooded.

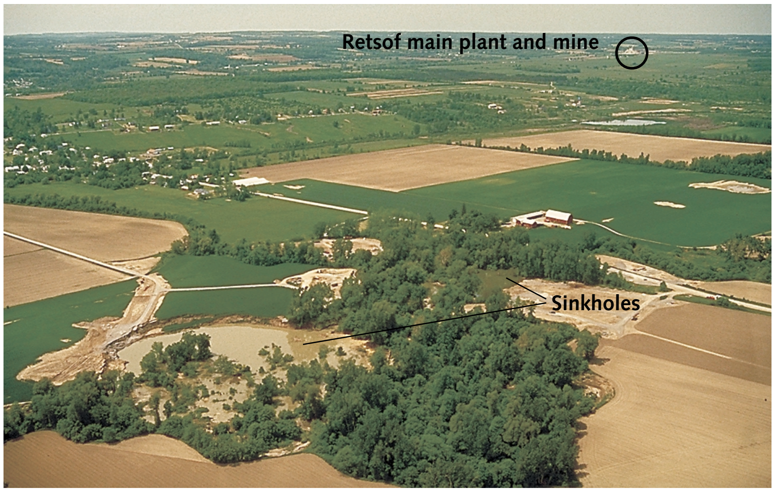
THE COLLAPSE TRIGGERED A SERIES OF LOCAL EVENTS

Four months before the collapse, in November 1993, room 2-Yard South was abandoned because of concerns over large and increasing rates of "convergence" or reduction of the opening between the floor and ceiling of the room. (A new mining technique, "yielding pillar," was used in this area in response to floor buckling and roof collapse, which was occurring with greater frequency in the south-



This cross-sectional schematic shows how water from the basal aquifer entered the mine through the collapsed area. After 21 months the salt mine was completely flooded.

This northwest aerial view shows sinkholes above room 11-Yard West (left foreground) and room 2-Yard South (right center, partially obscured by trees). Circle indicates location of the Retsof main plant area, some 4 miles northwest of the sinkholes.



(Ron Pretzer, LUXE, May 1994)

A sinkhole developed above room 11-Yard West and filled with water from Beards Creek.

(Richard Young, Geological Sciences, SUNY Geneseo, June 1994)

The roadbed of Route 20A was fractured on the east side of the collapsed bridge over Beards Creek. This view is above the room 2-Yard South collapse area looking west, toward the former Hamilton farm house (subsequently purchased by ANSI).

(Richard Young, Geological Sciences, SUNY Geneseo, April 12, 1994)

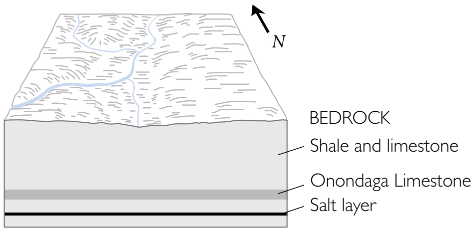
ern end of the mine.) After the March 12, 1994, collapse of room 2-Yard South, ground water flowed into the previously dry mine at a rate of about 7 million gallons per day, dissolving residual rock salt and filling the lowest, downdip levels of the mine with saturated brine. ANSI monitored the concentration of hazardous gases and the encroaching water level in the mine as the shoreline in the mine steadily moved northward.

Local governmental officials had posted warning signs at the Route 20A bridge over Beards Creek the day before the collapse because of small bumps in the pavement on the bridge approach sections. There is some anecdotal evidence that, several days earlier, local travelers had noticed a change in the smoothness of the roadbed near the bridge, suggesting a surface expression of the underground convergence that led to abandonment of room 2-Yard South several months earlier.

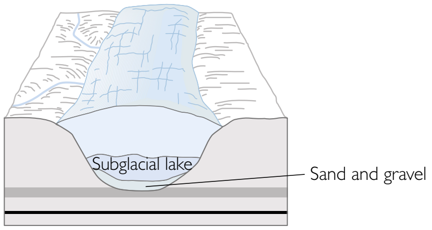
Within days of the collapse, impacts on the glacial and bedrock aquifer systems and on the land surface were reported on an expanding scale. Some homes had sustained structural damage due to the initial earth tremors and, within 1 week of the collapse, residents along Wheelock Road, south of Cuylerville and southwest of the mine, reported that several water wells had gone dry (NYSDEC, 1997). The USGS and the Livingston County Health Department began monitoring ground-water levels and streamflow in the area.

On April 6, a 200-foot diameter by 20-foot deep, cone-shaped sinkhole appeared along the channel of Beards Creek, immediately above the room 2-Yard South collapse zone, just south of the Route 20A bridge. And 2 weeks later, accompanied by additional earth tremors, this sinkhole expanded to about 600 feet in diameter.

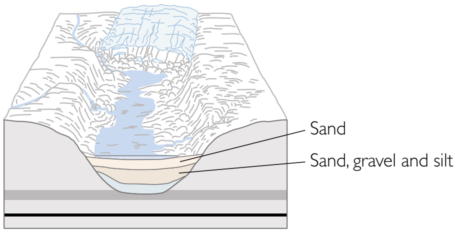
On April 8, seismic events indicated a roof collapse in mine room 11-Yard West, south of and adjacent to room 2-Yard South. Following this collapse, ground-water inflow to the mine increased to about 22 million gallons per day. An expanding sinkhole developed over 11-Yard West on May 25, 1994. The sinkhole was about 50 feet



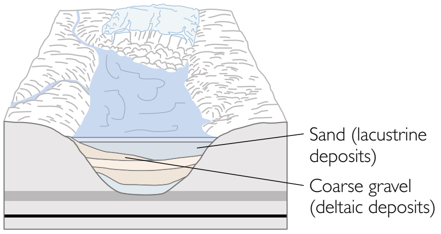
The ancient Genesee River crossed sedimentary rocks.



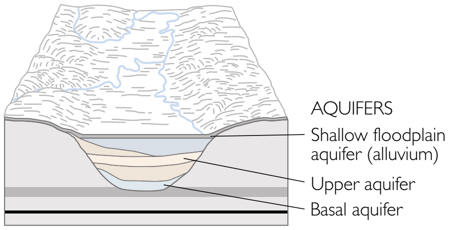
Glaciers scoured the bedrock, leaving a wide, deep valley that did not always follow the course of the Genesee River. At times the glaciers covered the entire area. During periods of glacial retreat, subglacial lakes formed and sediment was deposited.



The periodic retreat and advance of glaciers left behind mounds of debris (moraines) and thick glacial deposits (drift).



During deglaciation a series of proglacial lakes formed that deposited lake (lacustrine) sediments on the valley floor.



After glaciation alluvial (floodplain) gravel, sand, and silt were deposited on top of the glacial sediments.

deep, about 200 feet in diameter, and immediately filled with water captured from Beards Creek. Over time this sinkhole grew to about 800 feet in diameter.

THE NATURAL HISTORY OF THE GENESEE VALLEY SET THE STAGE FOR WIDESPREAD DAMAGE AFTER THE COLLAPSE

Current knowledge of the occurrence and flow of ground water and the complex stratigraphy of the glacial aquifer system in Genesee Valley is sparse. Prior to the collapse, the hydrogeologic framework of the valley-fill materials had not been investigated in detail. Since the mine collapse, several studies have addressed the hydrogeologic framework (Nittany Geoscience, 1995; Alpha Geoscience, 1996), but insufficient data exist to thoroughly characterize the interconnections among glacial units and bedrock aquifer zones.

The Genesee Valley from Dansville to Avon, New York, includes the Canaseraga Creek Valley and, from Mt. Morris northward, the Genesee River Valley. The valley formed as a result of several geologic processes including the ancestral uplift and stream erosion of gently dipping Paleozoic sedimentary rocks, followed by periods of glaciation in which ice scoured and modified the bedrock topography, leaving behind unconsolidated sediments. Recently, stream erosion and deposition added about 50 feet of alluvium (gravel, sand, and silt) to the glacial sediments.

The unconsolidated glacial sediments that fill the Genesee Valley were deposited during cycles of glacial advances and retreats. Glaciers several thousands of feet thick deepened and widened the valley. About 12,000 years ago the most recent glacier retreated from the valley, leaving behind thick glacial deposits. Where the glaciers paused and the ice melted, mounds of glacial debris, called end moraines, were deposited at the frontal (southern) ice margin. The melting ice produced large volumes of water that transported, sorted, and deposited boulders, gravel, cobbles, sand, silt, and clay and carried these sediments in meltwater streams to the south. Proglacial lakes existed in the glacially-deepened valley between the valley walls and the receding glacier during most of the glacial period.

During deglaciation, outlets low enough to drain the proglacial lakes did not exist until the ice margin was 10 to 12 miles north of Geneseo. During this period, the present Genesee River and Canaseraga Creek watersheds drained to the north, toward the glacier, into a series of progressively lower proglacial lakes. The final and lowest proglacial lake formed when the ice deposited the Fowlerville moraine, which extends from about 4.5- to 8-miles north of the collapse area. Water ponded in the Genesee Valley south of the Fowlerville moraine, depositing lake sediments on the valley floor. Eventually the lake drained as the Genesee River cut a channel in the Fowlerville moraine (Young, 1975). As much as 700 feet of glacially derived gravel, sand, silt, and clay were deposited in a subglacial and glaciolacustrine (glacial lake) environment.

The buried bedrock surface follows the slope of the resistant sedimentary carbonate beds of the Onondaga Limestone, dipping approximately 42 feet per mile to the south. Overlying the bedrock surface is a thickening wedge of glacial valley-fill sediments that ranges from a few hundred feet thick on the north, near the Fowlerville Moraine, to about 750 feet thick in the deepest part of the valley near Sonyea. South of Sonyea, the valley fill thins. Ground water in the glacial deposits and portions of the underlying carbonate bedrock has been the primary source for the inflows to the flooded Retsof Mine. The fine-grained lake silt and clay closer to the land surface form a barrier between the alluvial and deeper glacial aquifers.

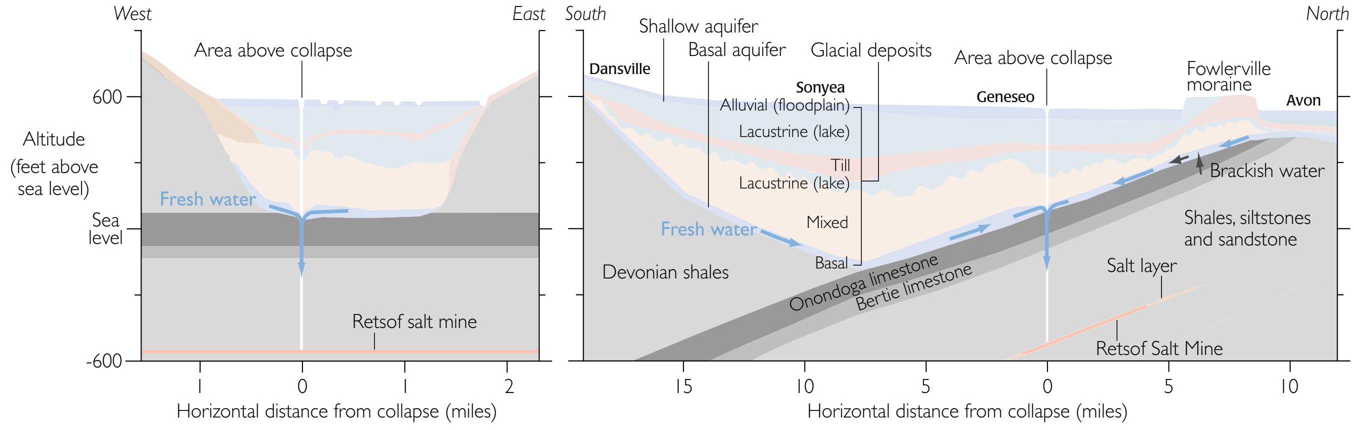
This view shows the Upper Genesee Valley looking east.

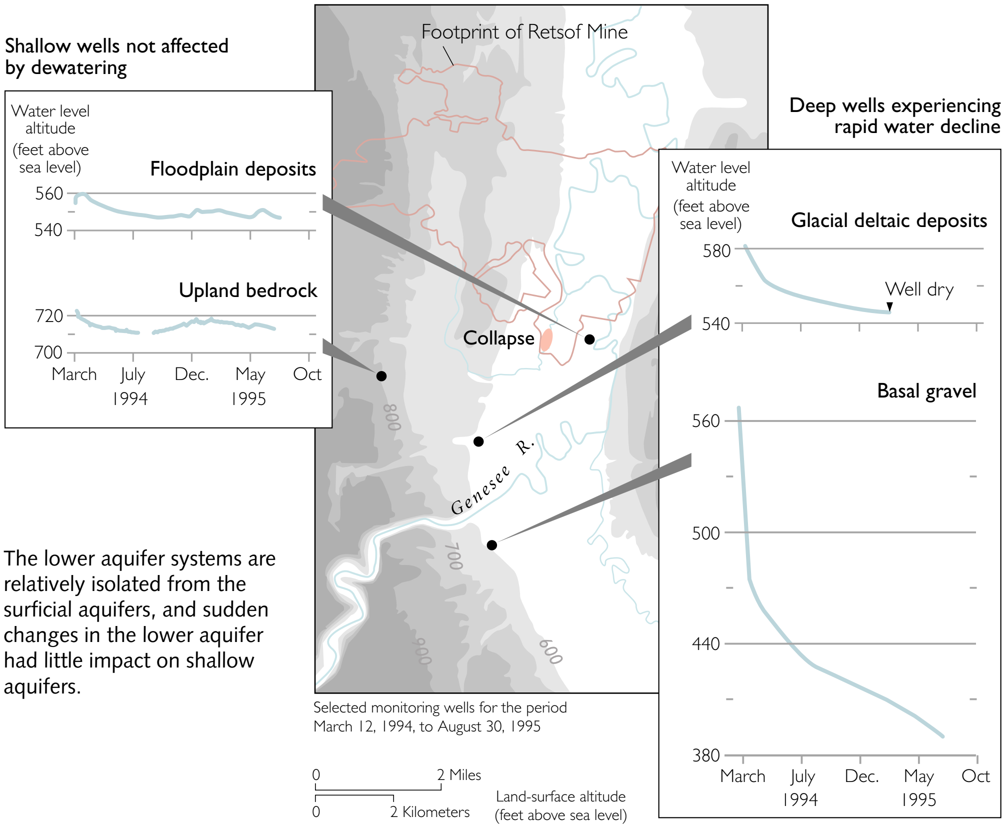
(Richard Young, Geological Sciences, SUNY Geneseo)

Water-bearing zones are found within the fractures and bedding planes near the top of the Onondaga Limestone at the base of the valley fill. Another water-bearing zone is found at the contact between the Onondaga Limestone and the underlying Bertie Limestone. Few valley wells tap bedrock, and the most productive wells completed in the Onondaga and Bertie Limestones seldom produce more than several tens of gallons per minute (Dunn, 1992). The Bertie Limestone subcrops beneath the valley floor north of the Fowlerville moraine, under several hundred feet of glacial sediment, and is generally considered a divide between fresher water above and a more mineralized water below.

The principal aquifer in the valley appears to occur at the base of the valley fill. The relatively thin basal aquifer is composed of sand and gravel deposited on top of the Onondaga Limestone in the central and northern parts of the valley and on top of the low-permeability Devonian shales to the south. The hydraulic connection between the basal aquifer and the underlying bedrock units throughout the valley is poorly understood, but the connection is generally assumed to be better in the northern half of the valley, where the aquifer is in direct contact with the weathered and fractured top of the Onondaga Limestone. Under natural conditions ground water flows upward from the Onondaga to the basal aquifer. Though the basal aquifer is generally overlain by lower-permeability

Water from the basal aquifer entered the mine through the collapsed area.





The lower aquifer systems are relatively isolated from the surficial aquifers, and sudden changes in the lower aquifer had little impact on shallow aquifers.

Selected monitoring wells for the period March 12, 1994, to August 30, 1995

glacial drift, in some areas north of the mine more permeable layers have been reported within the glacial deposits.

Some wells in the valley are completed within the glacial deposits, and some wells completed in the deeper basal aquifer are also screened in the glacial deposits, an indication that there is locally enhanced permeability at intermediate depths. There appears to be a vertical hydraulic connection between the basal aquifer and the permeable zones in the glacial deposits, based upon recent data from ground-water monitoring wells, but the areal extent of these vertically connected zones is unknown.

Shallow ground water occurs in the alluvial deposits found to a depth of 50 feet below the valley floor. The water table in the alluvium is generally less than 15 feet below land surface, and is in hydraulic connection with the Genesee River, Canaseraga Creek, and other tributaries on the valley floor. Other shallow ground water occurs in the Fowlerville Moraine deposits. Most recharge and discharge of the Genesee Valley aquifer system occurs between the Genesee River, its tributaries, and the shallow water-table aquifer in the alluvium (Nittany Geoscience, 1995). Water levels in wells completed in the alluvium were not affected by the mine collapse.

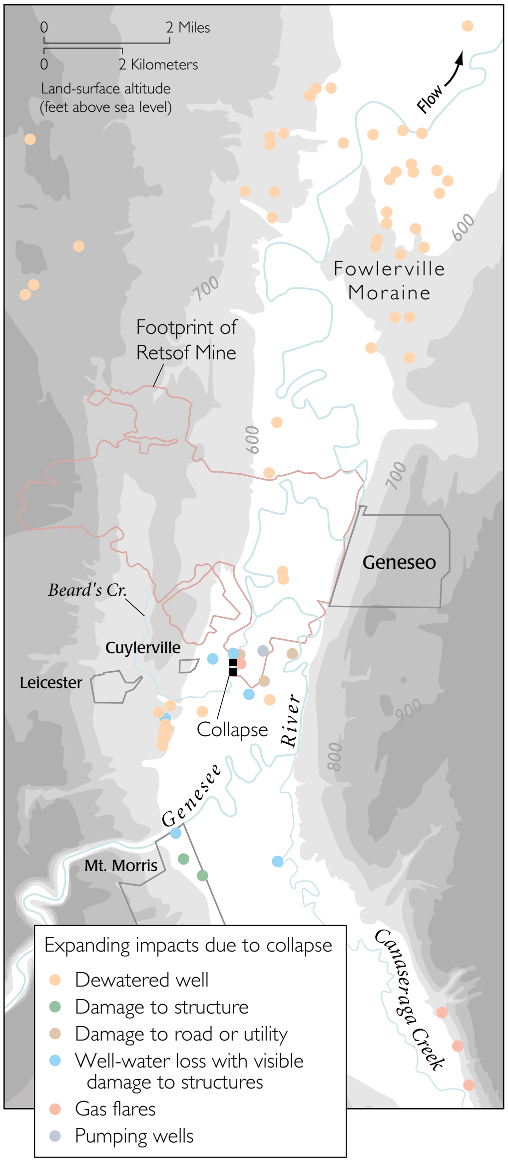
After the mine collapse, most of the inflows to the mine probably came from storage in the basal aquifer and the glacial deposits through the collapse areas above rooms 2-Yard South and 11-Yard

This view of the Genesee Valley floodplain was taken above the southern end of the mine looking southwest.

(Richard Young, Geological Sciences, SUNY Geneseo, 1995)

West. Water levels in wells began declining almost immediately near the collapse zones. Water levels continued to decline rapidly through 1994, and more slowly in 1995, until the mine was completely flooded in January 1996. By then, water levels had fallen more than 350 feet in some wells near the collapse zones. In total, an estimated 42,000 acre-feet of ground water invaded the mine.

The basal aquifer is relatively isolated from surficial sources of recharge and discharge, and changes in the lower part of the aquifer system are not likely to have immediate or significant impact on the shallow sources. However, the rate of ground-water drainage into the mine far exceeded the estimated rate of recharge to the deeper subsurface aquifers, and it is expected that it will take a decade or longer for ground-water levels to recover throughout the aquifer system.



IMPACTS OF THE COLLAPSE WERE OBSERVED MILES AWAY

The effects of the collapse include, but are not limited, to the following:

- Reduced air quality and public-safety issues resulting from the emanation of methane and hydrogen-sulfide gases
- The loss of potable water supplies—both a reduction of quantity and degradation in quality and
- Short- and long-term land subsidence

Natural gas was vented into the environment

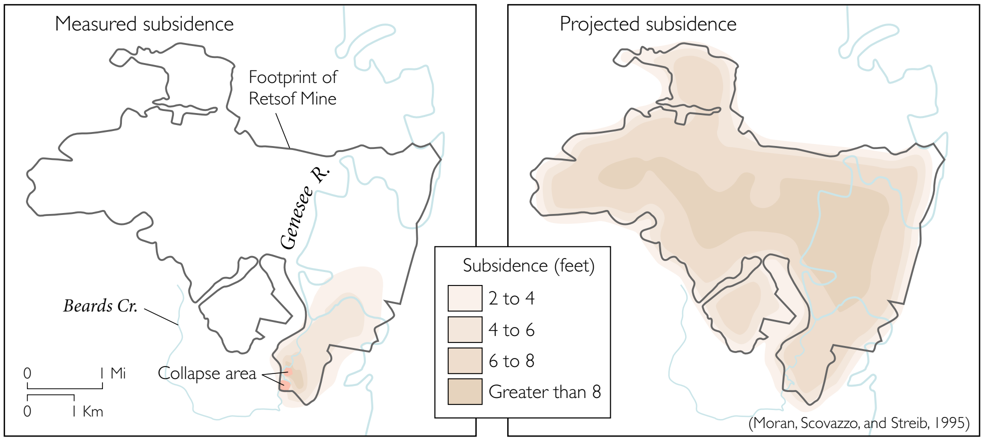
Soon after the mine began to flood and water levels in the basal aquifer were lowered, natural gas in the form of hydrogen sulfide (odor of rotten eggs) and methane (odorless, combustible) began exsolving from ground water—just as carbon dioxide comes out of solution after a bottle of soda is opened. In the area of the collapse, lowered water levels allowed natural gas to escape through test wells drilled near the collapse area and preexisting domestic water-supply wells several miles farther to the southeast. In September 1994 the State Department of Environmental Conservation ordered ANSI to develop a natural-gas monitoring and response plan. By May 1995 the County and State Health Departments required ANSI to flare-off (burn) gas from several collapse-area wells to reduce the odor and protect the health and safety of residents living in Cuylerville and the surrounding area.

Potable water supplies were diminished

Although some shallow alluvial wells near the mine were unaffected, some domestic wells along the margins of the valley and in the deeper zones of the Genesee Valley aquifer system experienced lowered water levels, and some wells went dry. The rate of water-level decline varied: water levels declined 20 feet or more along Wheelock Road (about 1 mile southwest of the mine) within days of the collapse, whereas water levels gradually declined 50 feet or more in the

Local subsidence occurred due to dissolution of salt pillars by freshwater inflow March 1994 to March 1996.

More extensive subsidence due to closure of the salt cavity is projected.



(Moran, Scovazzo, and Streib, 1995)

Fowlerville area (about 6 miles north of the mine) and in Mt. Morris (about 4 miles south of the mine) for 2 years following the collapse. Pursuant to an agreement between ANSI, Livingston County, and the State of New York, ANSI has been supplying water to residents whose wells have gone dry and where water quality has deteriorated.

The effects of ground-water flow to the mine extend more than 10 miles north and south of the collapse area. Following the mine collapse and lowering of ground-water levels, highly mineralized ground water has apparently migrated into freshwater supplies. There are two potential sources: a deep-basin brine that migrates upward along bedding-plane fractures within the Bertie Limestone to the intersection of the Bertie outcrop and the basal aquifer, and a halite (rock salt) component, which may be introduced through older natural-gas or salt-solution wells within the Fowlerville moraine. The mineralized ground water flows downdip (to the south) through the basal aquifer toward the mine collapse area, an apparent reversal of the pre-collapse hydraulic gradient. Presently, salinity is increasing in Fowlerville Moraine wells, south of where the Bertie outcrops and is in contact with the basal aquifer.

A well flares methane and hydrogen sulfide gases from a fracture zone on the eastern margin of the room 2-Yard South sinkhole.

(Richard Young, Geological Sciences, SUNY Geneseo, 1995)

Several types of subsidence were observed

Subsidence damage related to the mine collapse includes:

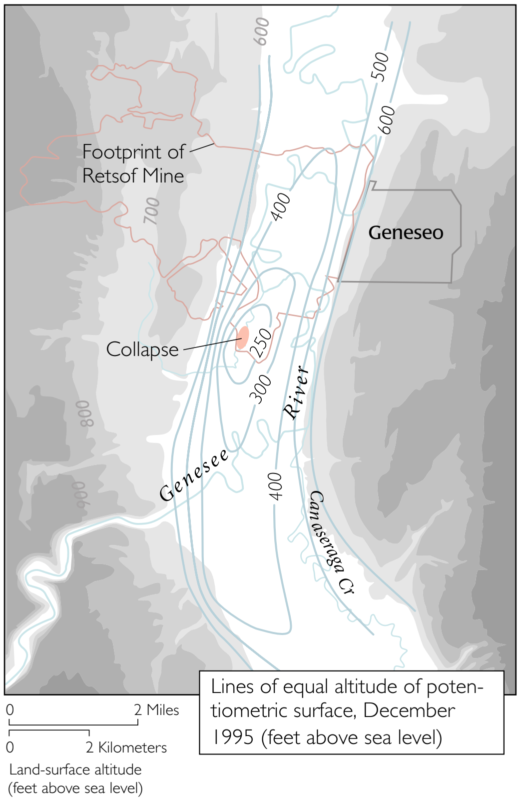
- The creation of 2 large sinkholes
- The temporary loss of State Route 20A through Cuylerville
- Structural damage to homes and businesses and
- Damage to agricultural lands, public utilities, and cultural resources.

Besides the catastrophic formation of sinkholes over rooms 2-Yard South and 11-Yard West, the damage involves three other types of subsidence, which are important at different scales.

An earth fissure ruptures a field above the western edge of the mine, northwest of 2-Yard South sinkhole. The field surrounding the fissure subsided almost 1 foot.

(Richard Young, Geological Sciences, SUNY-Geneseo, March 1995)

The lowering of water levels in areas beyond the mine footprint may eventually cause aquifer-system compaction and land subsidence.



The first type of subsidence that normally occurs over any mined-out area is due to the slow closure of the mine opening. Mining engineers expect the land overlying the Retsof Mine footprint to subside about 8 to 9 feet over the next 100 to 200 years (Van Sambeek, 1994). Most of the estimated subsidence is expected to be realized during the next 100 years (Shannon and Wilson, 1997). Differential subsidence is expected along the margins of the mine, where adjacent areas will subside nonuniformly. This creates stresses within the land mass, which may rupture the surface or subsurface. Some horizontal movement of land surface in these areas is expected, as well as some tilting of the land surface toward the mine. Structures located in these regions may continue to be prone to damage as the mine subsidence evolves.

A second type of subsidence seen near the collapse area and farther to the north and east was caused by the flow of ground water into the mine and resultant dissolution of unmined salt. Fresh ground water, less dense than saltwater, entered the mine cavity quickly, and preferentially dissolved the salt along the mine roof. As the mine roof collapsed, it allowed the freshwater to dissolve more salt in the supporting salt pillars and, over time, left large areas without roof support. This type of subsidence evolved rapidly as many salt pillars were quickly dissolved by the large inflow of freshwater, and subsidence in this area was greater and occurred sooner than would be expected for a dry mine situation (Van Sambeek, 1996). When the mine filled with saturated brine, this type of subsidence ceased.

The third type of subsidence to occur in the Genesee Valley is due to the dramatic lowering and anticipated slow recovery of ground-water levels in the confined-aquifer system. This type of subsidence is due to aquifer-system compaction that typically accompanies the depletion of alluvial aquifer systems. The ground-water level declines experienced after the mine-roof collapse—more than 350 feet near the collapse and as much as 50 feet as far as 8 miles away—is sufficient to cause measurable elastic compression of the glacial sediments of the Genesee Valley aquifer system. It is possible that the large stresses imposed on the aquifer-system skeleton by the large drawdowns may have caused some inelastic, and largely irreversible, compaction of aquitards in the Genesee Valley, but currently this effect is presumed to be small. Aquifer-system compaction may contribute to land subsidence on a spatial scale larger than the mine footprint, especially in regions where large changes in ground-water levels persist and where the glacial deposits contain an appreciable thickness of fine-grained, more compressible sediments. It is possible that the valley floor may continue to be affected by residual compaction long after ground-water levels have fully recovered in the aquifers (Riley, 1969). An accurate evaluation of the magnitude, timing, and areal extent of land subsidence due to aquifer-system compaction will depend on more detailed knowledge of the hydrogeology of the Genesee Valley.

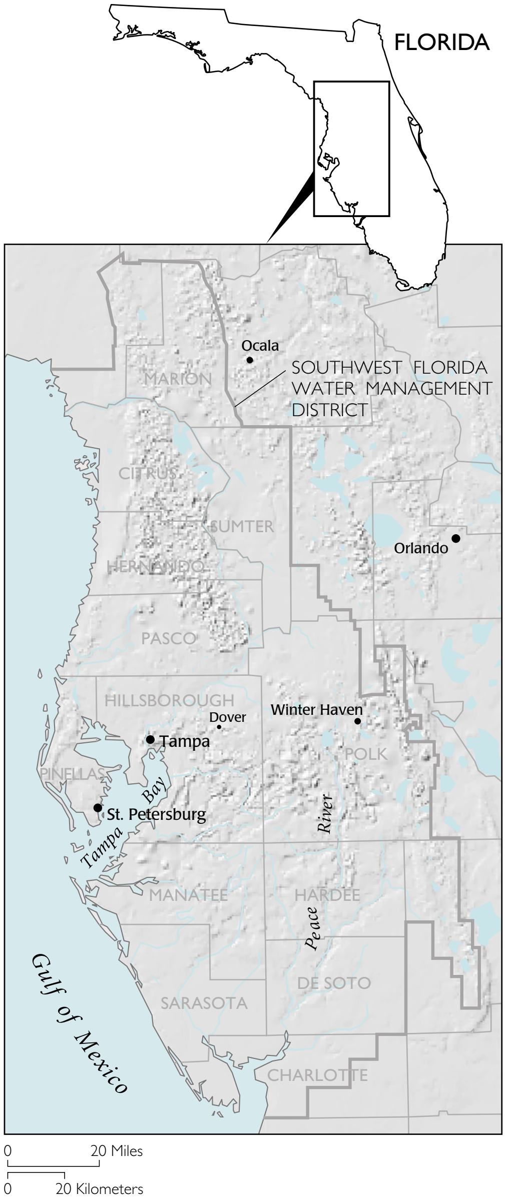
CONTINUING STUDIES WILL ASSESS FUTURE IMPACTS

The long-term lowering of aquifer hydraulic heads creates the potential for permanent compaction of the aquifer system and additional land subsidence. The distribution of compressible sediments and their mechanical behavior need to be better understood in order to predict potential impacts. The sources of poor-quality water and potential paths of migration in the aquifers also need to be assessed in order to evaluate and predict changes in ground-water quality throughout the Genesee Valley.

The USGS is currently implementing conceptual and numerical models of ground-water flow in Genesee Valley to assist in determining the impact of mine flooding on the regional aquifer system. Drainage of ground water into the collapse areas is being simulated using data collected by ANSI consultants; the State Departments of Law, Environmental Conservation, and Health; Livingston County; local citizens; the USGS; and others. The models will provide insight into the problems of lowered ground-water levels, land subsidence caused by aquifer-system compaction, and migration of mineralized ground water.

SINKHOLES, WEST-CENTRAL FLORIDA

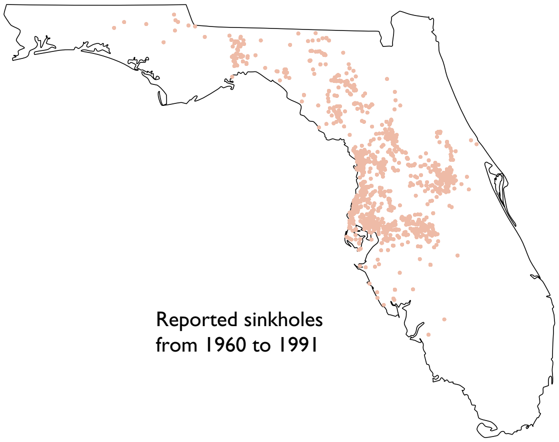
A link between surface water and ground water



Sinkholes are a common, naturally occurring geologic feature and one of the predominant landforms in Florida, where they pose hazards to property and the environment. Although many new sinkholes develop naturally, in west-central Florida and elsewhere, their increasing frequency corresponds to the accelerated development of ground-water and land resources. Usually little more than a nuisance, new sinkholes can sometimes cause substantial property damage and structural problems for buildings and roads. Sinkholes also threaten water and environmental resources by draining streams, lakes, and wetlands, and creating pathways for transmitting surface waters directly into underlying aquifers. Where these pathways are developed, movement of surface contaminants into the underlying aquifer systems can persistently degrade ground-water resources. In some areas, sinkholes are used as storm drains, and because they are a direct link with the underlying aquifer systems it is important that their drainage areas be kept free of contaminants. Conversely, when sinkholes become plugged, they can cause flooding by capturing surface-water flow and can create new wetlands, ponds, and lakes.

Most of Florida is prone to sinkhole formation because it is underlain by thick carbonate deposits that are susceptible to dissolution by circulating ground water. Florida's principal source of freshwater, ground water, moves into and out of storage in the carbonate aquifers—some of the most productive in the nation. Development of these ground-water resources for municipal, industrial and agricultural water supplies creates regional ground-water-level declines that play a role in accelerating sinkhole formation, thereby increasing susceptibility of the aquifers to contamination from surface-water drainage. Such interactions between surface-water and ground-water resources in Florida play a critical and complex role in the long-term management of water resources and ecosystems of Florida's wetlands (see Florida Everglades in Part II of this Circular).

Ann B. Tihansky
U.S. Geological Survey, Tampa, Florida



Reported sinkholes from 1960 to 1991

(Wilson and Shock, 1996)

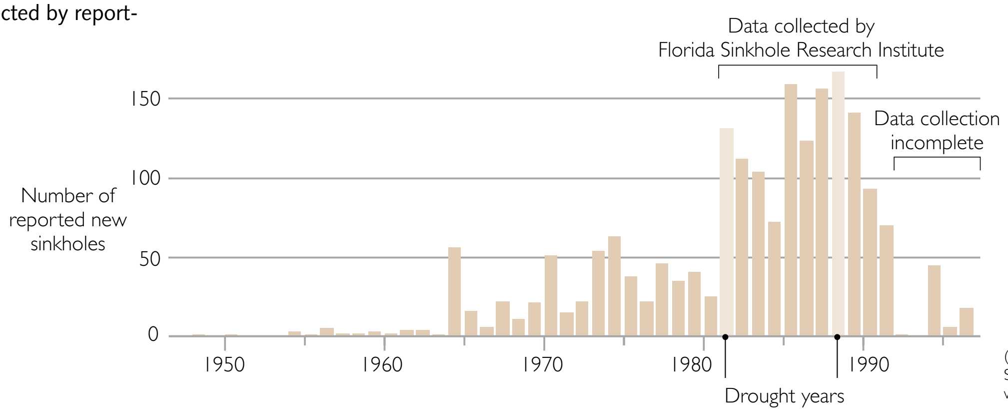
SINKHOLES ARE A NATURALLY OCCURRING FEATURE IN THE FLORIDA LANDSCAPE

The exposed land mass that constitutes the Florida peninsula is only part of a larger, mostly submerged carbonate platform that is partially capped with a sequence of relatively insoluble sand and clay deposits. Siliciclastic sediments (sand and clay) were deposited atop the irregular carbonate surface, creating a blanket of unconsolidated, relatively insoluble material that varies in composition and thickness throughout the State. In west-central Florida, the relation between the carbonate surface and the mantling deposits plays an important role in the circulation and chemical quality of ground water and the development of landforms. Sinkhole development depends on limestone dissolution, water movement, and other environmental conditions. Limestone dissolution rates (on the order of millimeters per thousand years) are highest in areas where precipitation rates are high. Cavities develop in limestone over geologic time and result from chemical and mechanical erosion of material (Ford and Williams, 1989).

Dissolving carbonate rocks create sinkholes and other features

The soluble limestones and dolomites that constitute the carbonate rocks are sculpted by dissolution and weathering processes into a

There appears to be an increasing frequency of sinkholes, although the statistics may be affected by reporting biases.



(William L. Wilson, Subsurface Evaluations, Inc., written communication, 1997) distinct geomorphology known as karst. Features characteristic of karst terranes are directly related to limestone dissolution and ground-water flow and include sinkholes, springs, caves, disappearing streams, internally drained basins, and subsurface drainage networks. Dissolution cavities can range in size from tiny vugs to gigantic caverns. As these enlarging voids coalesce and become hydraulically interconnected, they greatly enhance the movement of ground water, which can perpetuate further dissolution and erosion.

On a local scale, the caverns and cave networks can form extensive conduit systems that convey significant ground-water flow at very high velocities (Atkinson, 1977; Quinlan and others, 1993). On a regional scale, the many interconnected local-scale features can create a vast system of highly transmissive aquifers that constitute a highly productive ground-water resource.

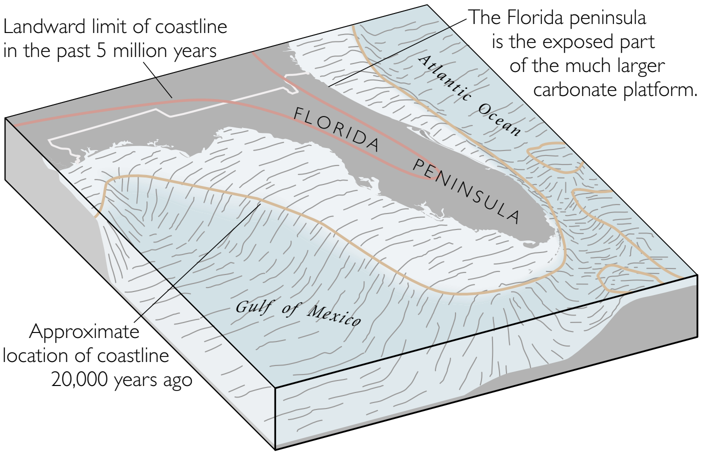
Mining exposed this typical karst limestone surface, which is riddled with dissolution cavities.

(William A. Wisner, 1972)

Changes in sea level helped develop karst terranes

Karst is well-developed in the carbonate rocks throughout the Florida carbonate platform. Throughout recent geologic time, fluctuations in sea level have alternately flooded and exposed the platform, weathering and dissolving the carbonate rocks. During the Ice Ages, an increased proportion of the Earth's water was frozen in polar ice and continental glaciers, lowering sea level along the Florida peninsula by 280 to 330 feet as recently as 18,000 years ago. The sea-level low stands exposed the great carbonate platforms of the Gulf of Mexico and the Caribbean Sea to karst processes. The lower sea-level stands were accompanied by lower ground-water levels (Watts, 1980; Watts and Stuiver, 1980; Watts and Hansen, 1988), which accelerated the development of karst. With the melting of the ice, sea levels and ground-water levels rose and many of the karst features were submerged. Examples of these flooded features include the "blue holes" found in the Bahamas, the cenotes of the Yucatan, the springs of Florida, and numerous water-filled cave passages throughout these terranes. Many of the numerous lakes and ponds of west-central Florida formed as overburden materials settled into cavities in the underlying limestone.

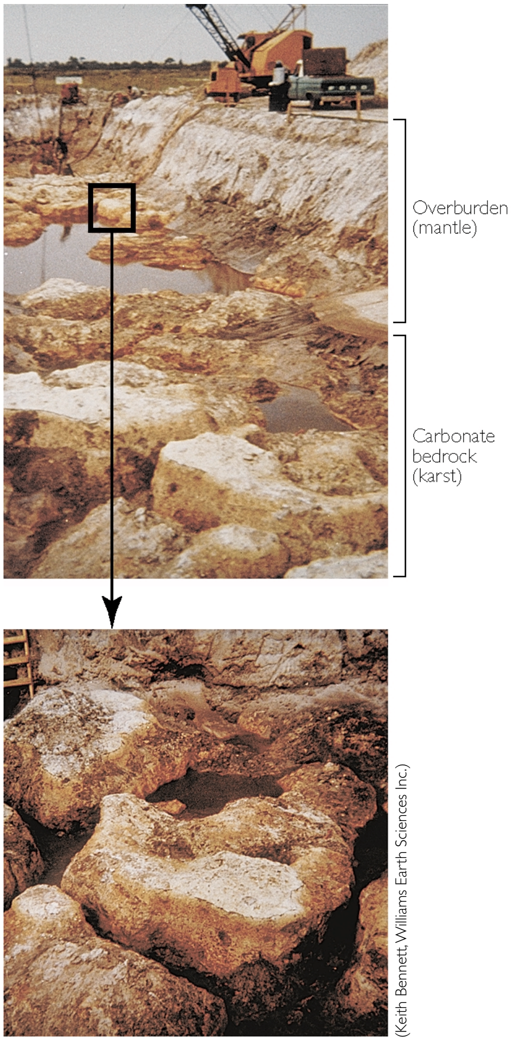
Changes in sea level have alternately submerged and exposed the carbonate platform.



Karst is an important part of the ground-water plumbing

At present, in west-central Florida, most of the soluble bedrock is below the water table. As ground water flows through the rock, geochemical processes continually modify both the rock and the chemical composition of the ground water. In many areas within the platform, the carbonates continue to dissolve, further enlarging cavities and conduits for ground-water flow. Fractures, faults, bedding planes and differences in the mineral composition of the carbonate rocks also play a role in the development, orientation, and extent of the internal plumbing system. Lineaments (linear features expressed in the regional surface terrain and often remotely sensed using aerial photography or satellite imagery) are often associated with locations of sinkholes and highly transmissive zones in the carbonate platform (Lattman and Parizek, 1964; Littlefield, and others, 1984).

In mantled karst terrane, the buried carbonate rock is furrowed and pitted. When the covering deposits subside into the underlying depressions, sinkholes and a hummocky topography result.



(Keith Bennett, Williams Earth Sciences Inc.)

THE MANTLED KARST OF WEST-CENTRAL FLORIDA

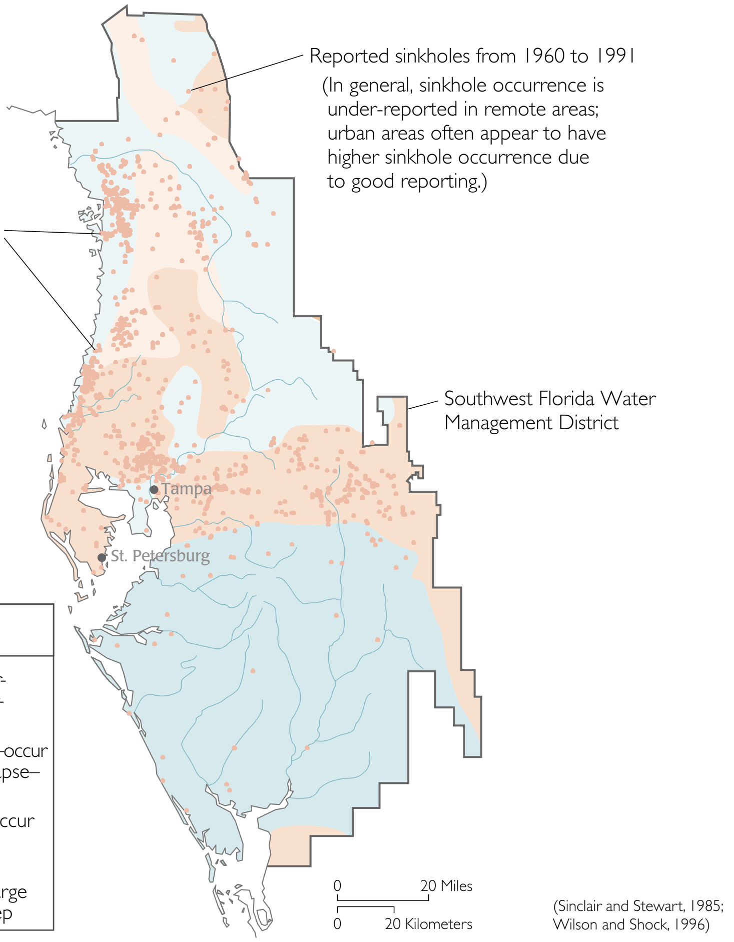
Where karst processes affect rocks that are covered by relatively insoluble deposits, the presence of buried karst features forms a distinctive type of terrain known as mantled karst. In mantled karst regions, the carbonate units are not exposed at land surface, but their presence may be indicated by sinkholes and the hummocky topography that results when the covering deposits take the shape of the underlying depressions. The mantled karst of west-central Florida has resulted in a number of distinct geomorphic regions (White, 1970; Brooks, 1981), including several lake districts with numerous lakes created by subsidence of overburden into the buried karst surface. In other areas, especially where the mantling deposits are thick, the buried karst surface is not reflected in the topography.

Sinkhole formation is related to the thickness and composition of the overlying materials

The mantled karst of west-central Florida has been classified into four distinct zones on the basis of the predominant type of sinkholes (Sinclair and Stewart, 1985). The type and frequency of sinkhole-subsidence activity have been correlated to the composition and thickness of overburden materials, the degree of dissolution within the underlying carbonate rocks, and local hydrologic conditions. Three general types of sinkholes occur: dissolution sinkholes—depressions in the limestone surface caused by chemical erosion of limestone; cover-subsidence sinkholes—formed as overburden materials gradually infill subsurface cavities; and cover-collapse sinkholes—also formed by movement of cover materials into subsurface voids, but characteristically formed more abruptly.

In the northern part of the region a thin (0 to 30 feet thick) mantle of highly permeable sediments overlies the carbonate rock. Rain water moves rapidly into the subsurface, dissolving the carbonate

The type, location, and frequency of sinkhole subsidence in the Southwest Florida Management District of west-central Florida have been related to the type and thickness of overburden materials.



Reported sinkholes from 1960 to 1991 (In general, sinkhole occurrence is under-reported in remote areas; urban areas often appear to have higher sinkhole occurrence due to good reporting.)

New sinkholes in the coastal region are small and numerous. The buried limestone surface is intensely karstified, and the thin, sandy over-burden materials constantly settle into the buried voids and cavities. Recent urban development in this region increases the observation and occurrence of sinkhole activity.

Southwest Florida Water Management District

	TYPE AND THICKNESS OF OVERBURDEN	FREQUENCY OF SINKHOLES	TYPE OF SINKHOLES
⬜	Thin; highly permeable	Generally few	Dissolution; cover-subsidence; cover-collapse
⬜	30 to 200 feet thick; permeable sands are dominant	Numerous	Cover-subsidence–occur slowly; cover-collapse–usually induced
🟧	30 to 200 feet thick; more clayey	Very numerous	Cover-collapse–occur abruptly
🟦	Greater than 200 feet	Few	Cover-collapse–large diameter and deep

(Sinclair and Stewart, 1985; Wilson and Shock, 1996)

rock, and dissolution-type sinkholes tend to develop. The slow dissolution of carbonates in these terranes has little direct impact on human activity (Culshaw and Waltham, 1987).

To the south, the overburden materials are generally thicker and less permeable. Where the overburden is 30 to 200 feet thick, sinkholes are numerous and two types are prevalent, cover-subsidence and cover-collapse. Where permeable sands are predominant in the overburden, cover-subsidence sinkholes may develop gradually as the sands move into underlying cavities. Where the overburden contains more clay, the greater cohesion of the clay postpones failure, and the ultimate collapse tends to occur more abruptly.

In the southernmost part of the region, overburden materials typically exceed 200 feet in thickness and consist of cohesive sediments interlayered with some carbonate rock units. Although sinkhole formation is uncommon under these geologic conditions, where sinkholes do occur they are usually large-diameter, deep, cover-collapse type.

A cover-collapse sinkhole formed in an orange grove east of Tampa.

Categorizing sinkholes

Two processes create three types of sinkholes

Three types of sinkholes are common in Florida: dissolution, cover-subsidence and cover-collapse sinkholes. They develop from dissolution and "suffosion." Dissolution is the ultimate cause of all sinkholes, but the type of sinkhole is also controlled by the thickness and type of overburden materials and the local hydrology.

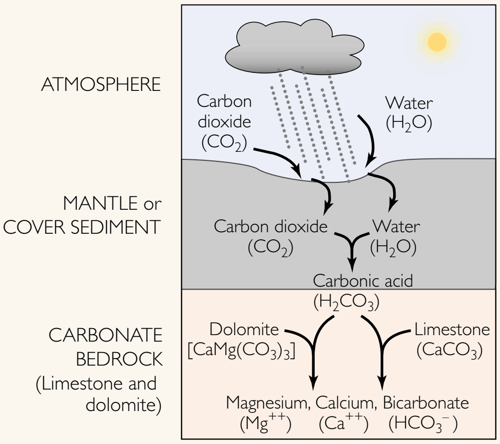
Although it is convenient to divide sinkholes into three distinct types, sinkholes can be a combination of types or may form in several phases.

Cover-collapse sinkhole near Ocala, Florida

(Tom Scott)

PROCESSES

Dissolution of soluble carbonate rocks by weakly acidic water is ultimately responsible for virtually all the sinkholes found in Florida.



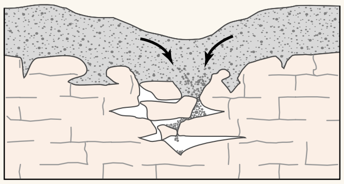
Water (H_2O) falling through the atmosphere and percolating the ground dissolves carbon dioxide (CO_2) gas from the air and soil, forming a weak acid—carbonic acid (H_2CO_3).

As the carbonic acid infiltrates the ground and contacts the bedrock surfaces, it reacts readily with limestone ($CaCO_3$) and/or dolomite $[CaMg(CO_3)_3]$.

Cavities and voids develop as limestone or dolomite is dissolved into component ions of calcium (Ca^{++}), magnesium (Mg^{++}), and bicarbonate (HCO_3^-).

When the ground water becomes supersaturated with dissolved minerals, further dissolution is not possible, and carbonate salts of calcium and magnesium may precipitate from the water, often forming interesting shapes such as stalactites. The reactions are fully reversible, and when precipitates are exposed to undersaturated ground water they may redissolve. The geochemical interactions are controlled partly by the rate of circulation of water.

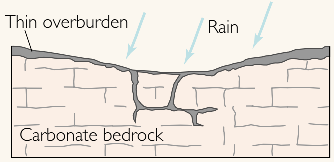
Suffosion occurs when unconsolidated overburden sediments infill preexisting cavities below them. This downward erosion of unconsolidated material into a preexisting cavity is also called raveling and describes both the catastrophic cover-collapse sinkhole and the more gradual cover-subsidence sinkhole.



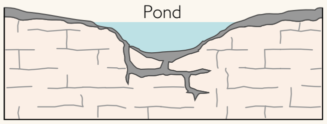
The erosion begins at the top of the carbonate bedrock and develops upward through the overlying sediments toward the land surface.

TYPES OF SINKHOLES

Dissolution of the limestone or dolomite is most intensive where the water first contacts the rock surface. Aggressive dissolution also occurs where flow is focussed in preexisting openings in the rock, such as along joints, fractures, and bedding planes, and in the zone of water-table fluctuation where ground water is in contact with the atmosphere.



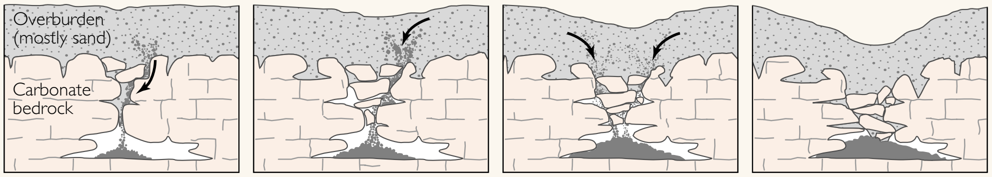
Rainfall and surface water percolate through joints in the limestone. Dissolved carbonate rock is carried away from the surface and a small depression gradually forms.



On exposed carbonate surfaces, a depression may focus surface drainage, accelerating the dissolution process. Debris carried into the developing sinkhole may plug the outflow, ponding water and creating wetlands.

Gently rolling hills and shallow depressions caused by solution sinkholes are common topographic features throughout much of Florida.

Cover-subsidence sinkholes tend to develop gradually where the covering sediments are permeable and contain sand.



Granular sediments spall into secondary openings in the underlying carbonate rocks.

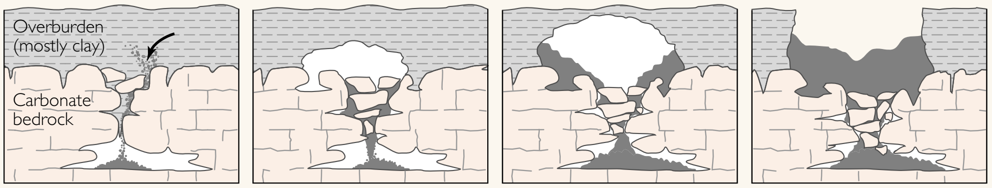
A column of overlying sediments settles into the vacated spaces (a process termed "piping").

Dissolution and infilling continue, forming a noticable depression in the land surface.

The slow downward erosion eventually forms small surface depressions 1 inch to several feet in depth and diameter.

In areas where cover material is thicker or sediments contain more clay, cover-subsidence sinkholes are relatively uncommon, are smaller, and may go undetected for long periods.

Cover-collapse sinkholes may develop abruptly (over a period of hours) and cause catastrophic damages. They occur where the covering sediments contain a significant amount of clay.



Sediments spall into a cavity.

As spalling continues, the cohesive covering sediments form a structural arch.

The cavity migrates upward by progressive roof collapse.

The cavity eventually breaches the ground surface, creating sudden and dramatic sinkholes.

Over time, surface drainage, erosion, and deposition of sediment transform the steep-walled sinkhole into a shallower bowl-shaped depression.

Many of the numerous lakes and ponds that dot the Florida landscape, such as these in central Polk County, are actually subsidence depressions that are filled with water.

SINKHOLE DEVELOPMENT IS AFFECTED BY THE HYDROGEOLOGIC FRAMEWORK

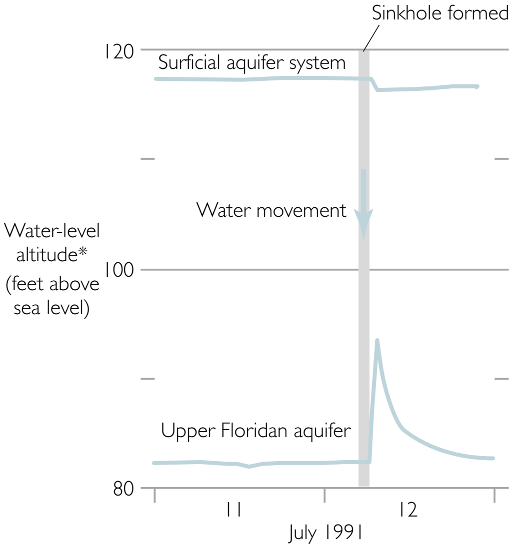
The flow of subsurface water through sediments and eroded carbonate rocks affects how, where, and when sinkholes develop. Thus, formation of sinkholes is sensitive to changes in hydraulic and mechanical stresses that may occur naturally or as the result of human activity. Whether the stresses are imposed over geologic time scales by changes in sea level or over the time scale of human ground-water-resources development, they are expressed as changes in ground-water levels (hydraulic heads) and the gradients of hydraulic head. The hydraulic properties of the aquifers and the extent, composition, and thickness of overburden materials control how these stresses are transmitted. The chemistry of the ground water determines where dissolution and karst development occurs. Together, these hydrogeologic factors control the type and frequency of sinkholes that develop in west-central Florida.

Just as the hydrogeologic framework influences the development of sinkholes, the sinkholes influence the hydrogeologic framework. Understanding of the hydrogeologic framework can lead to land- and water-resources management strategies that minimize the impact of sinkholes.

Vast aquifer systems underlie west-central Florida

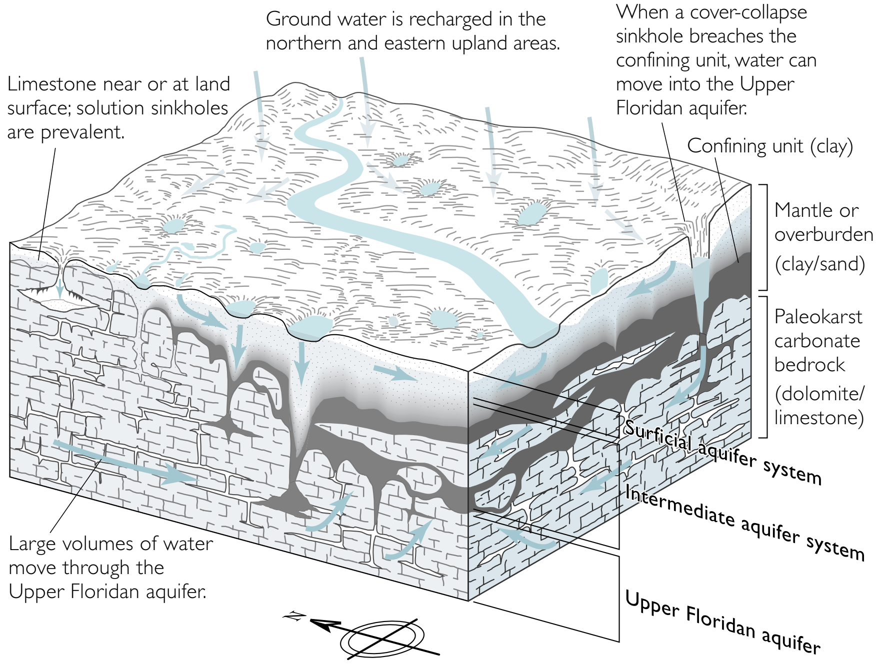
The hydrogeologic framework of west-central Florida consists of three layered aquifer systems that include both carbonate and siliciclastic rocks. The shallowest or "surficial" aquifer system generally occurs within unconsolidated sand, shell, and clay units. The surficial aquifer system ranges from less than 10 to more than 100 feet in thickness throughout west-central Florida. The water table is generally close to the land surface, intersecting lowlands, lakes, and streams. Recharge is primarily by rainfall. When sinkholes occur, it is the surficial aquifer deposits that commonly fail and move to infill any underlying cavities.

A sinkhole that breached a confining clay layer illustrates the interconnectivity of the aquifers. The water-level drop in the surficial aquifer system and the coincident rise in the Upper Floridan aquifer occurred as the sinkhole drained.



*Water levels were recorded at a SWFWMD Regional Observation Monitoring Program wellsite that is less than 1,000 feet from the sinkhole

(Southwest Florida Water Management District, written communication, 1998)

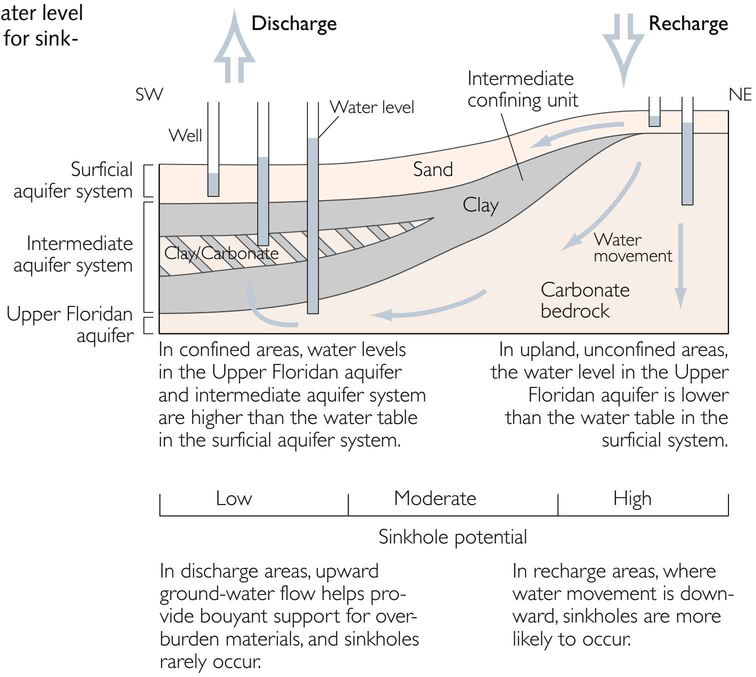


In most of west-central Florida the surficial aquifer system is separated from the Upper Floridan aquifer by a hydrogeologic unit known as either the "intermediate aquifer system" or "intermediate confining unit," depending upon its local hydraulic properties (Southeastern Geological Society, 1986). The intermediate confining unit, delineated as such where fine-grained clastic deposits are incapable of yielding significant quantities of water, impedes the vertical flow of ground water between the overlying surficial aquifer system and the underlying Floridan aquifer system. In northern west-central Florida, where this unit is absent, the surficial aquifer system lies directly above the Floridan aquifer system. In general, the intermediate confining unit consists of heterogenous siliciclastic sediments that mantle the carbonate platform. These deposits thicken westward and southward, where they include more permeable clastic sediments and interbedded carbonate units. In these regions they are referred to as the intermediate aquifer system. The lateral extent of permeable units within the intermediate aquifer system is limited, and the transmissivities of these units are significantly smaller than those of underlying carbonate rocks of the Floridan aquifer system. The type and frequency of sinkholes in west-central Florida are correlated to the presence or absence of this intermediate layer and, where present, its composition and thickness.

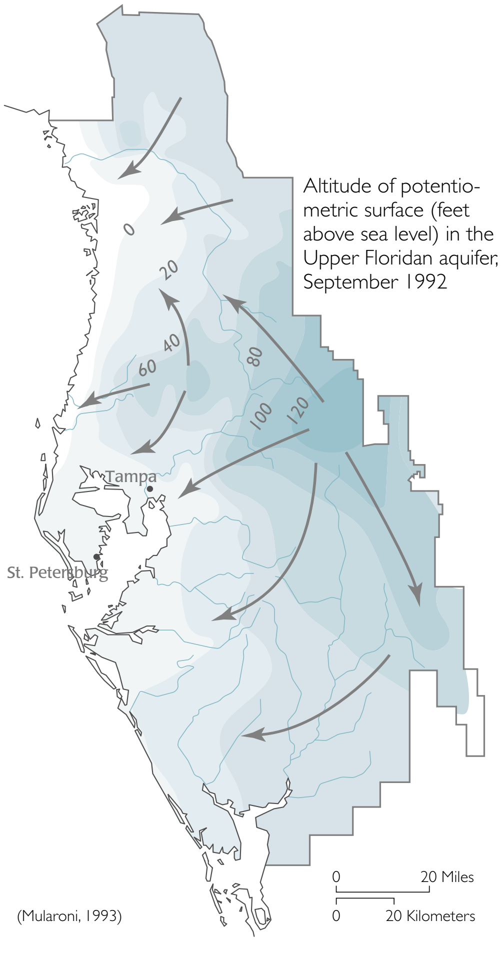
> The type and frequency of sinkholes in west-central Florida are related to the presence or absence of the intermediate aquifer system.

The thick carbonate units of the Floridan aquifer constitute one of the most productive aquifer systems in the world. The Upper Floridan aquifer is between 500 and 1,800 feet thick and is the primary source of springflow and ground-water withdrawals in west-central Florida. Transmissivities commonly range from 50,000 to 500,000 square feet per day and may be as large as 13,000,000 square feet per day near large springs (Ryder, 1985). These transmis-

The presence of a confining unit affects the water level and the potential for sinkholes.



Water in the Upper Floridan aquifer moves from recharge areas in the northern and eastern upland regions toward discharge areas near the coast.



Altitude of potentiometric surface (feet above sea level) in the Upper Floridan aquifer, September 1992

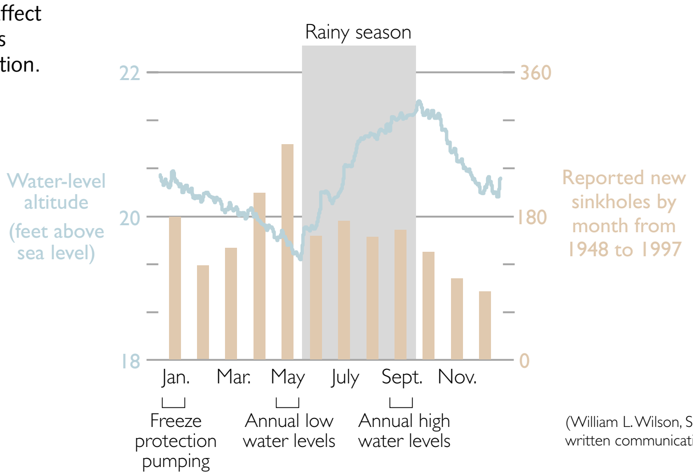
(Mularoni, 1993)

sivity values far exceed those typical of diffuse ground-water flow in porous media such as sand and reflect the influence of karst-dissolution features.

In upland regions, hydraulic heads in the Upper Floridan aquifer are generally lower than heads in the surficial and intermediate aquifer systems. In these areas ground water moves downward from the surficial aquifer system, recharging the intermediate aquifer system and the Upper Floridan aquifer. This downward movement of ground water enhances the formation of sinkholes by facilitating raveling of unconsolidated sediments into the subterranean cavities. Where the intermediate confining unit is present, recharge to the Upper Floridan aquifer may be diminished. However, where the clay content of the confining unit is low, or the unit has been breached by sinkhole collapse or subsidence, downward movement of water and sediments from the surficial aquifer system can be greatly accelerated. Vertical shafts and sand-filled sinkholes can form high-permeability pathways through otherwise effective confining units (Brucker and others, 1972; Stewart and Parker, 1992).

Artesian conditions exist along much of the coast and, where confinement is poor, springs commonly occur. Parts of the northern coastal area are highly karstified, and the Upper Floridan aquifer is exposed at the land surface except where it is covered by unconsolidated sands. In the southern coastal regions, where the intermediate aquifer system and the Upper Floridan aquifer are well confined, water levels in those deeper units are higher than those in the surficial aquifer system, and ground water moves upward toward the surficial aquifer. Sinkholes rarely occur under these conditions.

Seasonal changes affect ground-water levels and sinkhole formation.

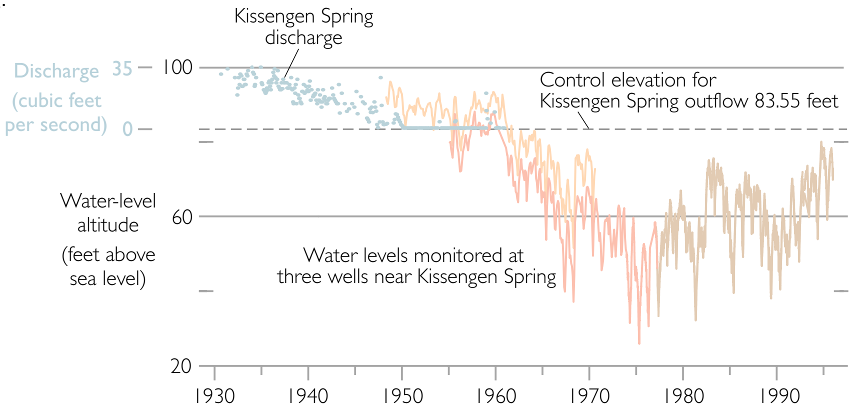


(William L. Wilson, Subsurface Evaluations, Inc., written communication, 1997)

Cyclical changes in water levels often occur in response to seasonal conditions in west-central Florida. At the end of the dry season, in May, ground-water levels are near their annual lows and, after the rainy season, in September, recover to their annual high levels. The range between the annual minimum and maximum levels can be significant. In some areas, especially during prolonged drought or large rainfall events, seasonal change in ground-water levels can lead to temporary reversals in the direction of vertical flow. More new sinkholes form during periods when ground-water levels are low.

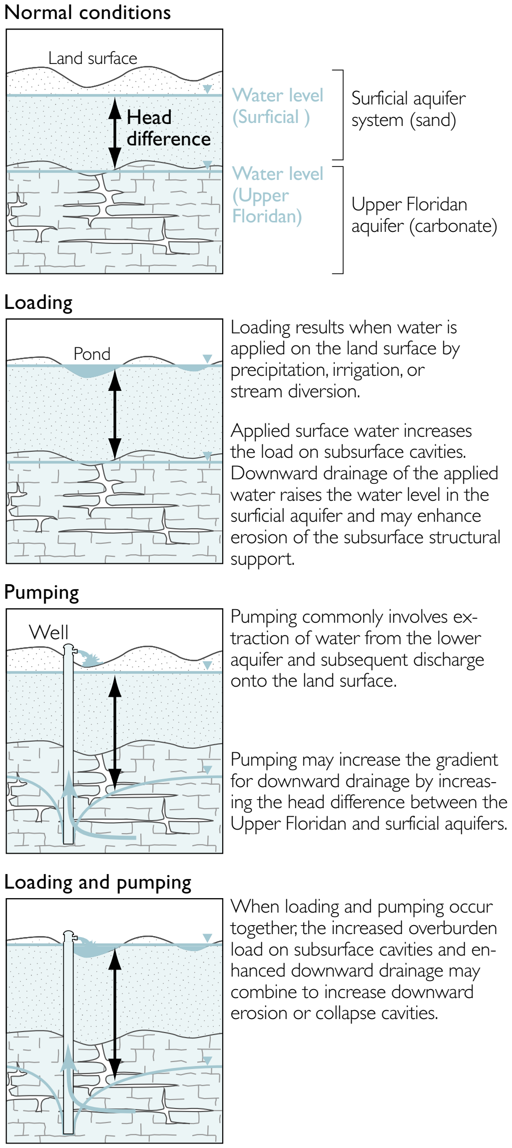
Temporary reversals in head gradients may also be created by extreme, short-lived pumping. Longer-term ground-water pumping can lead to sustained ground-water level declines and gradient reversals, creating new recharge areas within the aquifer system and sometimes converting flowing springs to dry sinkholes. After the pumping stops, ambient conditions are usually restored, but the changes can become semipermanent or permanent if pumping persists over long periods of time, or confining units are compromised.

Long-term ground-water pumping near Kissengen Spring in central Polk County led to a decline in water levels and ultimately caused the spring to stop flowing.



(Lewelling and others, 1998)

Changes in relative water levels caused by human activity can induce sinkholes



Loading results when water is applied on the land surface by precipitation, irrigation, or stream diversion.

Applied surface water increases the load on subsurface cavities. Downward drainage of the applied water raises the water level in the surficial aquifer and may enhance erosion of the subsurface structural support.

Pumping commonly involves extraction of water from the lower aquifer and subsequent discharge onto the land surface.

Pumping may increase the gradient for downward drainage by increasing the head difference between the Upper Floridan and surficial aquifers.

When loading and pumping occur together, the increased overburden load on subsurface cavities and enhanced downward drainage may combine to increase downward erosion or collapse cavities.

GROUND-WATER PUMPING, CONSTRUCTION, AND DEVELOPMENT PRACTICES INDUCE SINKHOLES

New sinkholes have been correlated to land-use practices (Newton, 1986). Induced sinkholes are conceptually divided into two types: those resulting from ground-water pumping (Sinclair, 1982) and those related to construction and development practices. Modified drainage and diverted surface water commonly accompany construction activities and can lead to focused infiltration of surface runoff, flooding, and erosion of sinkhole-prone earth materials. Manmade impoundments used to treat or store industrial- process water, sewage effluent, or runoff can also create a significant increase in the load bearing on the supporting geologic materials, causing sinkholes to form. Other construction activities that can induce sinkholes include the erection of structures, well drilling, dewatering foundations, and mining.

The overburden sediments that cover buried cavities in the aquifer systems are delicately balanced by ground-water fluid pressure. In sinkhole-prone areas, the lowering of ground-water levels, increasing the load at land surface, or some combination of the two may contribute to structural failure and cause sinkholes.

Aggressive pumping induces sinkholes

Aggressive pumping can induce sinkholes by abruptly changing ground-water levels and disturbing the equilibrium between a buried cavity and the overlying earth materials (Newton, 1986). Rapid declines in water levels can cause a loss of fluid-pressure support, bringing more weight to bear on the soils and rocks spanning buried voids. As the stresses on these supporting materials increase, the roof may fail and the cavity may collapse, partially filling with the overburden material.

Prior to water-level declines, incipient sinkholes are in a marginally stable stress equilibrium with the aquifer system. In addition to providing support, the presence of water increases the cohesion of sediments. When the water table is lowered, unconsolidated sediments may dry out and coarser-grained sediments, in particular, may move easily into openings.

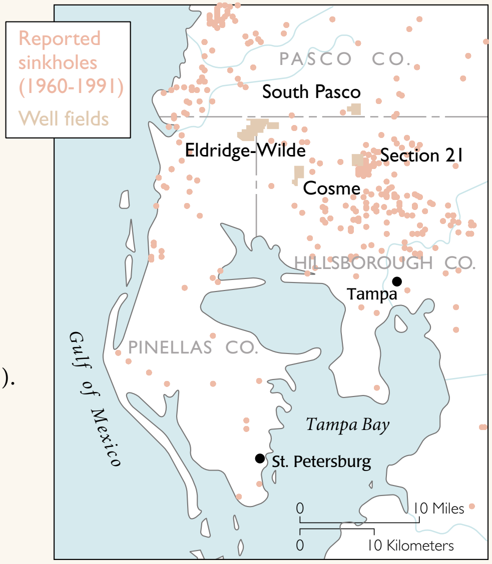
Induced sinkholes are generally cover-collapse type sinkholes and tend to occur abruptly. They have been forming at increasing rates during the past several decades and pose potential hazards in developed and developing areas of west-central Florida. The increasing incidence of induced sinkholes is expected to continue as our demand for ground-water and land resources increases. Regional declines of ground-water levels increase sinkhole occurrence in sinkhole-prone regions. This becomes more apparent during the natural, recurring periods of low annual rainfall and drought.

Section 21 Well Field

Ground-water pumping for urban water supply induces new sinkholes

By the early 1930s, ground-water pumping along the west coast of Florida had lowered hydraulic heads in the freshwater aquifers and caused upconing of saline water. Coastal municipalities began to abandon coastal ground-water sources and develop inland sources.

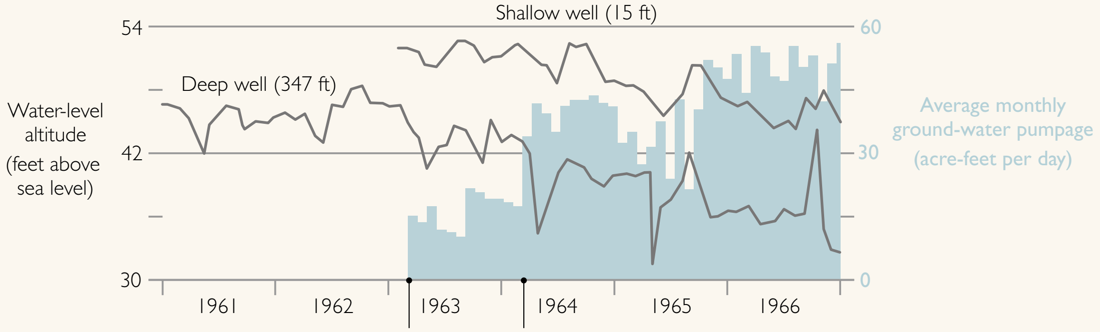
The city of St. Petersburg began pumping ground water from well fields in a rural area north of Tampa. By 1978, four well fields had been established in parts of Hillsborough, Pasco, and Pinellas Counties, and were pumping an average of 69,900 acre-feet per year. Sinkholes occurred in conjunction with the development of each of the well fields: Cosme (1930), Eldridge-Wilde (1954), Section 21 (1963), and South Pasco (1973).



(Wilson and Shock, 1996)

SECTION 21 WELL FIELD

The effects of pumping on sinkhole development near the Section 21 well field illustrate the general relation between aggressive pumping, ground-water declines, and sinkhole development.



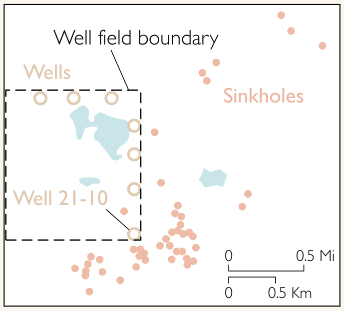
Pumping began in 1963 and ground-water levels began to decline.

In April 1964 the pumping rate nearly tripled, lowering ground-water levels more than 10 feet, and within 1 month, 64 sinkholes had formed.

(Sinclair, 1982)

Within 1 month of increasing the pumping rate, 64 new sinkholes formed within a 1-mile radius of the well field. Most of the sinkholes were formed in the vicinity of well 21-10, which was pumping at nearly twice the rate of the other wells. Neighboring areas also noticed dramatic declines in lake levels and dewatering of wetland areas.

The Section 21 well field is still in operation and researchers continue studying the effects of ground-water pumping on lake levels and wetlands.



The sinkholes were apparently distributed randomly, except for those south and east of well 21-10, which were clustered along preexisting joints.

(Sinclair, 1982)

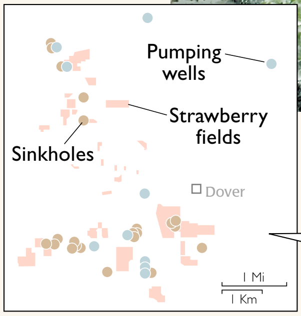
Crop freeze protection

Heavy ground-water pumping during winter freezes produces new sinkholes

The mild winters are an important growing season for west-central Florida citrus, strawberry and nursery farmers. However, occasional freezing temperatures can result in substantial crop losses. To prevent freeze damage,growers pump warm (about 73° F) ground water from the Upper Floridan aquifer and spray it on plants to form an insulating coat of ice. Extended freezes have required intense and prolonged ground-water pumping, causing large drawdowns in the Upper Floridan aquifer and the abrupt appearance of sinkholes.

A thin layer of ice provides insulation from freezing temperatures.

(Tom Scott)



The relation between freezing weather, prolonged ground-water withdrawals, and sinkhole occurrence has been well documented in the Dover area about 10 miles east of Tampa (Bengtsson, 1987).

In January 1977, extended freezes and associated ground-water withdrawals led to the sudden formation of 22 new sinkholes.

(Metcalf and Hall, 1984)

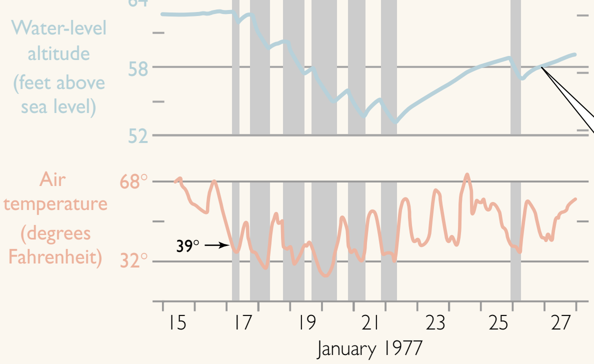
FREEZING AND PUMPING

During a 6-day period of record-breaking cold weather, ground water was pumped at night when temperatures fell below 39° F.

The new sinkholes were attributed to the movement of sandy overburden material through a breached clay confining unit into cavities in the limestone below.

During the period of cold weather, county officials received numerous complaints about new sinkholes.

Periods when pumps were turned on



Sinkhole formation ceased or slowed significantly when water levels recovered.

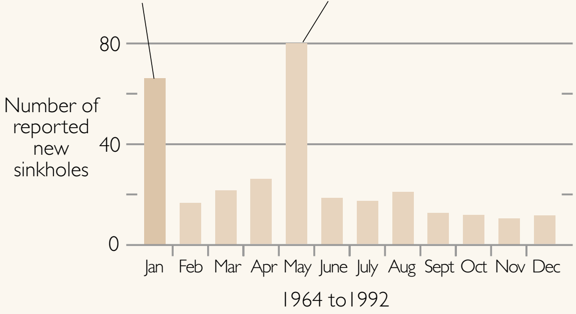
MANY NEW SINKHOLES

Ground-water pumping for crop freeze protection tends to induce sinkholes during the month of January in Hillsborough County.

(Wilson and Shock, 1996)

Sinkholes induced by crop freeze protection

Heavy pumping during the dry months of March through May also induced new sinkholes



(Tom Scott)

> *"A giant sink hole opened up on Thursday, September 19 [1975] at a drilling site near Tampa, Florida and swallowed up a well-drilling rig, a water truck, and a trailer loaded with pipe all valued at $100,000. The well being drilled was down 200 ft when the ground began to give way to what turned out to be a limestone cavern. Within 10 minutes all the equipment was buried way out of sight in a crater measuring 300 ft deep, and 300 ft wide. Fortunately, the drilling crew had time to scramble to safety and no one was hurt."*
>
> *—from National Water Well Association newsletter*

One factor confounding the relation between pumping wells and the distribution of induced sinkholes is the nonuniform hydraulic connection between the well and various buried cavities. The development of secondary porosity is not uniform. Dissolution cavities often form along structural weaknesses in the limestone, such as bedding planes, joints, or fractures—places where water can more easily infiltrate the rock. The distribution of cavities can be controlled by the presence of these features and thus may be preferentially oriented. It is not uncommon for a pumping well to have more impact on cavities that are well-connected hydraulically—although farther away from the pumping well—than on nearby cavities that are less well-connected hydraulically. Proximity to pumping wells is not always a reliable indicator for predicting induced sinkholes.

When structures such as buildings and roadways are constructed, care is usually taken to divert surface-water drainage away from the foundations to avoid compromising their structural integrity. Associated activities may include grading slopes and removal or addition of vegetative cover, installing foundation piles and drainage systems, and ditching for storm drainages and conduits for service utilities. The altered landscapes typically result in local changes to established pathways of surface-water runoff, infiltration, and ground-water recharge. Pavements, roofs, and storm-drainage systems can dramatically increase the rate of ground-water recharge to a local area, thus increasing flow velocity in the bedrock and potentially inducing sinkholes. A common cause of induced sinkholes in urban areas is broken water or sewer pipes. Pipelines strung through karst terrane are subject to uneven settling as soils compact or are piped into dissolution cavities. The result can be cracked water pipes or the separation of sewer line sections, further aggravating erosion and perpetuating the process.

> *"Construction practices often 'set the stage' for sinkhole occurrence."*
>
> *—J.G. Newton, 1986*

Loading by heavy equipment during construction or, later, by the weight of the structures themselves may induce sinkholes. A number of engineering methods are commonly used to prevent this type of sinkhole damage (Sowers, 1984), including drilling and driving pilings into competent limestone for support, injecting cement into subsurface cavities, and construction of reinforced and spread foundations that can span cavities and support the weight of the construction. Compaction by hammering, vibratory rollers, and heavy block drops may be used to induce collapse so that areas of weakness can be reinforced prior to construction.

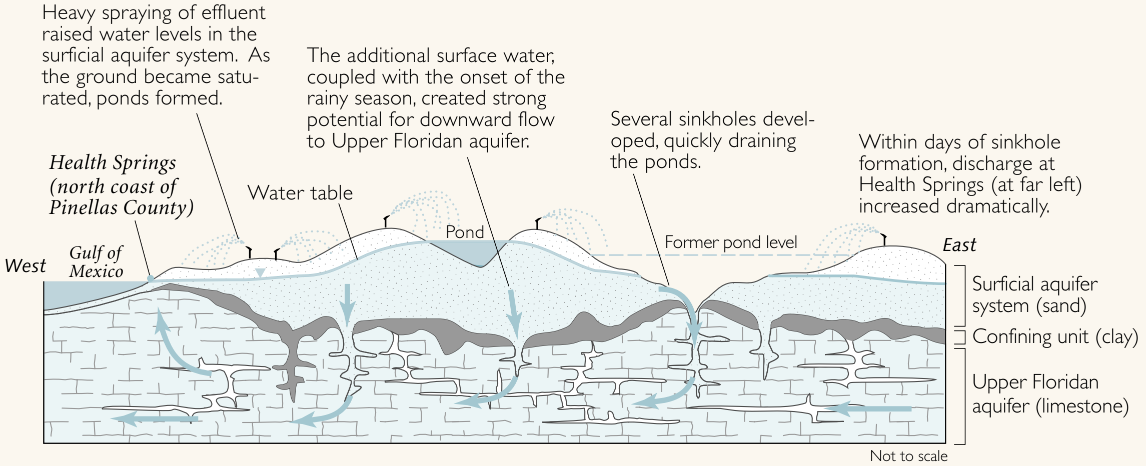
Excessive spray-effluent irrigation

Inducing sinkholes by surface loading

In April 1988 several cover-collapse sinkholes developed in an area where effluent from a wastewater treatment plant is sprayed for irrigation in northwestern Pinellas County. The likely cause was an increased load on the sediments at land surface due to waste-disposal activities, including periodic land spreading of dried sludge as well as spray irrigation. The 118-acre facility is located within a karst upland characterized by internal drainage and variable confinement between the surficial aquifer system and the Upper Floridan aquifer.

Spray-effluent volume applied for 1988 was equivalent to 290 inches per year (Trommer, 1992). Ponding of effluent occurred as the surficial sediments became saturated. The increased weight or load of the saturated sediments probably contributed to the ponding by causing some subsidence. At the beginning of the rainy season, several cover-collapse sinkholes developed suddenly, draining the effluent ponds into the aquifer system.

Sinkholes developed suddenly where water ponded due to excessive spray-effluent irrigation. (John Trommer)



LINKING SURFACE AND GROUND WATER

Within several days of sinkhole formation, discharge at Health Springs, 2,500 feet downgradient in the ground-water flow path, increased from 2 cubic feet per second to 16 cubic feet per second (Trommer, 1992). Water-quality sampling of the spring during the higher flow detected constituents indicative of the spray effluent. Within 2 weeks, discharge at Health Springs had dropped to the normal rate of 2 cubic feet per second. The existence of a preferential ground-water flow path linking the upland spray field with the spring was confirmed by timing the movement of artificially dyed ground water between a well in the spray field and the spring (Tihansky and Trommer, 1994). The ground-water velocity based on the arrival time of the dye was about 160 feet per day, or about 250 times greater than the estimates of the regional ground-water velocity (0.65 feet per day) in this area.

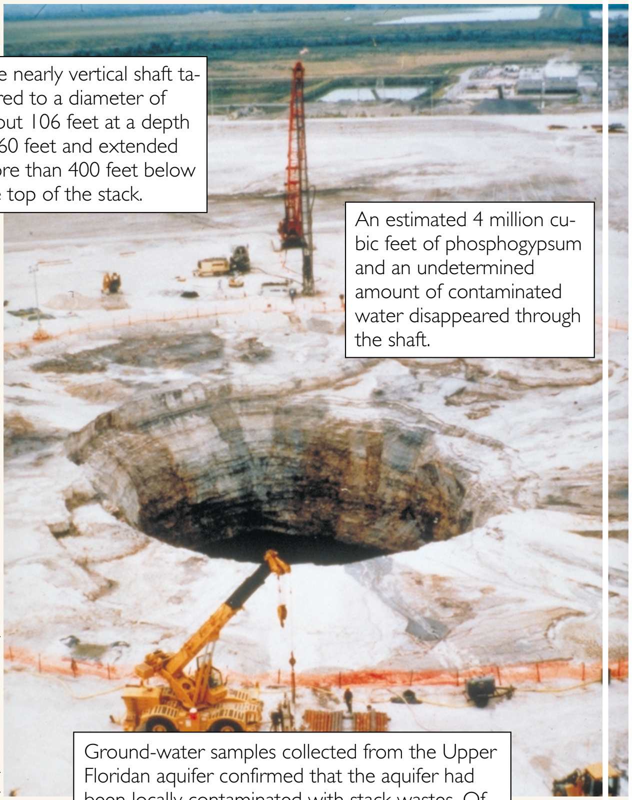
The dye-tracer test demonstrates how sinkholes and enhanced secondary porosity can provide a pathway directly linking surface-water runoff and the aquifer system. Sinkholes beneath holding ponds and rivers can convey surface waters directly to the Upper Floridan aquifer, and the introduction of contaminated surface waters through sinkholes can rapidly degrade ground-water resources.

Sinkhole collapse beneath a gypsum stack

Inducing sinkholes by surface loading and pumping

The sands and clays of the overburden sediments support a large phosphate mining and processing industry in west-central Florida. A gaping sinkhole formed abruptly on June 27, 1994, within a 400-acre, 220-foot high gypsum stack at a phosphate mine. The gypsum stack is a flat-topped pile of accumulated phosphogypsum—a byproduct of phosphate-ore chemical processing. The phosphogypsum precipitates when acidic mineralized water (about pH 1.5) used in processing the ore is circulated and evaporated from the top of the continually growing stack of waste gypsum. The waste slurry of slightly radioactive phosphogypsum results from the manufacture of phosphoric acid, a key ingredient in several forms of fertilizer.

The sinkhole likely formed from the collapse of a preexisting dissolution cavity that had developed in limestone deposits beneath the stack. Its development may have been accelerated by the aggressive chemical properties of the acidic waste slurry. Infiltration of the applied waste slurry into the underlying earth materials was unimpeded because there was no natural or engineered physical barrier immediately beneath the stack. Enlargement of cavities by dissolution and erosion combined with the increasing weight of the stack would have facilitated the sinkhole collapse. This effect may have been exacerbated by the reduction of fluid-pressure support for the overburden weight due to localized ground-water-level declines; the phosphate industry withdraws ground water from the Upper Floridan aquifer to supply water to the ore-refining plant.



The nearly vertical shaft tapered to a diameter of about 106 feet at a depth of 60 feet and extended more than 400 feet below the top of the stack.

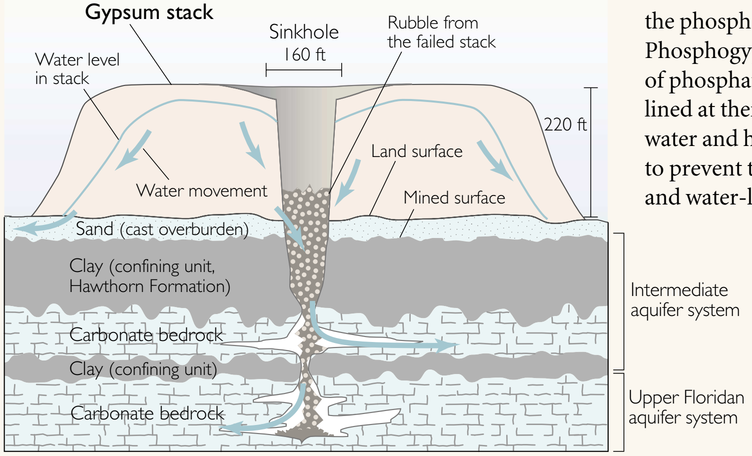
An estimated 4 million cubic feet of phosphogypsum and an undetermined amount of contaminated water disappeared through the shaft.

Ground-water samples collected from the Upper Floridan aquifer confirmed that the aquifer had been locally contaminated with stack wastes. Officials began pumping nearby wells to capture the contaminated ground water and prevent its movement off-site.

(Hayward Baker, Inc., 1997)

Before the collapse, acidic water was ponded on top of the stack to evaporate, leaving gypsum as a precipitate.

Acidic water percolated into the stack and ground-water system, thus accelerating development of the sinkhole.



Horizonal distance not to scale

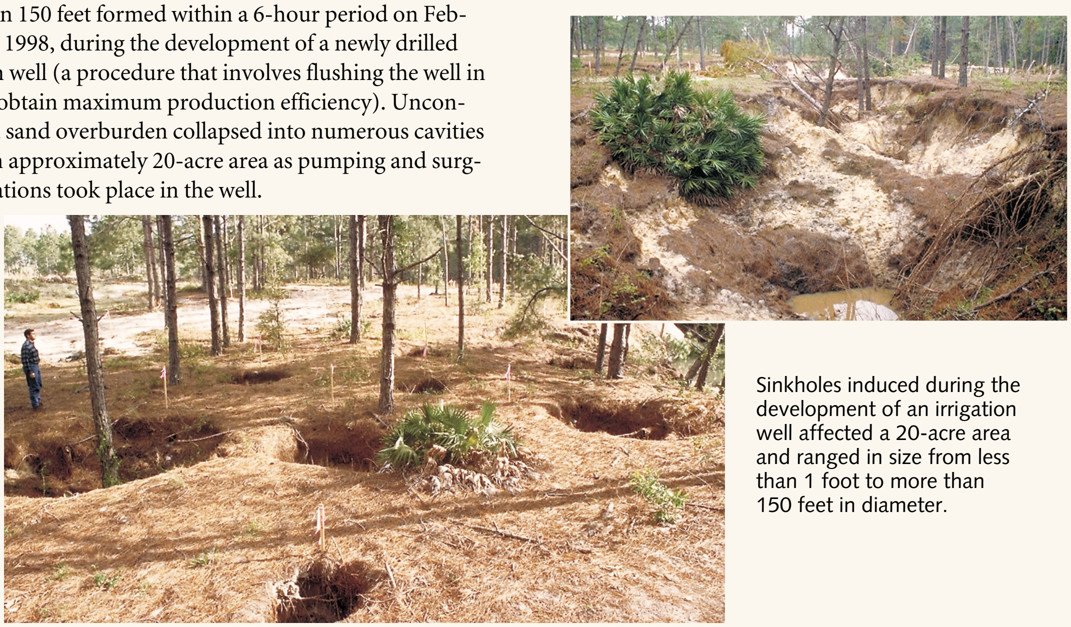
PREVENTING SINKHOLE COLLAPSE

There are approximately 20 gypsum stacks located within the sinkhole-prone region of west-central Florida and, with the exception of new construction, all of these stacks are unlined. Because of potential environmental impacts from the phosphate industry, the State of Florida created the Phosphogypsum Management Rule to manage all aspects of phosphate chemical facilities. All new gypsum stacks are lined at their bases to impede the infiltration of process water and have specially designed water-circulation systems to prevent the escape of waste slurry. Ground-water-quality and water-level monitoring are also required. Efforts are being made to close all unlined stacks and reduce impacts on the underlying ground-water system. All new gypsum stacks must undergo an assessment of the susceptibility to subsidence activity and ground-water contamination. Geophysical surveys are used to locate potential zones of weakness so that any cavities or preexisting breaches can be plugged or avoided.

A swarm of sinkholes suddenly appeared on a forest floor

Development of a new irrigation well triggered hundreds of sinkholes in a 6-hour period

Hundreds of sinkholes ranging in diameter from 1 foot to more than 150 feet formed within a 6-hour period on February 25, 1998, during the development of a newly drilled irrigation well (a procedure that involves flushing the well in order to obtain maximum production efficiency). Unconsolidated sand overburden collapsed into numerous cavities within an approximately 20-acre area as pumping and surging operations took place in the well.



Sinkholes induced during the development of an irrigation well affected a 20-acre area and ranged in size from less than 1 foot to more than 150 feet in diameter.

The affected land is located near the coast in an upland region that straddles parts of Pasco and Hernando counties. A 20-foot-thick sediment cover composed primarily of sand with little clay is underlain by cavernous limestone bedrock. The well was drilled through 140 feet of limestone, and a cavity was reported in the interval from 148 to 160 feet depth, where drilling was terminated. Very shortly after development began, two small sinkholes formed near the drill rig. As well development continued, additional new sinkholes of varying sizes began to appear throughout the area. Trees were uprooted and toppled as sediment collapse and slumping took place, and concentric extensional cracks and crevices formed throughout the landscape. The unconsolidated sandy material slumped and caved along the margins of the larger sinkholes as they continued to expand. The first two sinkholes to form eventually expanded to become the largest of the hundreds that formed during the 6-hour development period. They swallowed numerous 60-foot-tall pine trees and more than 20 acres of forest, and left the well standing on a small bridge of land.

TEST BORINGS AND HYDROGEOLOGIC DATA INDICATE SUSCEPTIBILITY TO SINKHOLES

The affected land contains several ponds formed by sinkholes long ago (paleosinkholes). Because west-central Florida is susceptible to sinkhole development, stability was tested along the margins of these ponds to determine if the site had higher-than-normal risks of sinkhole occurrence. Many test borings were made to measure the structural integrity of the bedrock, revealing a highly variable limestone surface. Two of the borings, approximately 100 feet apart, were made within a few hundred feet of the well site. One boring indicated that there was firm limestone at depth, whereas the other never encountered a firm foundation.

Irregularity in the limestone surface is typical of much of west-central Florida. Cavities, sudden bit drops, and lost circulation are frequently reported during drilling in this area. These drilling characteristics indicate the presence of significant cavernous porosity in the underlying limestone and, while commonly noted in drilling logs, only occasionally cause trouble during well construction.

Sinkhole susceptibility in this area is high

- The area is located within a mantled karst terrane where the limestone surface at depth is cavernous and highly irregular; the presence of nearby caves and springs suggests that major limestone dissolution has occurred.
- Water-level gradients are downward.
- Very little clay separates loose sand from limestone below.
- Previous sinkhole occurrence is well documented; the presence of paleosinkholes is evident on topographic maps of the region.

SINKHOLE IMPACTS CAN BE MINIMIZED

Sinkholes have very localized structural impacts, but they may have far-reaching effects on ground-water resources. Sinkholes can also impact surficial hydrologic systems—lakes, streams, and wetlands—by changing water chemistry and rates of recharge or runoff. Because the Earth's surface is constantly changing, sinkholes and other subsidence features will continue to occur in response to both natural and human-induced changes. We have seen how specific conditions can affect the type and frequency of sinkholes, including a general lowering of ground-water levels, reduced runoff, increased recharge, or significant surface loading. Recognition of these conditions is the first step in minimizing the impact of sinkholes.

Cover-collapse sinkhole
Winter Park, 1981

(Tom Scott)

In areas underlain by cavernous limestone with thin to moderate thickness of overburden, increased sinkhole development and property loss are strongly correlated to human activity and cultural development. There are several reasons for this correlation. First, rapid growth and development makes it more likely that new sinkholes will be reported, and the construction of roads and industrial or residential buildings increases exposure to the risk of property damage. Second, land-use changes in rapidly developing areas are often loosely controlled and include altered drainage, new impoundments for surface water, and new construction in sinkhole-prone areas. Finally, the changing land use is often associated with population increases and increasing demands for water supplies, which may lead to increases in ground-water pumpage and the lowering of local and regional ground-water levels.

Although we cannot adequately predict sinkhole development, we may be able to prevent or minimize the effects of sinkholes or reduce their rate of occurrence. Well-documented episodes of accelerated sinkhole activity are directly related to ground-water pumping events that lower ground-water levels. In many instances, the changes in ground-water levels are only a few tens of feet. It is

A newly formed sinkhole 20 miles north of Tampa is being examined by a team of scientists.

likely that many induced sinkholes can be prevented by controlling fluctuations in ground-water levels.

The overall regional decline in water levels in the Upper Floridan aquifer has been a long-standing concern of water-resource managers. Local declines around municipal well fields, often much greater than the regional declines, have led to dewatering of lakes and wetlands, upconing of poorer-quality water, saltwater intrusion, and accelerated sinkhole development. The Southwest Florida Water Management District has been working with other water-resources agencies to establish critical levels for ground water within the west-central Florida area. The establishment of minimum ground-water levels will help minimize sinkhole impacts by ameliorating some of the conditions that cause them.

Land-use planners, resource managers, and actuaries have been able to estimate the probability of sinkhole occurrence and associated risks. The Florida Department of Insurance designed insurance premiums for four sinkhole probability zones (Wilson and Shock, 1996) on the basis of insurance claims for sinkhole damages and hydrogeologic conditions. West-central Florida was delineated as an area having the highest frequency of sinkhole activity. The use of scientific information to assess risks and establish insurance rates demonstrates the benefits of understanding the hydrogeologic framework and potential effects of water-resource development. This scientific understanding is key to assigning meaningful risks to both property and the environment, and essential for formulating effective land- and water-resources management strategies.