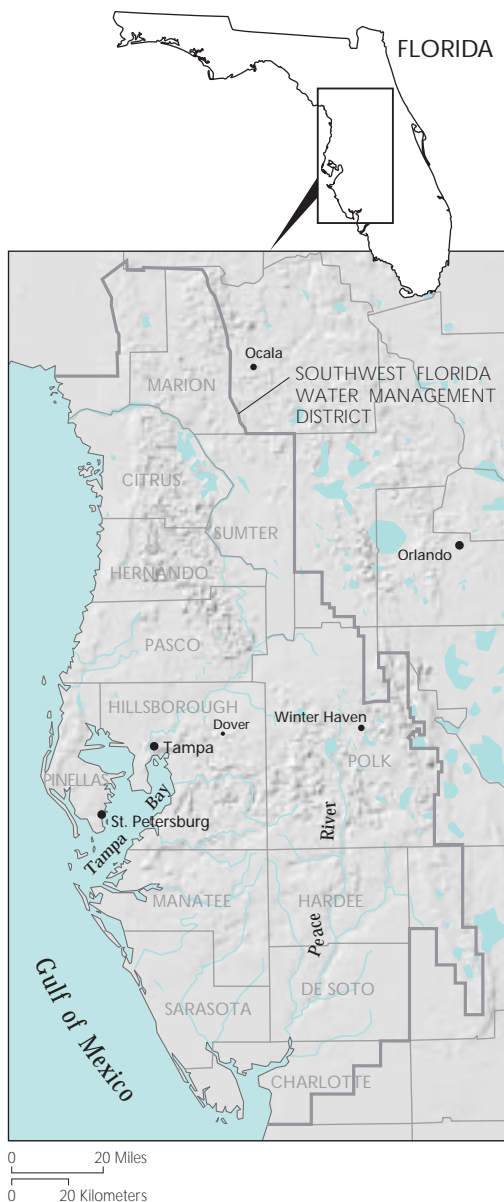


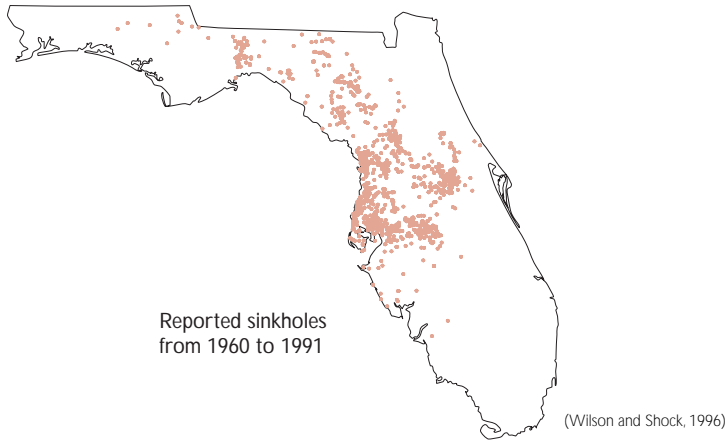
SINKHOLES, WEST-CENTRAL FLORIDA

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).



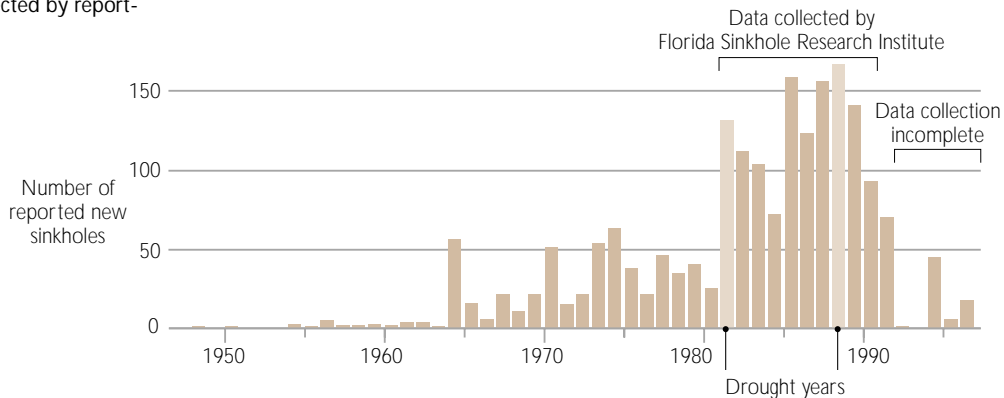
SINKHOLES ARE A NATURALLY OCCURRING FEATURE IN THE FLORIDA LANDSCAPE

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)

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



(William A. Wisner, 1972)

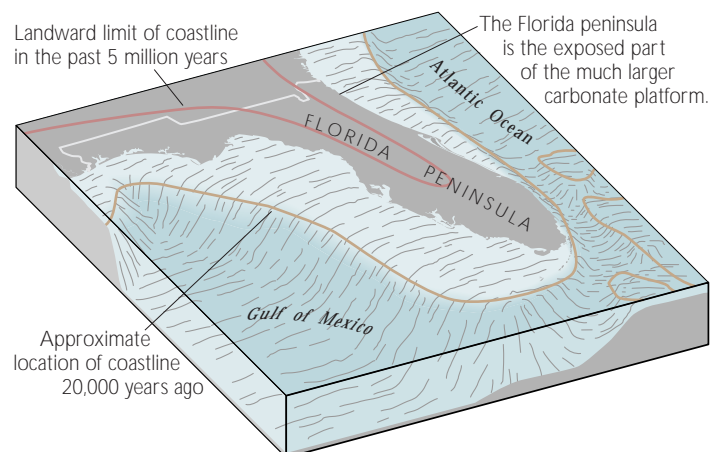
distinct geomorphology known as karst. Features characteristic of karst terranes are directly related to limestone dissolution and ground-water flow and include sinkholes, springs, caves, disappearing streams, internally drained basins, and subsurface drainage networks. Dissolution cavities can range 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.

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.



THE MANTLED KARST OF WEST-CENTRAL FLORIDA

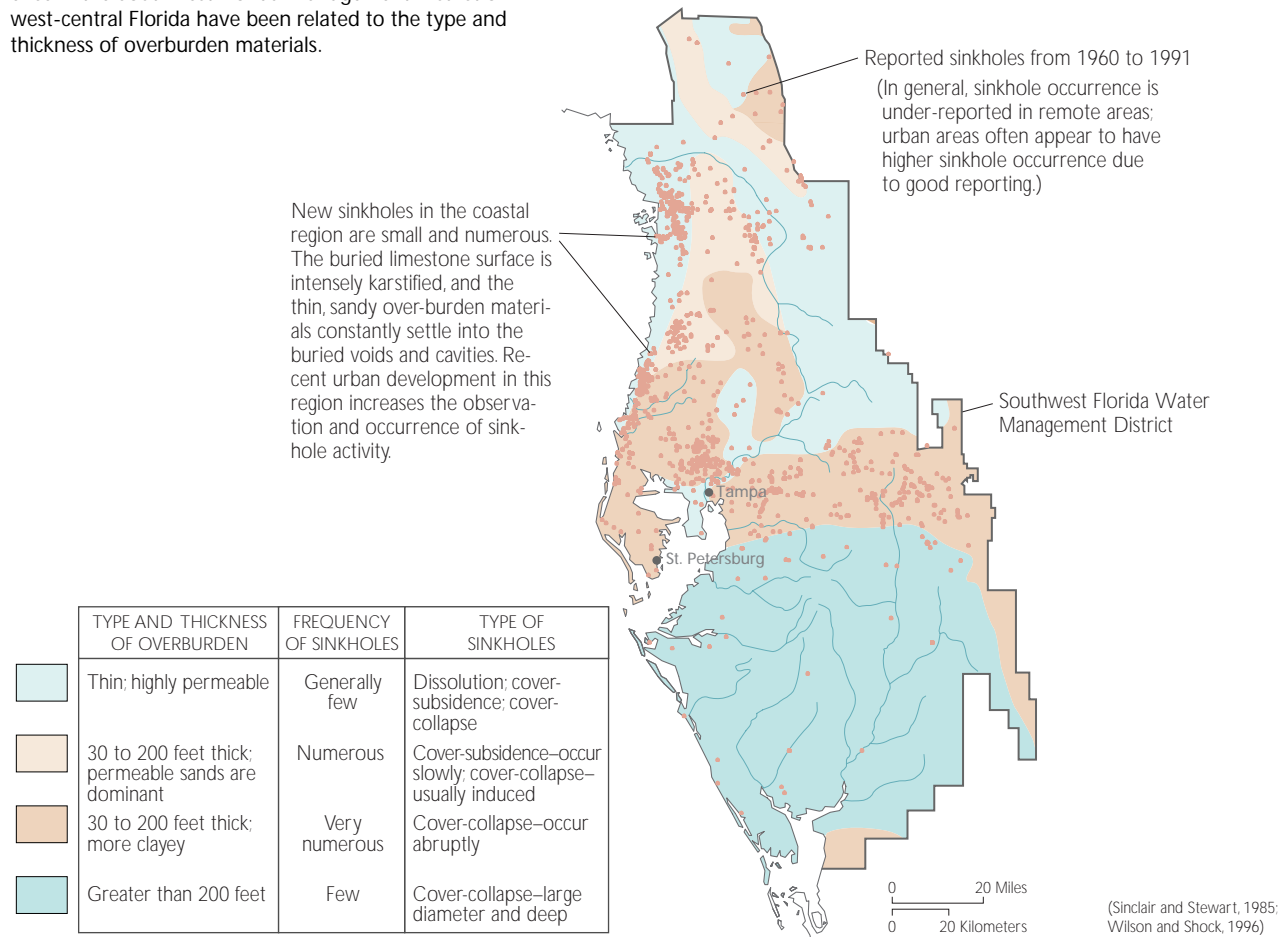
Where karst processes affect rocks that are covered by relatively insoluble deposits, the presence of buried karst features forms a distinctive type of terrain known as mantled karst. In mantled karst regions, the carbonate units are not exposed at land surface, but their presence may be indicated by 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.



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



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.

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.

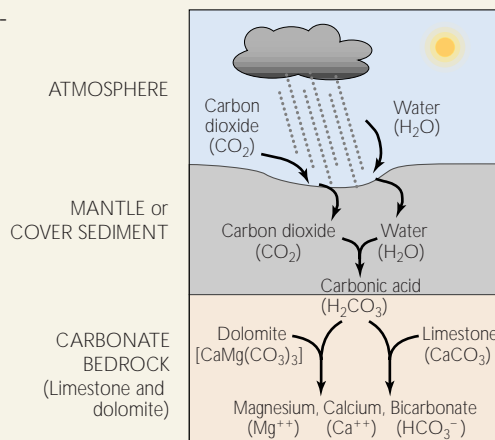


Cover-collapse sinkhole near Ocala, Florida

(Tom Scott)

PROCESSES

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



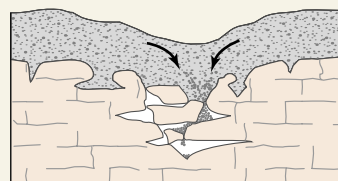
Water (H₂O) falling through the atmosphere and percolating the ground dissolves carbon dioxide (CO₂) gas from the air and soil, forming a weak acid—carbonic acid (H₂CO₃).

As the carbonic acid infiltrates the ground and contacts the bedrock surfaces, it reacts readily with limestone (CaCO₃) and/or dolomite [CaMg(CO₃)₂].

Cavities and voids develop as limestone or dolomite is dissolved into component ions of calcium (Ca⁺⁺), magnesium (Mg⁺⁺), and bicarbonate (HCO₃⁻).

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.

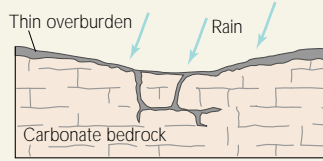
Suffosion occurs when unconsolidated overburden sediments infill preexisting cavities below them. This downward erosion of unconsolidated material into a preexisting cavity is also called raveling and describes both the catastrophic cover-collapse sinkhole and the more gradual cover-subsidence sinkhole.



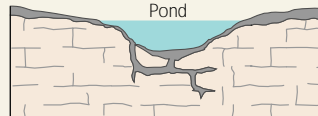
The erosion begins at the top of the carbonate bedrock and develops upward through the overlying sediments toward the land surface.

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 pre-existing 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.

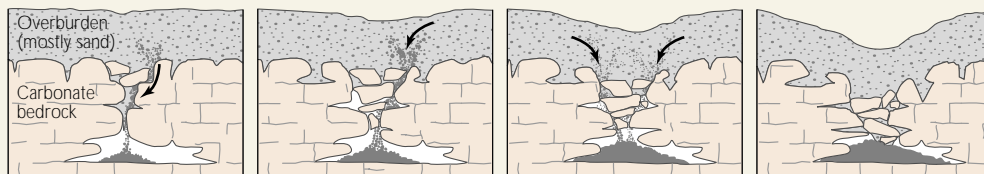
Cover-subsidence sinkholes tend to develop gradually where the covering sediments are permeable and contain sand.

Granular sediments spill 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 noticeable 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.

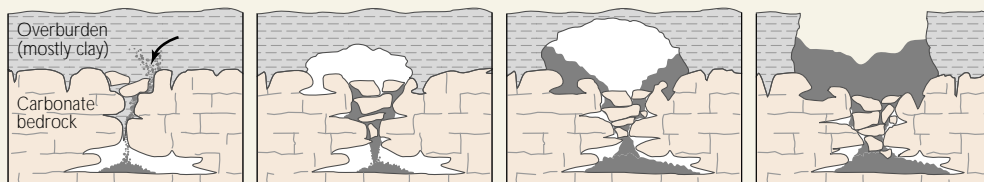
Cover-collapse sinkholes may develop abruptly (over a period of hours) and cause catastrophic damages. They occur where the covering sediments contain a significant amount of clay.

Sediments spill 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.

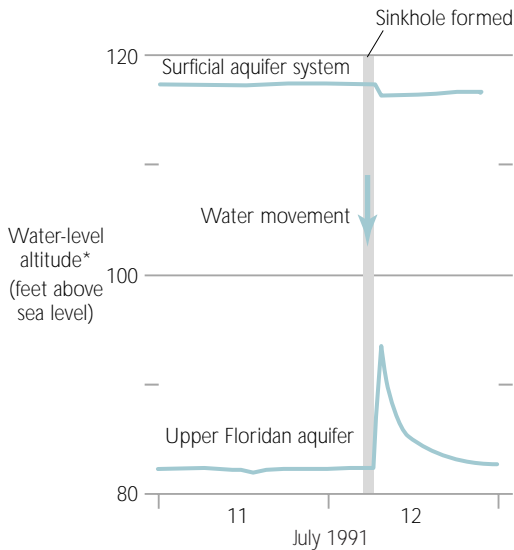
Many of the numerous lakes and ponds that dot the Florida landscape, such as these in central Polk County, are actually subsidence depressions that are filled with water.



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.

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.



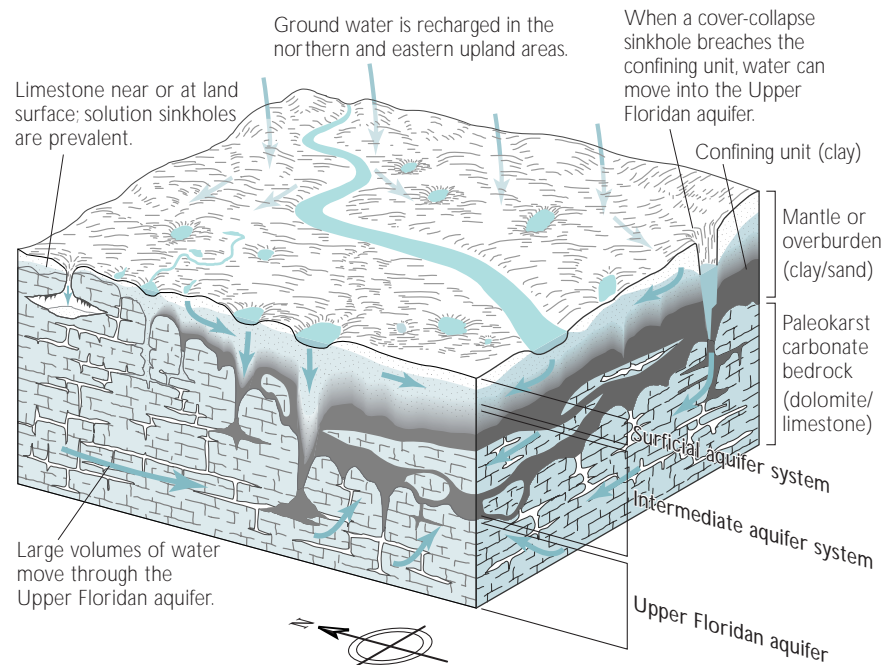
*Water levels were recorded at a SWFWMD Regional Observation Monitoring Program wellsite that is less than 1,000 feet from the sinkhole

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

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 siliclastic 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.

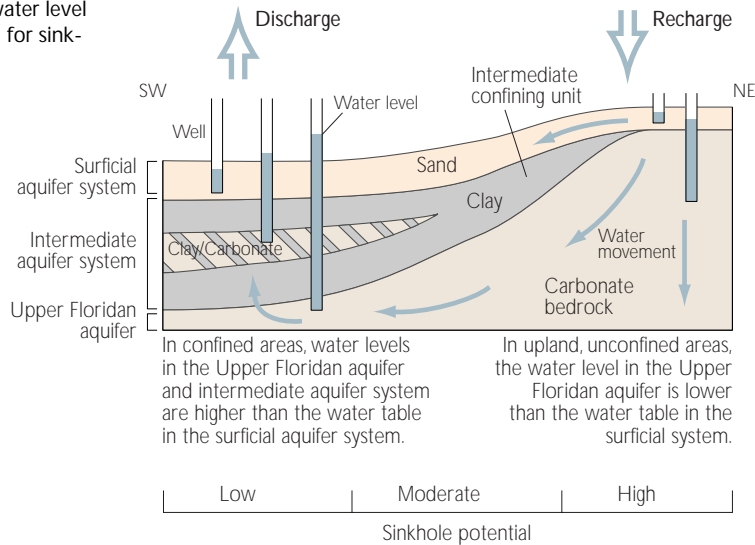


The type and frequency of sinkholes in west-central Florida are related to the presence or absence of the intermediate aquifer system.

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 heterogeneous 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 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-

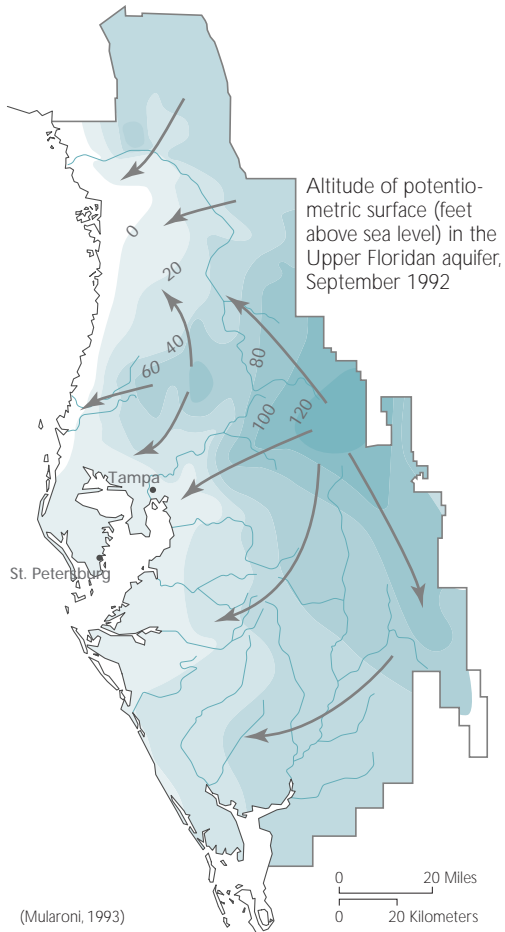
The presence of a confining unit affects the water level and the potential for sink-holes.



In discharge areas, upward ground-water flow helps provide buoyant support for overburden materials, and sinkholes rarely occur.

In recharge areas, where water movement is downward, sinkholes are more likely to occur.

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

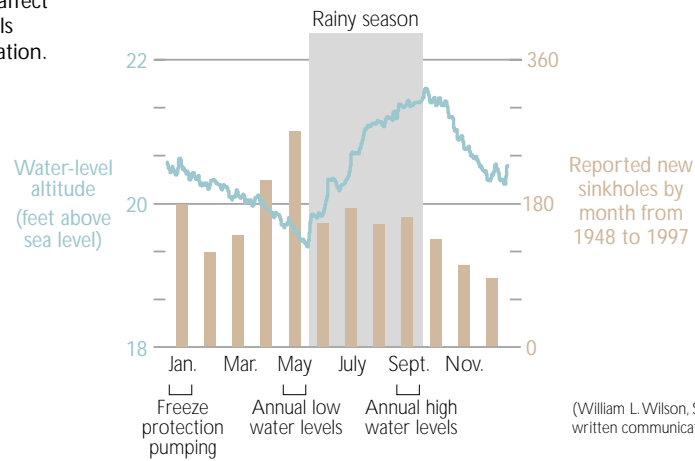


sivity values far exceed those typical of diffuse ground-water flow in porous media such as sand and reflect the influence of karst-dissolution features.

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.

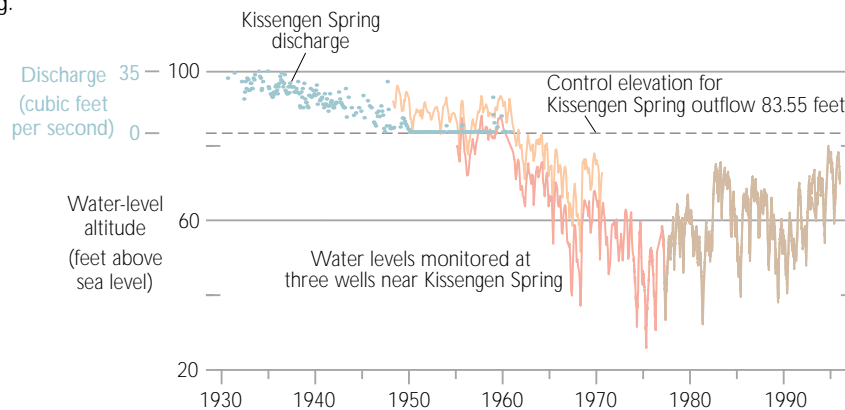


(William L. Wilson, Subsurface Evaluations, Inc., written communication, 1997)

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.

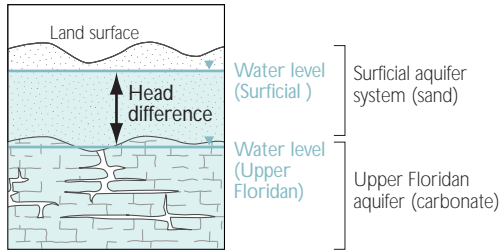
Long-term ground-water pumping near Kissengen Spring in central Polk County led to a decline in water levels and ultimately caused the spring to stop flowing.



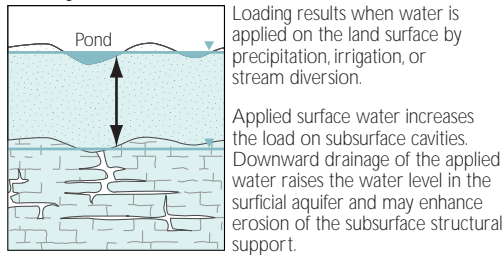
(Lewelling and others, 1998)

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

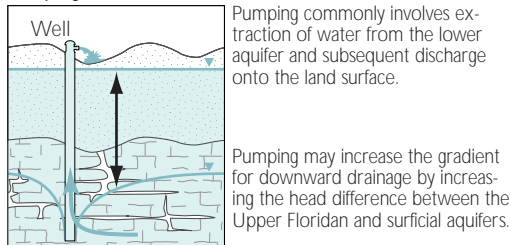
Normal conditions



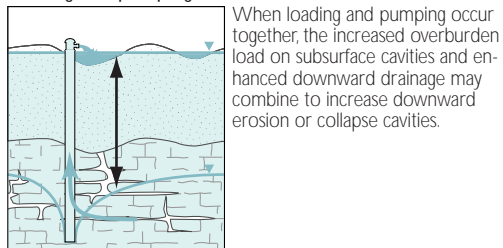
Loading



Pumping



Loading and pumping



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.

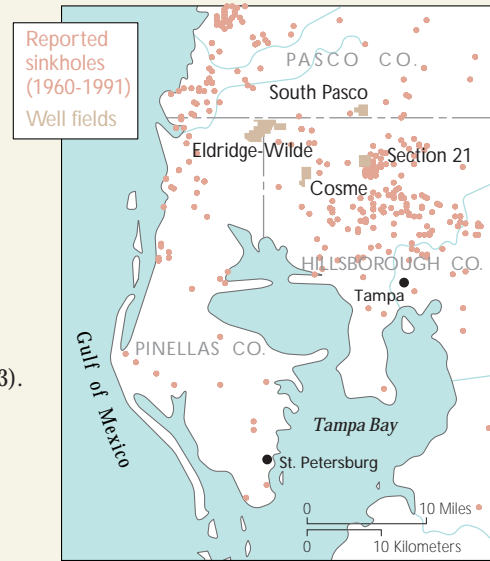
Induced sinkholes are generally cover-collapse type sinkholes and tend to occur abruptly. They have been forming at increasing rates during the past several decades and pose potential hazards in developed and developing areas of west-central Florida. The increasing incidence of induced sinkholes is expected 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 fresh-water aquifers and caused upconing of saline water. Coastal municipalities began to abandon coastal ground-water sources and develop inland sources.

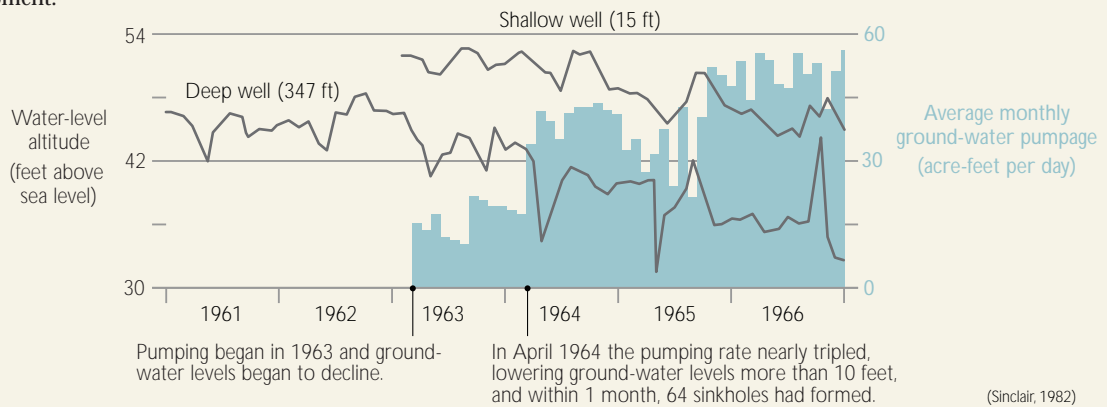
The city of St. Petersburg began pumping ground water from well fields in a rural area north of Tampa. By 1978, four well fields had been established in parts of Hillsborough, Pasco, and Pinellas Counties, and were pumping an average of 69,900 acre-feet per year. Sinkholes occurred in conjunction with 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

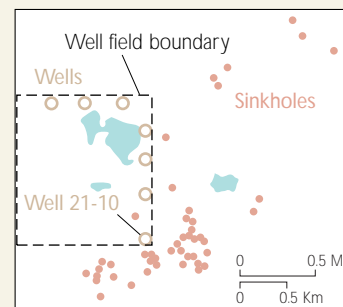
The effects of pumping on sinkhole development near the Section 21 well field illustrate the general relation between aggressive pumping, ground-water declines, and sinkhole development.



(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 pre-existing joints.

(Sinclair, 1982)

Crop freeze protection

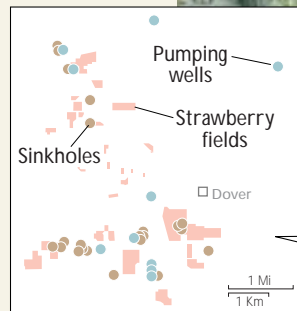
Heavy ground-water pumping during winter freezes produces new sinkholes

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.



(Tom Scott)

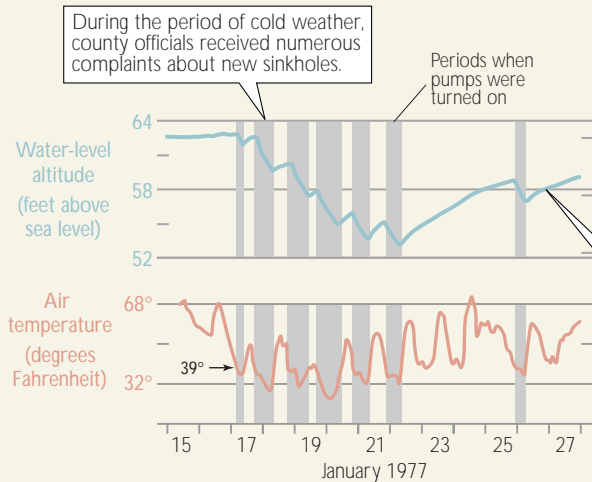
A thin layer of ice provides insulation from freezing temperatures.



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

(Metcalf and Hall, 1984)

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).



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.

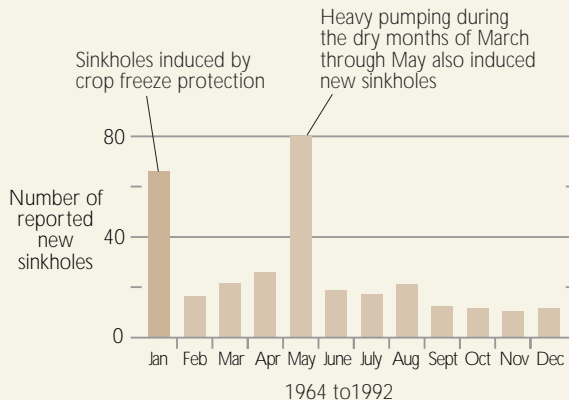
The new sinkholes were attributed to the movement of sandy overburden material through a breached clay confining unit into cavities in the limestone below.

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)





(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.

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.

“Construction practices often ‘set the stage’ for sinkhole occurrence.”

—J.G. Newton, 1986

Excessive spray-effluent irrigation

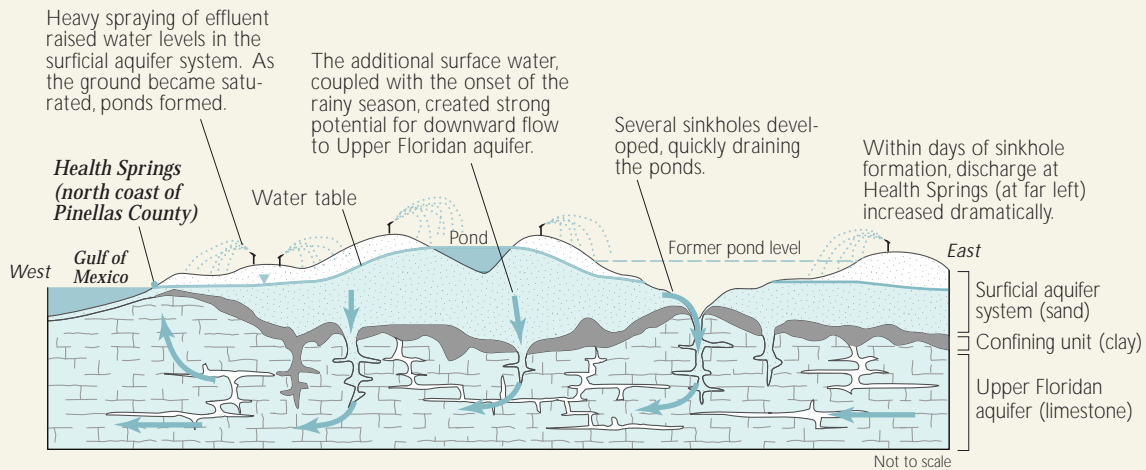
Inducing sinkholes by surface loading

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.



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

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.



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.

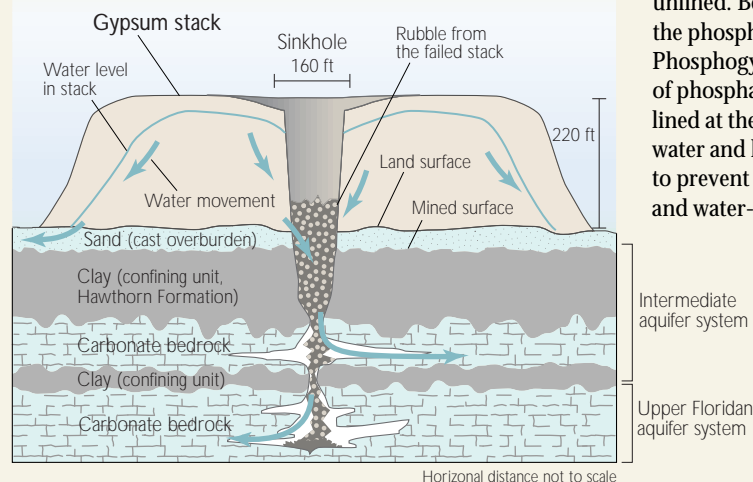
An estimated 4 million cubic feet of phosphogypsum and an undetermined amount of contaminated water disappeared through the shaft.

(Hayward Baker, Inc., 1997)

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.

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.



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.

SINKHOLES, WEST-CENTRAL FLORIDA

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