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# Development of Sinkholes Resulting From Man's Activities in the Eastern United States

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## FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

| Multiply inch-pound units | by | To obtain SI units |
|---|---|---|
| inch (in) | 25.4 | millimeter |
| inch (in) | 2.540 | centimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| square foot ($ft^2$) | 0.09294 | square meter |
| acre | 0.4047 | hectare |
| square mile ($mi^2$) | 2.590 | square kilometer |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| million gallons per day (Mgal/d) | 0.04381 | cubic meters per second |
| pound per square foot ($lb/ft^2$) | 4.882 | kilograms per square meter |

# Development of Sinkholes Resulting from Man's Activities in the Eastern United States

By J.G. Newton


## ABSTRACT

Development of induced sinkholes in carbonate terranes in the Eastern United States has resulted in costly damage and water pollution. Previously, detailed investigations of sinkholes were limited to Alabama and Missouri, with the most comprehensive being in Alabama. An investigation of the remainder of the area was made in 1981 to regionalize previous findings. More than 850 sites of sinkhole development have been identified in 19 States. It is estimated that more than 6,500 sinkholes or related features have formed at these sites. Most have occurred since 1950. Based on information available, States most impacted are Alabama, Florida, Georgia, Missouri, Pennsylvania, and Tennessee.

The total cost of damage and associated protective measures resulting from induced sinkholes is unknown. Costs reported for a limited number of sites were about $170 million—expended almost entirely after 1970. About $140 million were expended at five dams in four States and to repair or protect highways in two States.

Sinkholes are of two types, natural and induced (accelerated or caused by man). The sudden development of both types results from the collapse of the roof of a cavity or cavern in rock, or from the downward migration of unconsolidated deposits into solutionally enlarged openings in the top of bedrock. The occurrence of sinkholes resulting from bedrock roof collapses, in comparison with the occurrence of sinkholes resulting from downward migration of unconsolidated deposits, is rare.

Induced sinkholes are of two types: those resulting from a decline in water level due to ground-water withdrawals and those resulting from construction. Sinkholes resulting from water-level declines are caused by loss of buoyant support, increase in velocity of water movement, water-level fluctuations, and induced recharge. Most induced sinkholes resulting from construction are caused by the diversion or impoundment of surface drainage over unconsolidated deposits resting on openings in the top of bedrock. Collapse mechanisms include loading, saturation, and piping.

Assessment of existing or potential sinkhole problems at a site requires recognition of features associated with sinkhole development and knowledge of triggering mechanisms that cause sinkholes. Natural sinkhole development is generally not predictable. Induced sinkhole development is predictable in some instances, but is predictable only in the sense that it will occur in a particular area. The most predictable development results from dewatering by wells, quarries, and mines.

Alternatives that allow avoiding or minimizing sinkhole hazards are most numerous when a problem or potential problem is recognized during site evaluation. The number of alternatives declines after the beginning of site development. Where sinkhole development is predictable, zoning of land use can minimize hazards.


## INTRODUCTION

Sudden large collapses of the land surface during the formation of sinkholes in recent years (figs. 1, 2) have focused attention on a little-understood geologic hazard. Few people realize that thousands of similar but smaller sinkholes have formed in the United States since 1950. Costly damage and accidents have resulted from their sudden development beneath highways, railroads, buildings, sewers, dams, reservoirs and other impoundments, pipelines, vehicles, and, in some instances, people and animals. Sinkholes have also resulted in, or are potential sources of, pollution of water supplies. Concern about the problem has increased with the growing awareness that much, if not most, active sinkhole development in many areas is induced (accelerated or caused) by man's activities and that most of these activities involve changes in the hydrologic environment.

Sinkholes (also called dolines) are natural features that occur in carbonate terranes. These terranes are characteristically underlain, at relatively shallow depths, by soluble carbonate rocks such as limestone, dolomite, and marble. About 15 percent of the United States is underlain by these rocks. The distinctive topographic features that develop in carbonate terranes are unique in that their development is accomplished by surface and subsurface mechanical and solutional erosion. Subsurface erosion is accomplished mechanically, just as it is on the surface, and solutionally when water

FIGURE 1.—Collapse forming new sinkhole in Shelby County, Ala., 1972. (Photograph by T.V. Stone.)

dissolves the carbonate rocks. These types of erosion are responsible for the creation of sinkholes and cave systems throughout the World.

Under natural conditions, the formation of new sinkholes during a man's lifetime is relatively rare. In contrast, sinkholes induced by man's activities are comparatively abundant. Recognition of induced sinkhole development and limited reports resulting from scientific investigations of it are confined to this century. Almost all investigations dealing with mechanisms or processes involved in induced sinkhole development have been made since 1950. Research on this relatively new environmental problem has been limited and local in nature.

## SCOPE AND OBJECTIVES

This report is devoted almost entirely to the initial collapse or subsidence that forms an induced sinkhole. Few reports describe this stage of sinkhole development, and those that do rarely discuss the triggering mechanisms. A natural collapse is a product of a process that can span many thousands of years. This time frame, unfortunately, can be reduced to hours or days by man's activities.

Regional investigations of active sinkhole development in the United States have not been made. Detailed studies of recent sinkhole occurrence are available only for Missouri (Williams and Vineyard, 1976) and Alabama (Newton, 1976a). The Alabama study included natural and induced sinkholes. Most of the Alabama inventory, prompted by intense sinkhole activity in populated areas, was acquired from multiple investigations spanning more than a decade. This work, and the findings from it, were used as a basis of and a guide in this assessment.

The primary objective of this report is to document and regionalize previous findings relating to causes and mechanisms that trigger induced sink-

FIGURE 2.—Collapse forming new sinkhole in Winter Park, Fla., 1981. (Photograph by A.S. Navoy.)

hole development. Other objectives are to describe (1) the extent and magnitude of induced sinkhole problems, (2) ways of recognizing active subsidence, (3) methods of assessing a site for potential sinkhole development, including predictive methodology that aids in the assessment, and (4) alternative courses of action that will aid in minimizing sinkhole problems.

## AREA OF STUDY

The area of study is the Eastern United States. Within this broad area, the study is further limited to that part underlain at relatively shallow depths by soluble carbonate rocks (fig. 3). The absence of these rocks eliminates the possibility of sinkhole occurrence.

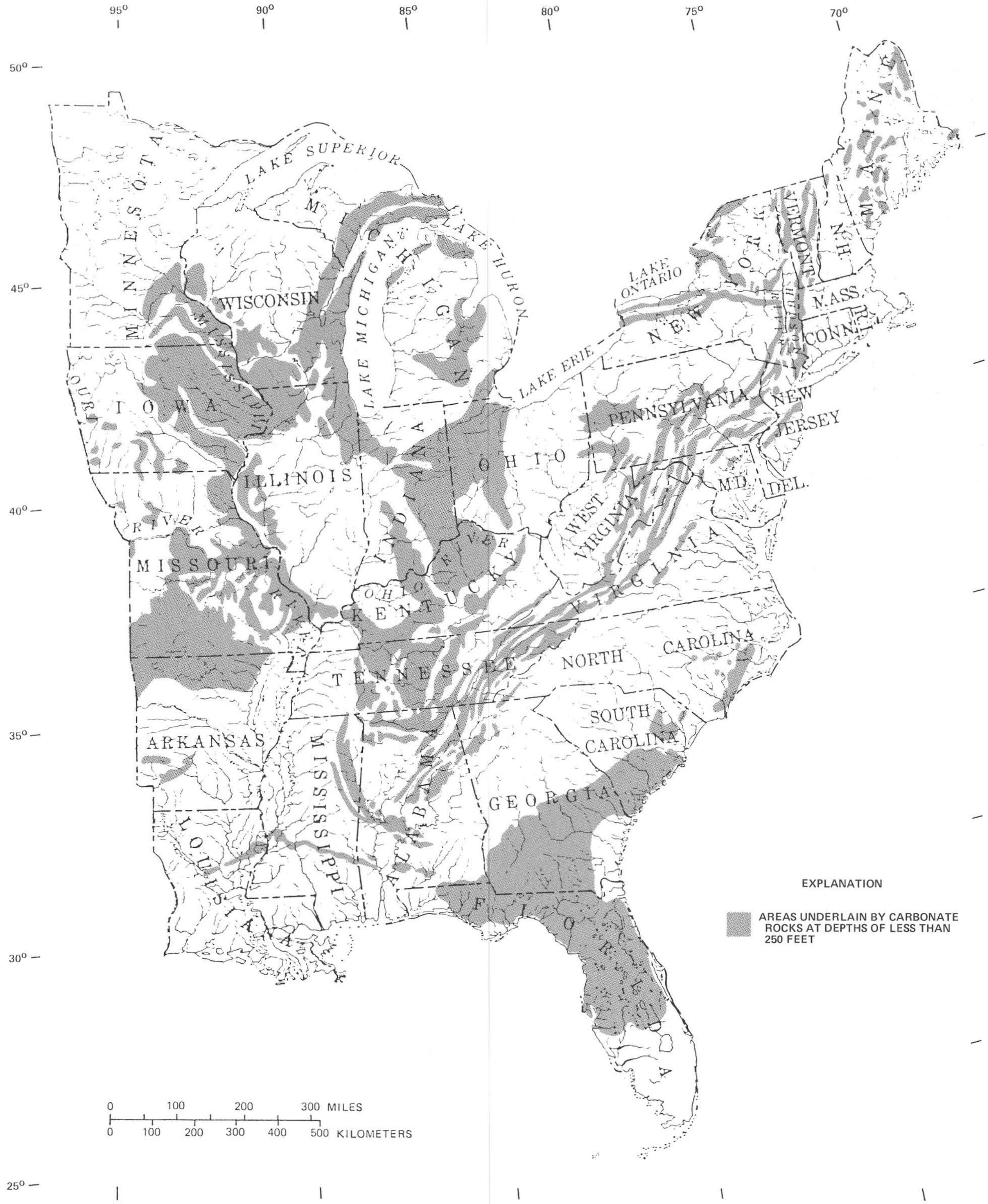



FIGURE 3.—Area of study and distribution of carbonate rocks.

The topography within the study area varies from essentially flat in coastal areas and in basins of the Mississippi River and other large streams to extremely rugged in the Appalachian Mountains. Maximum relief is about 6,600 feet. Climatic conditions also vary widely. Although almost all of the study area is classified as humid, the range in average annual precipitation is large—generally from about 25 inches in Minnesota to about 65 inches in parts of Florida and Louisiana.

Man's principal activities within the study area that are associated with active sinkhole development include ground-water withdrawals and diversion or impoundment of surface water. Ground-water withdrawals from carbonate rocks are through many thousands of wells that provide supplies for domestic, agricultural, public, and industrial use. Large withdrawals are also made locally as part of dewatering processes necessary in the construction and mining industries.

Manmade impoundments of surface water are very common in the study area; they vary in size from small ponds to major reservoirs. Many impoundments are also used to store or treat industrial process water or to process wastes such as sewage. Diversion of surface-water runoff from its natural course is extremely common; it accompanies almost all construction.

### METHOD OF INVESTIGATION

Most data for this investigation were collected in 1981. The first phase of work was to obtain information on the occurrence of sinkholes in areas in Alabama not previously studied. This was accomplished by contacting local agencies, officials, and consulting firms. Sites of multiple sinkhole occurrence were examined in the field. This was followed by a literature search to locate previous findings dealing with processes or mechanisms involved in sinkhole development, and to locate sites of sinkhole occurrence in the remainder of the study area.

The investigation of sinkhole occurrence in States other than Alabama was accomplished by contacting the primary agencies within the various States that would be expected to deal with the problem. These agencies included the Federal and State Geological Surveys and Departments of Transportation, and the U.S. Army Corps of Engineers. Other investigators in subsidence and related studies in carbonate terranes were also contacted. Where necessary, information was obtained by field visits.

### ACKNOWLEDGMENTS

Appreciation is expressed to the many individuals, government agencies, and companies that provided information on active subsidence. Special acknowledgment is due C.W. Copeland, Geological Survey of Alabama, and S.W. Shannon and L.W. Lockett, Alabama Highway Department, for contributing information on sinkholes occurring in Alabama since 1976. Similar acknowledgment is due numerous individuals and agencies that deal with sinkhole problems for providing their time and information. These contributors and their agencies include the following: Douglas Wilson, Georgia Geological Survey; Drs. H. Gray and C. Rexroad, and M. Wright and S. Frushour, Indiana Geological Survey; Preston McGrain, Kentucky Geological Survey, and Henry Mathis, Kentucky Highway Department; A.D. Martin, Maryland Department of Transportation; J.H. Williams and J.D. Vineyard, Division of Geology and Land Survey, Missouri Department of Natural Resources; R. Shiver, North Carolina Department of Natural Resources and Community Development, and W.D. Bingham, North Carolina Department of Transportation; J. Peter Wilshusen, Pennsylvania Geological Survey; D.L. Royster and H.L. Moore, Tennessee Department of Transportation; and Berke L. Thompson, West Virginia Department of Highways. B.C. Spigner, Soil and Material Engineers Inc., Columbia, S.C., provided information for South Carolina.

Charles Cressler and William Sinclair of the U.S. Geological Survey are also acknowledged for providing their inventories on active subsidence in Georgia and Florida, respectively.

## MAGNITUDE OF SINKHOLE-RELATED PROBLEMS

Recent development of sinkholes has occurred in 19 of 31 States in the project area. Available information does not define accurately the magnitude of the problem in many areas, owing primarily to the limited nature of this investigation.

Available information shows that the occurrence and impact of sinkhole development in the study area has been most significant in Alabama, Florida, Georgia, Missouri, Pennsylvania, and Tennessee (fig. 4). States underlain by carbonate rocks that have been least affected by recent sinkhole development are located in areas affected by ancient glaciers (fig. 4). Most underground openings that might ultimately have caused sinkholes to form in these areas were either destroyed by the ice, filled with glacial debris, or covered with thick glacial deposits.

## DISTRIBUTION AND SIGNIFICANCE OF SINKHOLES

The total number of sites of induced and natural sinkhole occurrence inventoried exceeds 850. Their locations are shown in figure 4. Because of the number of sites in some areas, some location symbols represent groups of sites. More than 75 sites in Polk County, Fla., for instance, are not shown because of the density of location symbols on the map. The number of sinkholes occurring at sites also varies. While single sinkholes have occurred at some sites, multiple sinkholes have occurred at others. Summaries or case histories for selected sites are given in table 1 (at back of report).

Most of the estimated 4,000 sinkholes or related features that have occurred in Alabama since 1900 (Newton, 1976a) are located at multiple sinkhole sites. The inventory for the remainder of the States includes more than 1,500 sinkholes. This total is misleading because information is not available to determine how many sinkholes have occurred at sites of intense development. At one location in Lehigh County, Pa. (site 4 in table 1), for instance, records indicate that 128 sinkholes formed during 1953–57 and that 25 additional sinkholes formed from October 1970 to January 1971 (Pennsylvania Department of Transportation, 1971). The number of sinkholes that occurred between 1957 and 1970 and since 1971 is unknown. The number that have occurred at similar sites in Georgia, Maryland, North Carolina, Pennsylvania, South Carolina, and Tennessee is also unknown.

## HAZARDS, DAMAGE, AND POLLUTION

The development of sinkholes commonly poses hazards to man. The danger depends more on where and how rapidly they form than on their size. For instance, the largest collapse in Alabama (fig. 1) occurred in a wooded area in 1972. Even though it apparently occurred very rapidly, it posed little hazard because of its location. In contrast, a small but dangerous collapse (fig. 5) occurred beneath a railroad in Birmingham during the same year.

Only a small number of fatalities and injuries associated with sinkholes have been reported. One fatality resulted from a collapse beneath three men at a U.S. Geological Survey test well near Keystone Heights, Fla., in 1960 (site 48 in table 1). One fatality and five injuries in 1968 were attributed to sinkhole activity beneath a bridge over Anclote River near Tarpon Springs, Fla. (fig. 6) (J.W. Stewart, U.S. Geological Survey, oral commun., 1982). Another fatality resulted in 1981 from an explosion of natural gas leaking from a pipeline in West Catasauqua, Pa. (site 2 in table 1), that reportedly was located at a site of active subsidence and collapse. A tragic event also occurred in 1967 in Hannibal, Mo. Several small collapses occurred in depressions that formed during highway construction through limestone containing caves. Three boys entered a cave through one of the collapses and were never found (Williams and Vineyard, 1976). In addition to the above events, injuries have been reported in Alabama, Florida, and South Carolina.

The cost of damage and measures to protect structures against additional or potential sinkhole collapse has been significant. Costs reported for a limited number of sites amounted to about $170 million, expended almost entirely between 1970 and 1981. Of this cost, about $130 million was expended to eliminate or minimize sinkhole-related problems at five dams in Alabama, Georgia, Kentucky, and North Carolina and $10 million was expended to repair or protect highways in Alabama and Tennessee. None of the costs reported included loss of property values, which would be significant in many areas. Considering the magnitude of the problem in other areas such as Florida, Missouri, and Pennsylvania, available data do not allow a reliable estimate of the overall cost.

All sinkholes are potential avenues of pollution to underlying aquifers and nearby streams. Because of their relation to man's water activities, recent collapses are common beneath sewers, storm drains, and sewage and industrial process impoundments. Collapses and the draining of sewage lagoons into underlying aquifers have been reported in Alabama (Warren, 1974) and in Missouri, where effluent reappeared in springs and wells located as much as 1.5 miles from the source (Aley and others, 1972). In one area in Birmingham, Ala., nearby streams were affected by sinkhole damage to sewers in 1963. The damage resulted in the discharge of about 40 million


FIGURE 4.—Locations of sites of active sinkhole development.

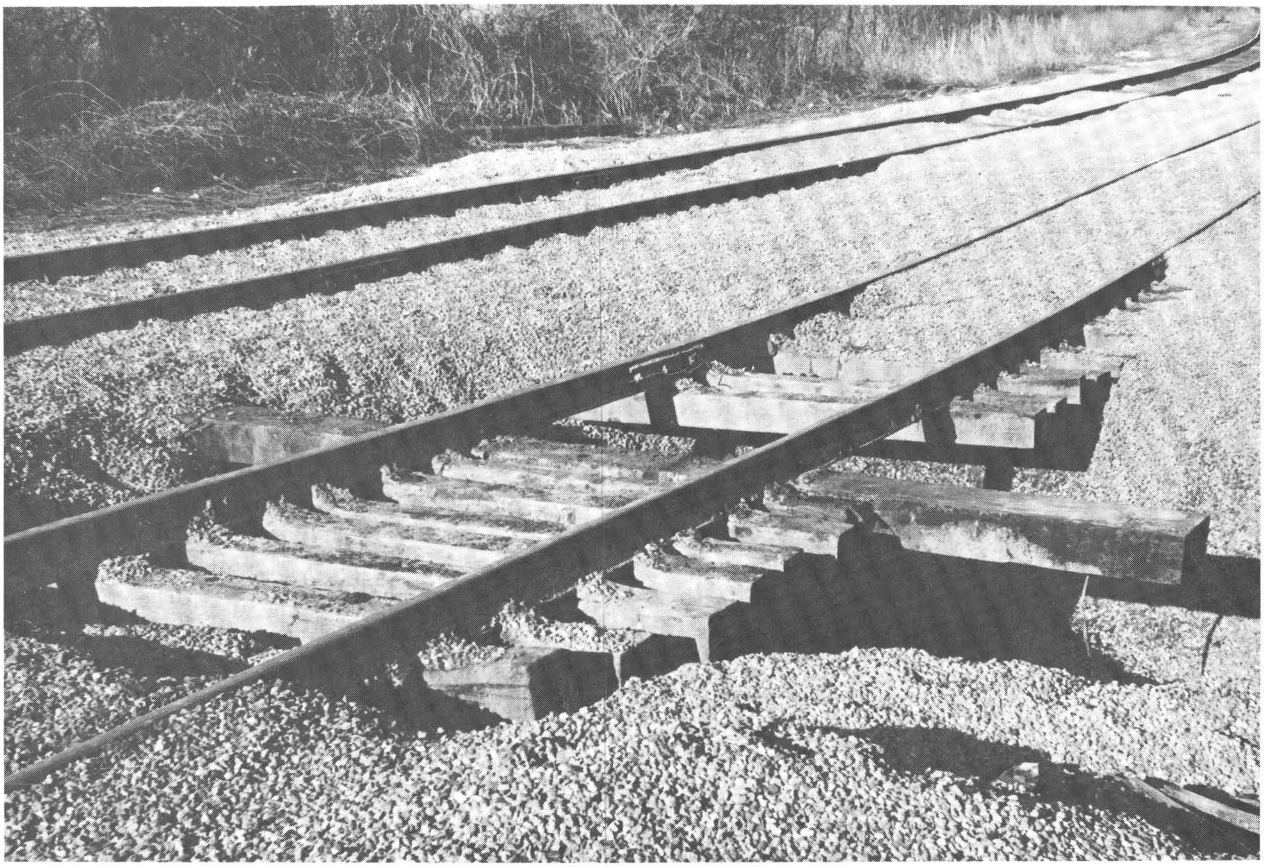


FIGURE 5.—Collapse beneath railroad in Birmingham, Ala., in 1972. (Photograph by B. Fitzgerald.)

gallons per day of raw sewage into streams for more than 3 months while repairs to the sewer were made (Newton and Hyde, 1971). Similar sinkhole development beneath sewers, sewage lagoons, and industrial process impoundments has occurred in Alabama, Florida, Georgia, Minnesota, Missouri, North Carolina, Pennsylvania, and Tennessee. Examples are sites 1, 19, 20, 41, and 43 in table 1.

## DEVELOPMENT OF SUBSURFACE OPENINGS

The physical characteristics of carbonate terranes, including the presence or absence of sinkholes in them, commonly vary from area to area and, within an area, from site to site. These variations require an understanding of basic processes such as the solution of carbonate rocks and the creation of subsurface openings in them. Mechanical erosion is also part of the basic process and involves both carbonate rock and unconsolidated material overlying or filling openings in carbonate rocks.

### SOLUTION

The solutional enlargement of subsurface openings in carbonate rocks by water occurs over thousands of years. This process, with the exception of the time involved, is similar to the solution of salt or sugar in water. Water must be acidic to dissolve carbonate rocks. Water becomes a weak carbonic acid solution ($H_2CO_3$) with the addition of carbon dioxide ($CO_2$), a product of decomposing organic matter, as the water percolates through the soil zone. When it comes in contact with calcite ($CaCO_3$), the principal mineral in limestone, the reaction results in the conversion of calcite into soluble calcium bicarbonate. The part of the rock dissolved is then transported from the site by the movement of ground water. The two reactions described are

FIGURE 6.—Collapse of bridge over Anclote River near Tarpon Springs, Fla., in 1968. (Photograph by J.W. Stewart.)

$$CO_2+H_2O \text{ (water)} \rightarrow H_2CO_3 \text{ (carbonic acid)}$$

and

$$H_2CO_3+CaCO_3 \text{ (calcite)} \rightarrow Ca^{+2}+2\ HCO_3{}^{-1}.$$

Similar reactions occur when acidic water comes in contact with dolomite or marble.

The effectiveness of acidic water as a solute is greatest when it first comes in contact with rock. Effectiveness declines as the water becomes increasingly saturated with dissolved minerals such as calcite. Once the water becomes saturated with a particular mineral such as calcite, the water will not dissolve any more of that mineral. For this reason, most solution occurs at the top of bedrock or in shallow existing openings in bedrock such as those along bedding planes, joints, fractures, and faults. Initially, solution-enlarged openings in many carbonate terranes are most common at relatively shallow depths. Over long periods of time, continuous solutional enlargement of openings results in progressively increasing interconnection. The interconnected system of enlarged openings then stores and transmits even larger quantities of the solute (water). This progressive solution of carbonate rocks sets the stage for the development of sinkholes.

The residue of the solution process, the insoluble part of rock not removed by solution, also plays an important role in the later formation of many sinkholes. The amount of residue varies with the chemical composition of the rocks involved. In Kentucky, the residue has been estimated to occupy about one-tenth of the space of the rock removed by solution (Walker, 1956, p. 23, 24). The resulting deposit, called residuum, commonly forms a mantle over the top of bedrock. This mantle consists chiefly of clay containing varying amounts of chert and other insoluble debris and, at or near its base, boulders or fragments of bedrock not completely removed by solution. The clay and other unconsolidated deposits commonly

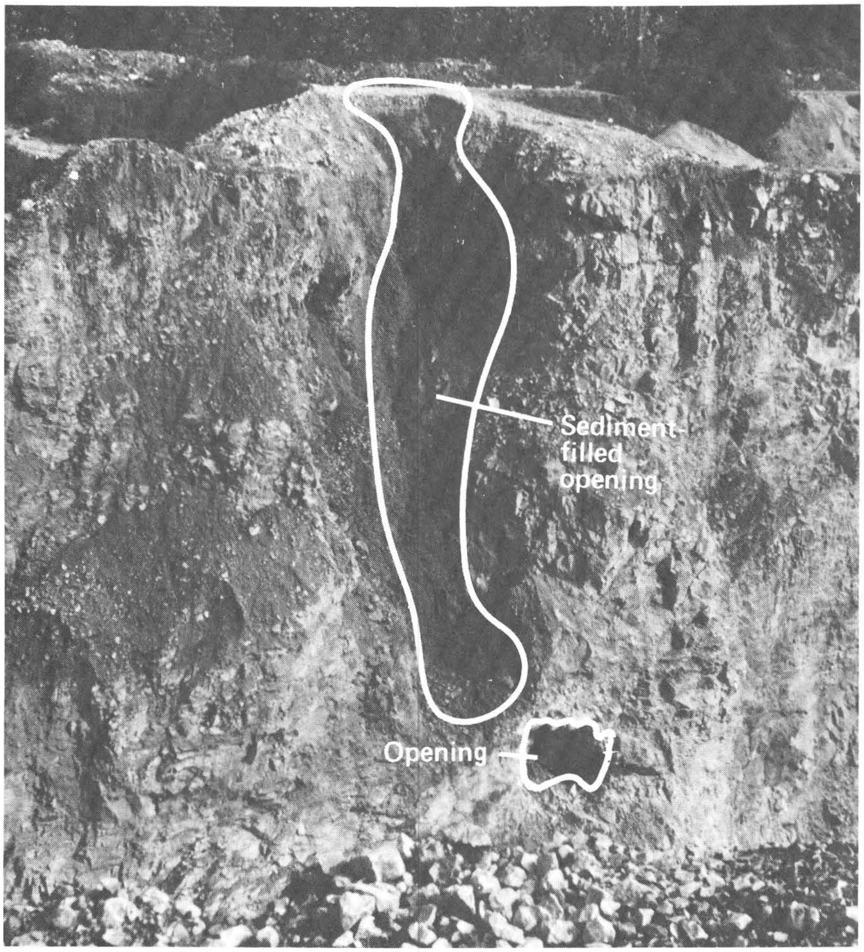



FIGURE 7.—Sediment-filled solutionally enlarged opening extending downward from top of bedrock.

fill openings in bedrock (fig. 7). These filled openings are numerous in many terranes.

### MECHANICAL EROSION OF BEDROCK AND UNCONSOLIDATED DEPOSITS

Solution-enlarged openings in the top of bedrock are abundant in most carbonate terranes, even those in which sinkholes are uncommon. They are the avenues through which water enters the rock. The presence of these openings is important in the development of sinkholes because they are also the avenues through which overlying unconsolidated deposits, by mechanical erosion, can migrate or be transported downward into bedrock openings. Sediment-laden water, in some instances, can also contribute to the mechanical erosion and removal of bedrock by abrasion.

Many sudden collapses forming sinkholes result from roof failures of cavities in unconsolidated deposits overlying carbonate rocks. These cavities are created when the deposits migrate or are eroded downward into openings in the top of bedrock. Their occurrence and growth has been described in the development of natural and induced sinkholes by Donaldson (1963), Jennings and others (1965), Foose (1967), Newton and Hyde (1971), and many other investigators.

The typical cavity in unconsolidated deposits such as residual clay is circular, with the configuration of the top resembling a dome or an arch (fig. 8*A*). The sides generally coincide with the occur-

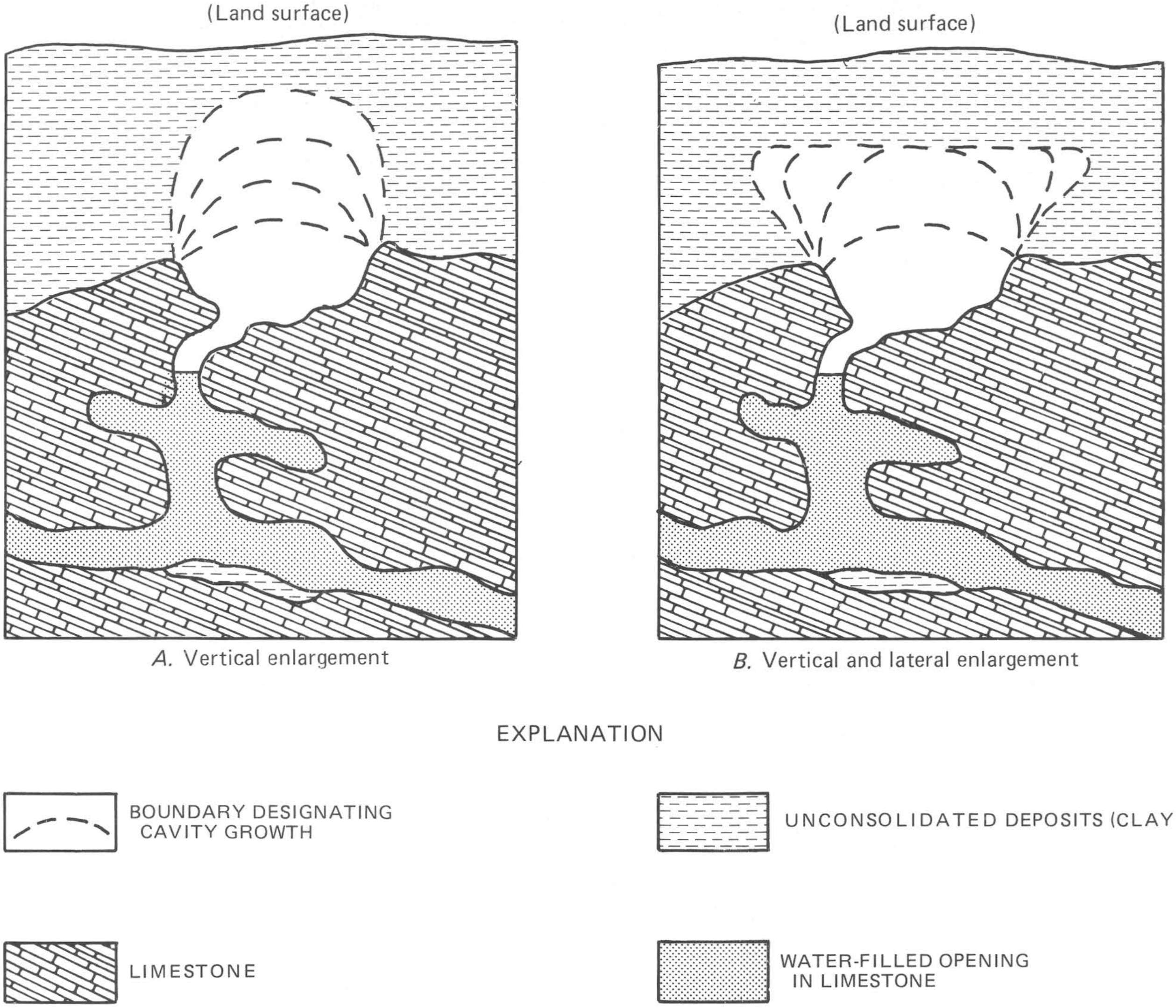



FIGURE 8.—Development of cavities in unconsolidated deposits.

rence of pinnacles or irregularities in the top of bedrock. The walls are usually vertical as the opening grows toward the land surface. This configuration, however, can be modified by the configuration of the underlying openings in bedrock and by variations in the cohesion or competence of overlying beds. The configuration of the typical opening can change if its upward growth reaches a more competent bed. The roof flattens, the growth continues laterally, and the walls taper toward the opening in bedrock (fig. 8*B*). These stages of growth in one cavity were photographed and observed through a small adjacent opening (figs. 9–11). The cavity enlargement, occurring during a 5-month period, resulted from the downward migration of unconsolidated deposits through two solution-enlarged openings, each 1 foot in diameter, exposed in the top of bedrock (fig. 11). An unusual elongated, narrow cavity, evidently mimicing the shape of an underlying fracture in the top of bedrock, was also observed in a nearby collapse. The competent bed causing the flat roofs and cavity shapes observed in this vicinity is residual clay that has been exposed to weathering. The greater resistance and toughness of this horizon, in relation to that of underlying unweathered residuum, has been described by Sowers (1956). Numerous other cavity configurations,

FIGURE 9.—Inclined opening adjacent to cavity in residual clay in November 1970 in Birmingham, Ala.

including horizontal tunneling along the top of bedrock and in associated overlying unconsolidated deposits (fig. 24), were also observed.

## CAUSES AND OCCURRENCE OF INDUCED SINKHOLES

Induced sinkhole occurrence, like natural sinkhole occurrence, basically results from (1) the collapse of the roof of a cavity or cavern in rock or (2) the downward migration of soil and other unconsolidated deposits into openings in the top of bedrock. Collapses resulting from failures of rock roofs are rare. According to Williams and Vineyard (1976, p. 32) in a study involving 97 collapses in Missouri, "Although cavern roof collapse in bedrock has been cited as a cause of catastrophic sinkhole formation, no contemporary event that could be attributed directly to this cause has been observed." Similar observations have been made in Tennessee (Moore, 1980), Alabama (Newton and Hyde, 1971; Newton, 1976a), and elsewhere. Of hundreds of recent collapses observed by the author, only one could be classified as a possible collapse of bedrock roof (Newton, 1976a, p. 15). Similarly, of 650 sinkholes recorded in Florida, only one might be a rock roof collapse, and this is not certain (Beck, 1984, p. x). The rarity of a rock-roof collapse is inferred from the fact that, in the many thousands of caves in the United States, no extensive rockfall has been recorded in historic times (Davies, 1951, p. 36; Davies, U.S. Geological Survey, written commun., 1983).

Induced sinkholes were first classified by separating those caused by lowering the water level from those caused by raising the water level (Aley and others, 1972). This classification system was mod-

FIGURE 10.—Cavity in residual clay in November 1970 in Birmingham, Ala.

ified by Newton (1976a), who categorized induced sinkholes as those caused by declines in water levels due to ground-water withdrawals and those caused by construction. Sinkholes resulting from construction include those caused by erection of structures, by impoundment or diversion of surface water, and by modifications of the land surface. Types of induced sinkhole activity identified in the States in the area of study are shown in figure 12.

Most induced sinkholes result from acceleration of natural processes by man's activities. If these activities had not been undertaken, sinkholes either (1) would not have occurred, (2) would not have occurred during a man's lifetime, or (3) would, under natural conditions, have occurred as subsidence rather than collapse.

Because of the impossibility of describing induced sinkhole development in the many carbonate terranes, two terranes have been selected to illustrate sinkhole development. For discussion purposes, they are identified as the "interior" and "coastal" terranes. Factors related to sinkhole development in them are generally applicable to other terranes. These terranes are used as examples to describe processes and (or) mechanisms associated with sinkhole development.

The interior terrane is geologically and hydrologically similar to terranes observed in 11 areas in which intense sinkhole development has been examined by the author. The coastal terrane is similar to that in many parts of Florida and probably in some parts of South Carolina and North Carolina. The interior terrane is used to illustrate sinkhole development primarily under water-table conditions, and the coastal terrane is used to illustrate sinkhole development primarily under artesian conditions.

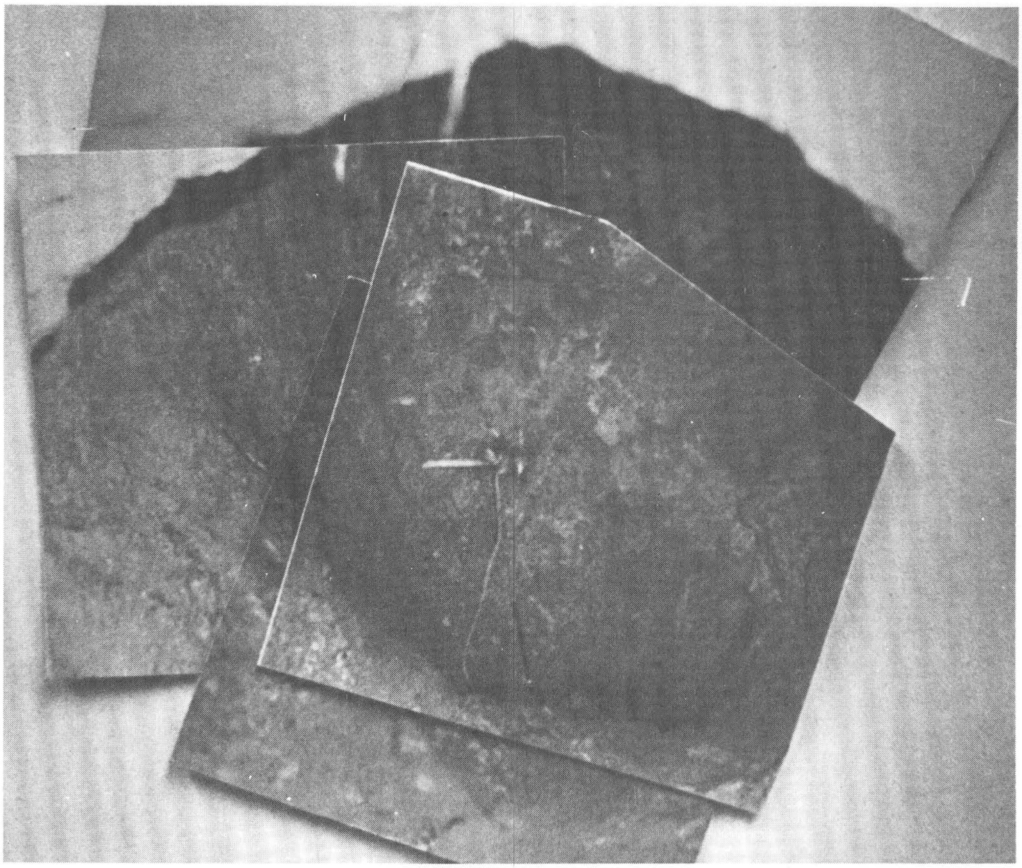


FIGURE 11.—Composite photograph of cavity in residual clay in April 1971 in Birmingham, Ala.

## DECLINE OF WATER LEVEL

The first recognizable sinkhole activity identified in the literature as resulting from groundwater withdrawals occurred near Sylacauga, Ala., when pumpage from a spring caused sinkholes one-half mile away (Prouty, 1916). The occurrence of this type of activity is not restricted to Alabama. Sites in the Eastern United States in which similar sinkhole activity has been investigated or reported are shown in figure 12, and selected sites are described in table 1.

The first scientific investigation associating the occurrence of sinkholes with pumping and a decline in the water table was made in Pennsylvania by Foose (1953). He determined that sinkhole formation was confined to areas where a drastic lowering of the water table had occurred, that their occurrence ceased when the water table recovered, and that the shape of recent collapses indicated a lowering of the water table and a loss of buoyant support.

Jennings and others (1965, p. 51) associated development of sinkholes with pumpage and the creation of cones of depression. They determined that sinkhole and subsidence problems increased where the water table was lowered. Spigner (1978) attributed intense sinkhole development near Jamestown, S.C., to a water-level decline resulting from pumpage, provided descriptions indicating loss of buoyant support, and attributed some downward movement of unconsolidated deposits to piping. Sinclair (1982) attributed similar activity in Florida to water-level declines resulting from ground-water withdrawals and identified loss of buoyant support and water-level fluctuations as contributing mechanisms.

Subsidence also accompanies the formation of sinkholes due to declines in water level. In Alabama, subsidence sometimes precedes collapse. The downward movement of unconsolidated deposits into bedrock, where the strength of the overlying material is not sufficient to maintain a cavity roof, will result in subsidence at the surface


FIGURE 12.—Areas of induced sinkhole activity.

(Donaldson, 1963, p. 124). Subsidence can also result from consolidation or compaction due to the draining of water from deposits previously located beneath the water table (Jennings, 1966, p. 48). Both processes would apply to subsidence in the study area.

Cited reports have associated the occurrence of sinkholes and subsidence with, or attributed the occurrence to, a lowering of the water table, and some have described the related development of cavities in unconsolidated deposits. These reports, however, have described only indirectly, or in part, the hydrologic mechanisms resulting from a water-level decline that cause or accelerate the development of sinkholes. These mechanisms, based on studies in Alabama (Newton and Hyde, 1971, p. 17–20; Newton and others, 1973, p. 20; Newton 1976a), are (1) a loss of buoyant support to roofs of cavities in bedrock and to unconsolidated deposits overlying openings in the top of bedrock, (2) an increase in the velocity of movement of ground water, (3) an increase in the magnitude of water-level fluctuations, and (4) the movement of water from the land surface to openings in bedrock where recharge had previously been rejected.

Schematic diagrams of the interior and coastal terranes illustrate water-level declines, the downward migration of unconsolidated deposits, the creation of cavities in them, and subsequent sinkhole development (figs. 13*B*, and 14*B*). An opening in bedrock in the stream in figure 13*A* has been sealed with a cement plug (fig. 13*B*), a common mine-dewatering practice, to prevent flooding in the cone of depression.

The water level in the interior terrane (fig. 13*B*) has declined below the top of bedrock and the hydraulic gradient has increased to the new point of discharge (the pump intake).

The cone of depression illustrated in the coastal terrane (fig. 14*B*) differs from that in the interior terrane. The decline in the potentiometric surface of the artesian carbonate rock aquifer represents a loss of pressure rather than a dewatering of the openings. Descriptions of mechanisms resulting from the declines in water level that initiate sinkhole development follow.

## LOSS OF SUPPORT

Water in aquifers in carbonate terranes provides some buoyant support, in places, to rocks that are or will be potentially involved in the development of sinkholes. In the interior terrane (fig. 13*A*), support is exerted on rocks below the water table. In the coastal terrane (fig. 14*A*), hydrostatic pressure exerted by the artesian aquifer provides some support to overlying rocks and water in the shallow sand aquifer.

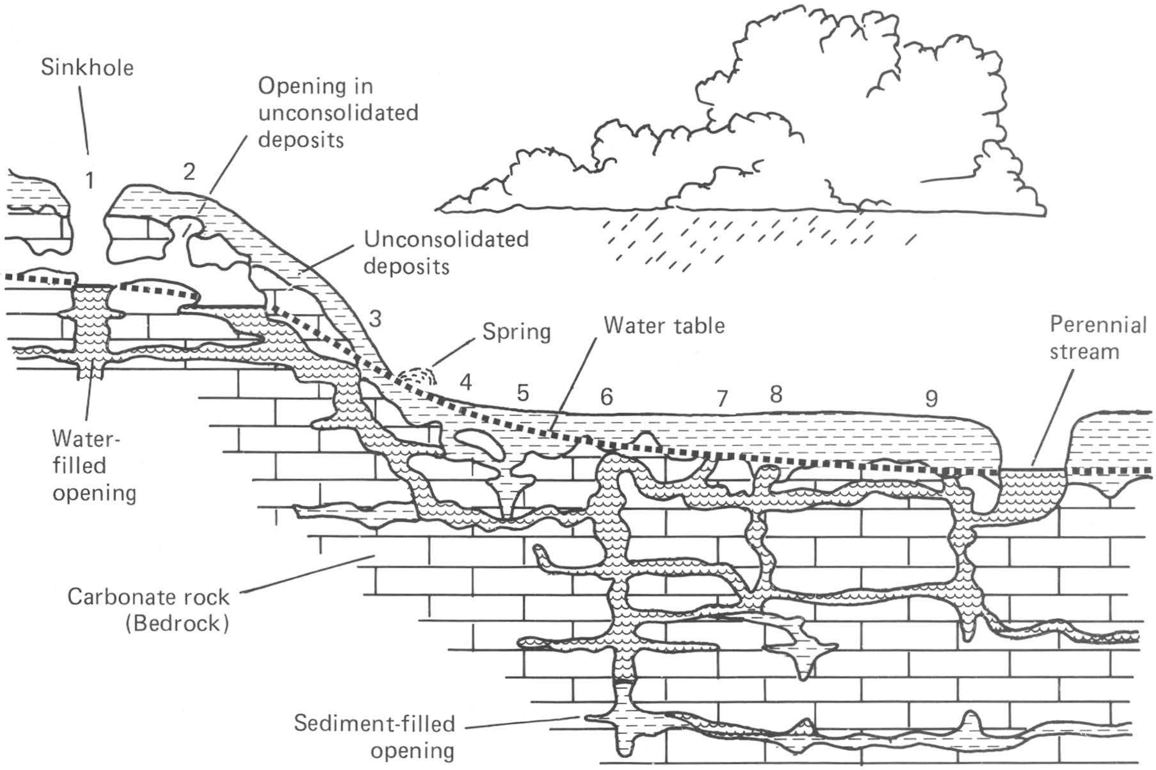
The loss of buoyant support following a decline of the water table in the interior terrane (fig. 13*B*) can result in an immediate collapse of the roofs of cavities in bedrock and unconsolidated deposits, or can cause a downward migration of unconsolidated deposits spanning or filling openings in the top of bedrock. The support exerted by water on a solid and, hypothetically, unsaturated clay that overlies an opening in bedrock, for instance, would be equal to about 40 percent of the weight of the clay. This determination is based on the specific gravities of constituents involved.

Sinkholes initiated by a loss of buoyant support are illustrated at locations 3 and 8 in figure 13*B*. The collapse of location 3 resulted from the failure of the bedrock roof of the cavity. The collapse at location 8 resulted from the failure of the roof of a cavity in unconsolidated deposits that existed prior to the decline (fig. 13*A*). The loss of support also triggered the downward movement of residual clay and the creation of a cavity in the deposits at location 7 (fig. 13*B*). The development of this type of cavity is enhanced by the physical characteristics of residual clay, which commonly has a pastelike consistency and can become a mud slurry when saturated (Kemmerly, 1980, p. 21). The sloughing of wet residual clay into foundation excavations (Sowers, 1956) also reflects its limited cohesiveness.

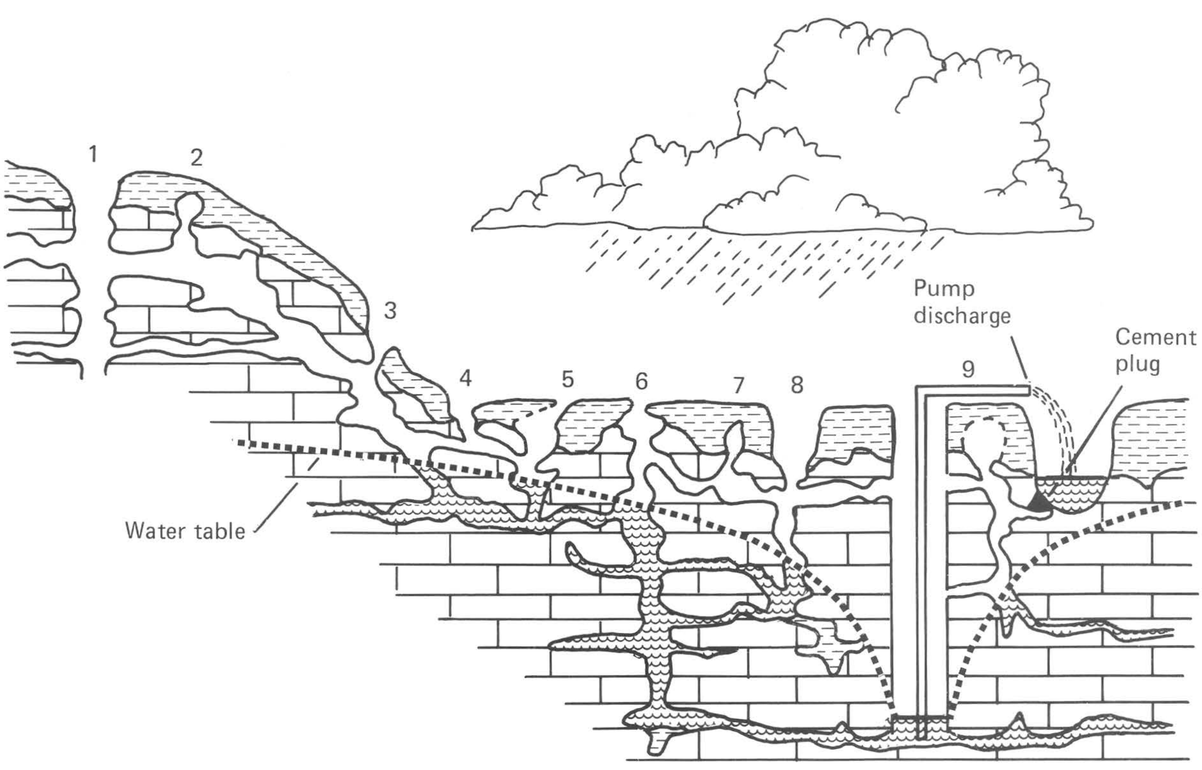
Hydrostatic pressure exerted by the artesian carbonate rock aquifer in the coastal terrane (fig. 14*A*) provides some support to overlying sand, clay, and water. A decline of this pressure (fig. 14*B*) resulting from ground-water withdrawals can initiate the development of sinkholes. This occurrence near Pierson, Fla. (site 49 in table 1), has been described by Rutledge (1982). Declines in the potentiometric surface and resulting increases in head differential result in loading on the confining bed and on underlying openings in or near the top of bedrock.

Changes in load are best described using hydrographs of the water levels involved (fig. 15). At the

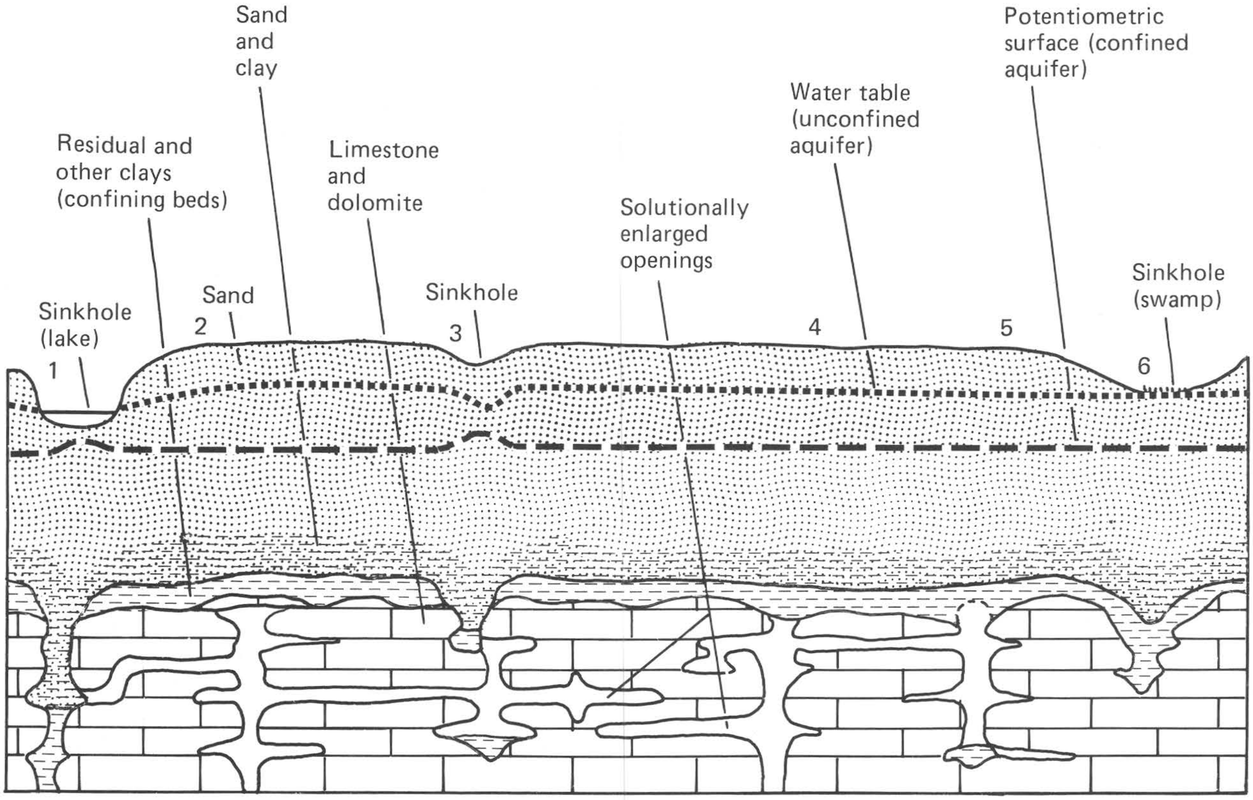
FIGURE 13.—Schematic cross sections of interior terrane showing water-level decline and resulting sinkhole development. (Numbers correspond to locations described in text.)



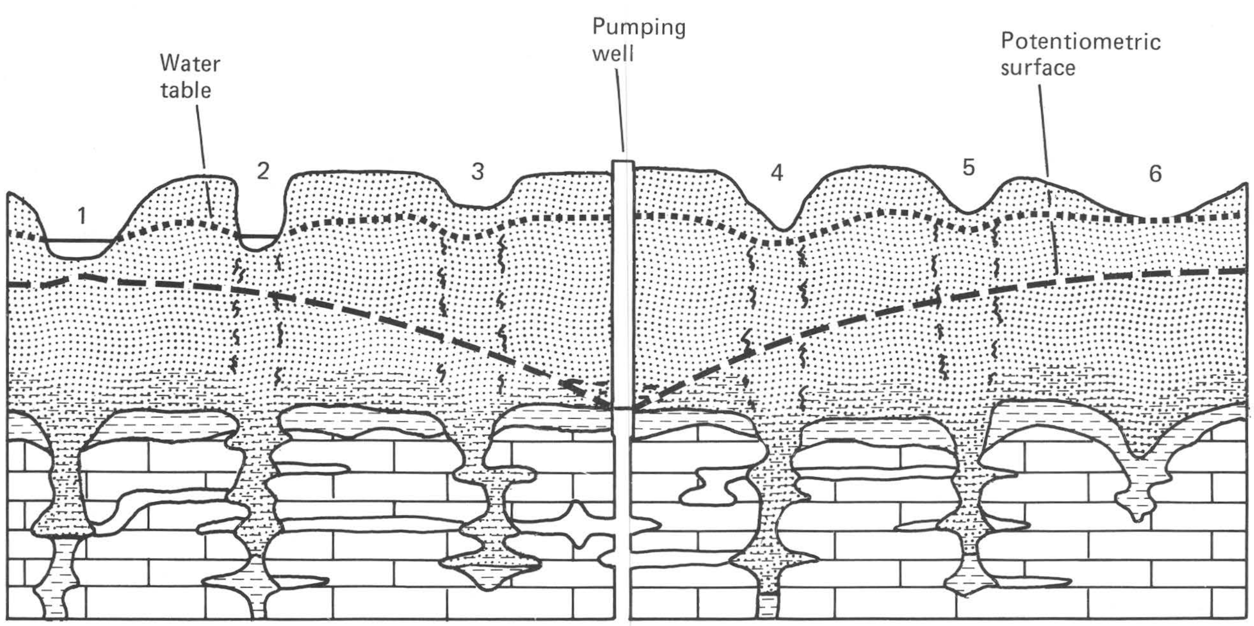

*A.* Prior to water-level decline




*B.* Pumping and water-level decline




*A.* Prior to decline in potentiometric surface




*B.* Pumping and decline in potentiometric surface

FIGURE 14.—Schematic cross sections of coastal terrane showing decline in potentiometric surface and resulting sinkhole development. (Numbers correspond to locations described in text.)

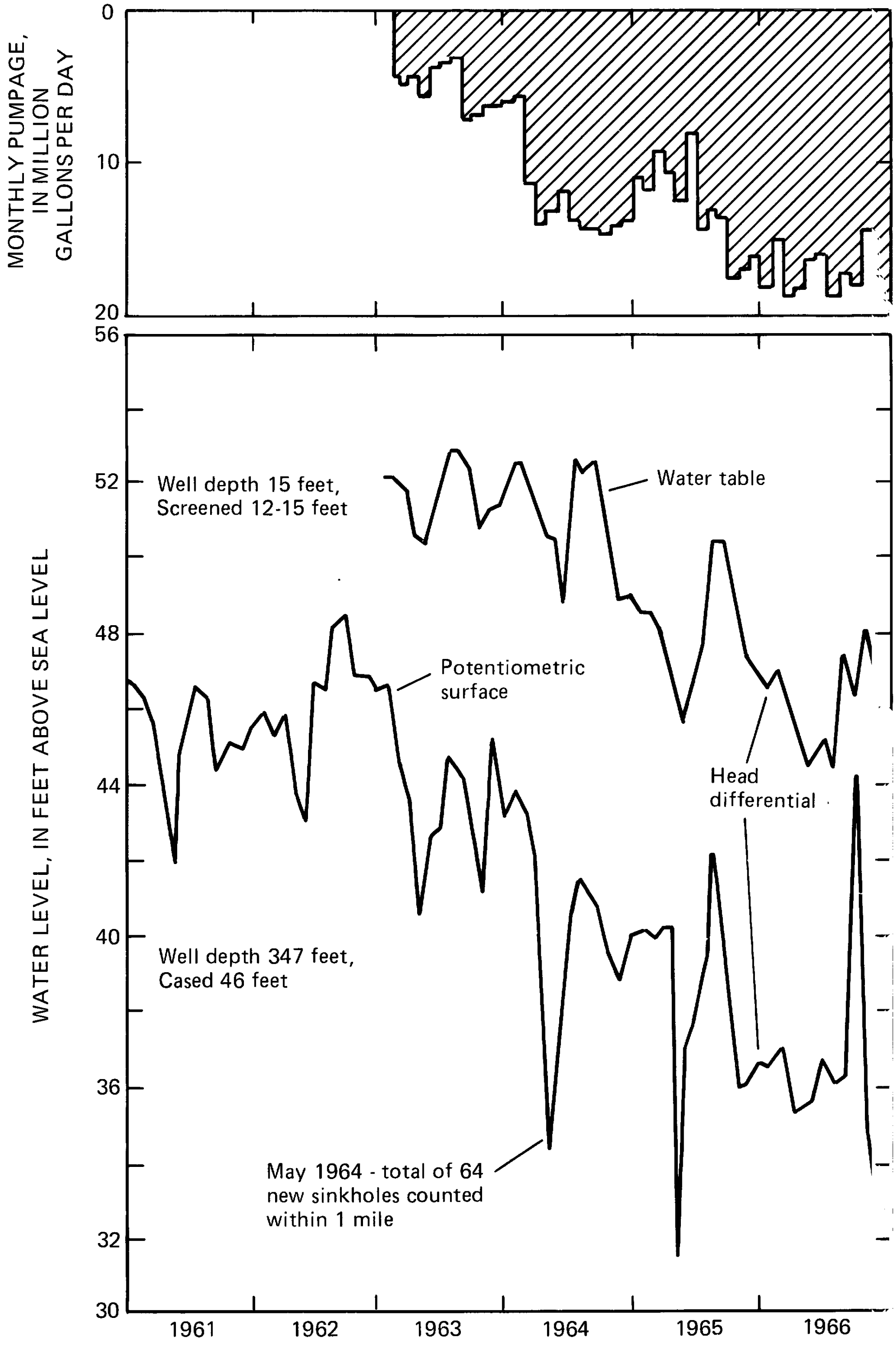



FIGURE 15.—Pumpage at well field and water-level fluctuations in wells tapping unconfined and confined aquifers in the coastal terrane (modified from Stewart, 1968, and Sinclair, 1982).

site of the observation wells at a well field near Tampa, Fla. (site 51 in table 1), the depth to the top of the confining bed is 45 feet. Prior to pumpage, the water table and potentiometric surface were 4 and 9.5 feet below the land surface, respectively. The natural load or pressure exerted on the top of the confining bed at this site, in pounds per square foot, is the total weight of water and the overlying sand and clay in a 1-square-foot column extending to the land surface minus the weight equivalent to a similar column of water extending to the potentiometric surface. The column extending from the confining bed to the potentiometric surface is the support furnished by artesian pressure. The natural load, using a specific gravity of 2.5 for sand and sandy clay and a porosity of 35 percent, was calculated to be about 3,200 pounds per square foot.

Changes in load on the confining bed resulting from declines in water levels or artesian pressure levels causing increased head differential were computed in the same manner as the natural load. Loads due to declines resulting from the beginning of pumping in 1963 and a large increase in pumpage in 1964 (fig. 15) were about 3,600 and 3,900 pounds per square foot, respectively. These loads are 13 and 22 percent greater than that determined prior to pumpage. Following the increased pumpage in 1964, 64 new sinkholes were reported within a mile of the well field (Sinclair, 1982). The actual loads at collapse sites resulting from the declines may have been smaller or greater than those estimated because of factors, such as natural seasonal declines, that were not taken into account.

Collapses resulting from loss of support in the coastal terrane are illustrated at locations 2, 4, and 5 in figure 14*B*. The collapse at location 2 resulted from the failure of a thin bedrock roof spanning an opening immediately below the confining bed (fig. 14*A*). Collapses at locations 4 and 5 resulted from the failure of the confining bed spanning an opening in the top of bedrock and the roof of a cavity in the confining bed over a similar opening (fig. 14*A*).

### INCREASE IN VELOCITY

The creation of a cone of depression in the interior terrane results in an increased hydraulic gradient toward the point of discharge (fig. 13*B*) and a corresponding increase in the velocity of movement of water. The increase in velocity has resulted in the erosion and removal of sediment from previously filled openings at locations 4 and 5 (fig. 13*A*). Collapses resulted in the formation of sinkholes (fig. 13*B*).

Collapses and subsidence that occurred under and along Interstate Highway 59 in Birmingham, Ala., in 1972 (fig. 16) are excellent examples of those caused by subsurface erosion due to increased velocity (Newton, 1976a). Clay-filled openings in bedrock beneath the highway (black areas leveled with asphalt) extend more than 50 feet below the top of bedrock. The water moving rapidly through interconnected openings from highland areas beyond the highway to the point of discharge in the bottom of the adjacent quarry eroded the clay and caused subsidence and collapses at the surface. The muddy water discharging in the bottom of the quarry results from the downward movement of weathered residuum from collapses that have just occurred.

A decline in the potentiometric surface in the coastal terrane results in increased head differential (fig. 15) which increases the velocity of recharge through the confining bed. The energy of this movement is diffuse and would not generally be expected to contribute to sinkhole development. It can contribute to sinkhole development where the confining bed has been breached. The opening in the top of bedrock underlying the shallow sinkhole at location 3 in figure 14*A* is filled with collapse debris from the ruptured confining bed and overlying sand and clay. The velocity of recharge under the natural head is much greater than that through the confining bed. An additional increase in head differential caused by pumpage could increase the velocity sufficiently to transport the debris to a greater depth in the same opening. This, in turn, would allow the downward flow of overlying sand that would result in the collapse illustrated at location 3 in figure 14*B*.

The significance of the contribution of increased velocity to sinkhole occurrence in the coastal terrane is unknown. Treatment of the subject is not readily available in the literature.

### WATER-LEVEL FLUCTUATIONS

Pumpage results in fluctuations in ground-water levels that are of greater magnitude than fluctuations that occur under natural conditions. The magnitude depends principally on the transmissivity and storage coefficient of the aquifer and on variations in withdrawals and recharge. In the interior terrane, the movement of water through openings in bedrock against overlying unconsolidated deposits causes a repeated addition and

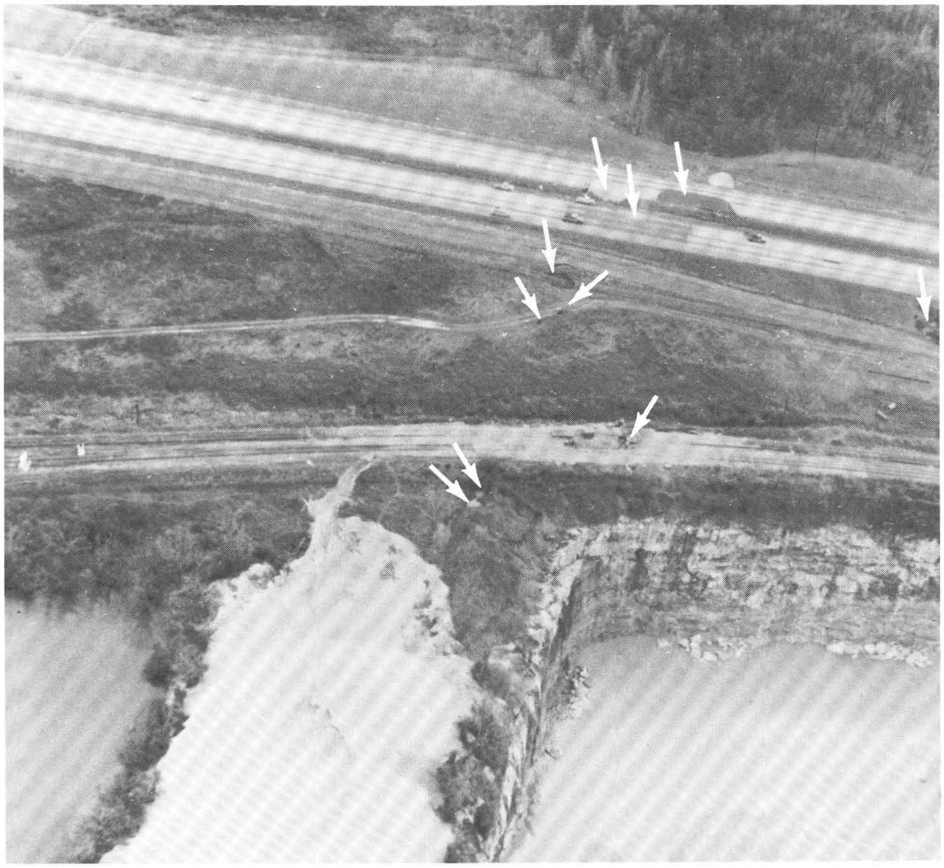


FIGURE 16.—Sinkholes and subsidence beneath and near Interstate Highway 59 in Birmingham, Ala., in 1972. (Photograph by B. Fitzgerald.)

subtraction of buoyant support and repeated saturation and drying. Both actions can result in the desiccation, spalling, and downward migration of the deposits, all of which create or enlarge cavities. These processes have been termed "erosion from below" because they result in the creation of cavities in unconsolidated deposits, cavity enlargement, and eventual collapse (Newton and others, 1973, p. 21).

Fluctuations of the water table against the roof of a cavity in unconsolidated deposits near Greenwood, Ala., in conjunction with other mechanisms, resulted in the formation of the cavity and its collapse (Newton and others, 1973, p. 22). The relation of these fluctuations in a nearby observation well to precipitation and to the contact between bedrock and residuum is shown in figure 17. Water rose against the base of residual clay three times during the 3-month period.

Rapid water-level fluctuations can also cause or contribute to the creation and collapse of cavities in residuum where the water table prior to pumping is above the top of bedrock (fig. 18*A*). The saturated zone is in the lower part of the residuum containing chert fragments and calcareous debris not completely dissolved by solution. Because of its clay content and limited permeability, the residuum will not yield water from storage as rapidly as will openings in bedrock. Large withdrawals from a nearby well cause a rapid decline in water level to a position below the top of bedrock while water stored in the residuum continues to drain into the underlying opening in bedrock. The drainage and accompanying erosion causes or contributes to the creation of a cavity in the residuum (fig. 18*B*). Repeated water-level fluctuations (figs. 18*C*, 18*D*) cause enlargement of the cavity. This process, as related to natural fluctuations and leakage from sewers in Missouri, has been described by Reitz and Eskridge (1977, p. 433). It could contribute to intensive sinkhole development like that in Rossville, Ga., and in an

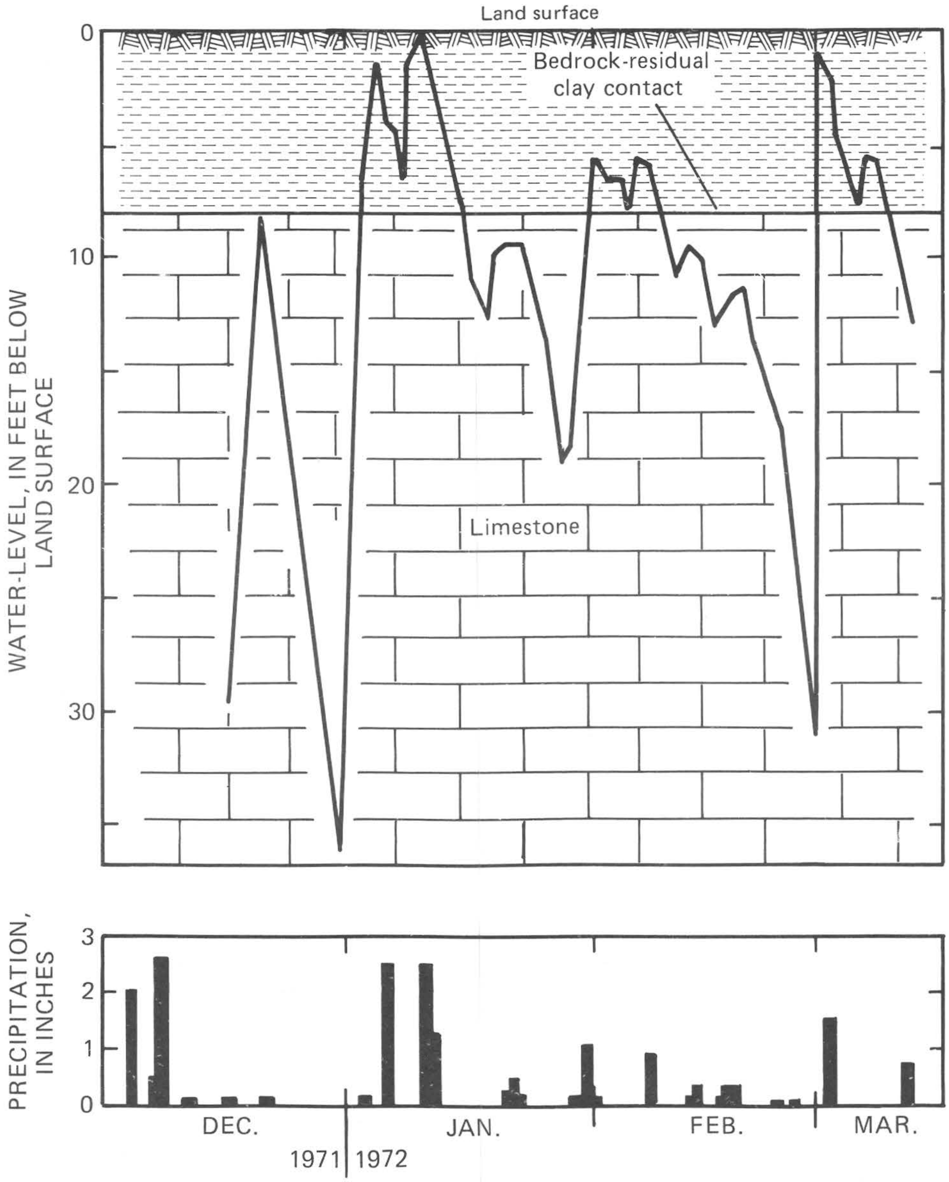


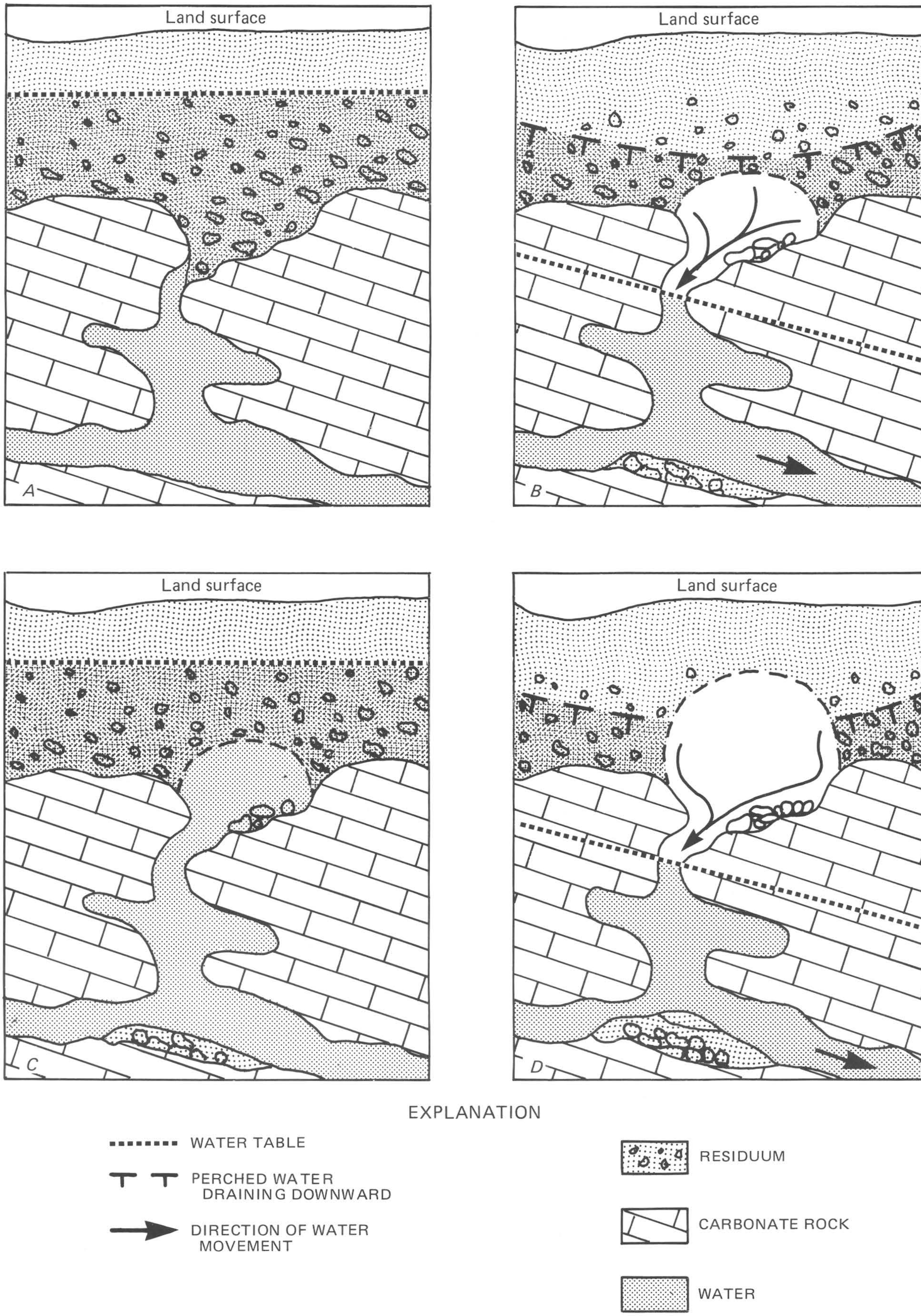

FIGURE 17.—Relation between water-level fluctuations and the bedrock-residual clay contact at Greenwood, Ala. (Precipitation data from National Weather Service.)

adjacent area in Tennessee (site 38 in table 1), where daily fluctuations due to pumpage generally ranged from 25 to 45 feet and were as much as 70 feet.

Depending on the magnitude of water-level fluctuations, any of the collapses or cavities in unconsolidated deposits overlying the cone of depression illustrated in the interior terrane (fig. 13*B*) could have resulted from the above-described mechanism.

Fluctuations in the potentiometric surface in the coastal terrane (fig. 14) result in fluctuations in hydrostatic pressure and accompanying changes in load. Load on the confining bed spanning an opening in bedrock (location 4 in fig. 14*A*) increases when the potentiometric surface declines and decreases when it recovers. The slight downward

FIGURE 18.—Subsurface erosion caused by water-level fluctuations resulting from pumpage. *A*, prior to decline of water level; *B*, decline, drainage from and erosion of residuum, and creation of cavity; *C*, recovery; and *D*, decline, drainage and erosion, and cavity growth.



Land surface
A
Land surface
B
Land surface
C
Land surface
D
EXPLANATION
WATER TABLE
PERCHED WATER DRAINING DOWNWARD
DIRECTION OF WATER MOVEMENT
RESIDUUM
CARBONATE ROCK
WATER

FIGURE 19.—Erosion of soil into rotted-out root opening.

deflection of the confining bed resulting from increased loading and the rebound resulting from decreased loading, when the changes in load are instantaneous, would exert stress on potential shear planes and weaken the confining bed.

### INDUCED RECHARGE

A drastic decline of the water table in lowland areas in the interior terrane (fig. 13*B*) drains openings in underlying rocks that were previously water filled (fig. 13*A*) and results in increases in recharge from precipitation. This recharge was partly rejected prior to the decline because the openings were water filled. The quantity of surface water available as recharge to a lowland is generally large because of runoff moving to and through it from higher areas.

Movement of induced recharge through openings such as animal burrows or rotted-out root openings (fig. 19) into openings in underlying bedrock results in the creation of cavities in the unconsolidated deposits. This occurs where the deposits overlying bedrock openings are eroded through the openings to lower elevations. The process, referred to as "piping," also results in the development of natural sinkholes. It is illustrated in figure 20. The piping process generally occurs where the water table, previously located above the top of bedrock, is no longer in a position to dissipate the mechanical energy of the downward-moving recharge. Rains result in progressive cavity enlargement, which eventually results in a collapse.

A surface opening and underlying cavity formed by piping illustrated at location 5 in figure 13*B* and in figure 20*B* are the same as those shown in photographs in figures 9, 10, and 11. The process is also illustrated in figures 21 and 22. Figure 21 shows a vortex, or small whirlpool, in a stream caused by induced recharge entering the subsurface where openings in bedrock have been dewatered. The collapse that occurred at the site a few days later (fig. 22) resulted in the loss of

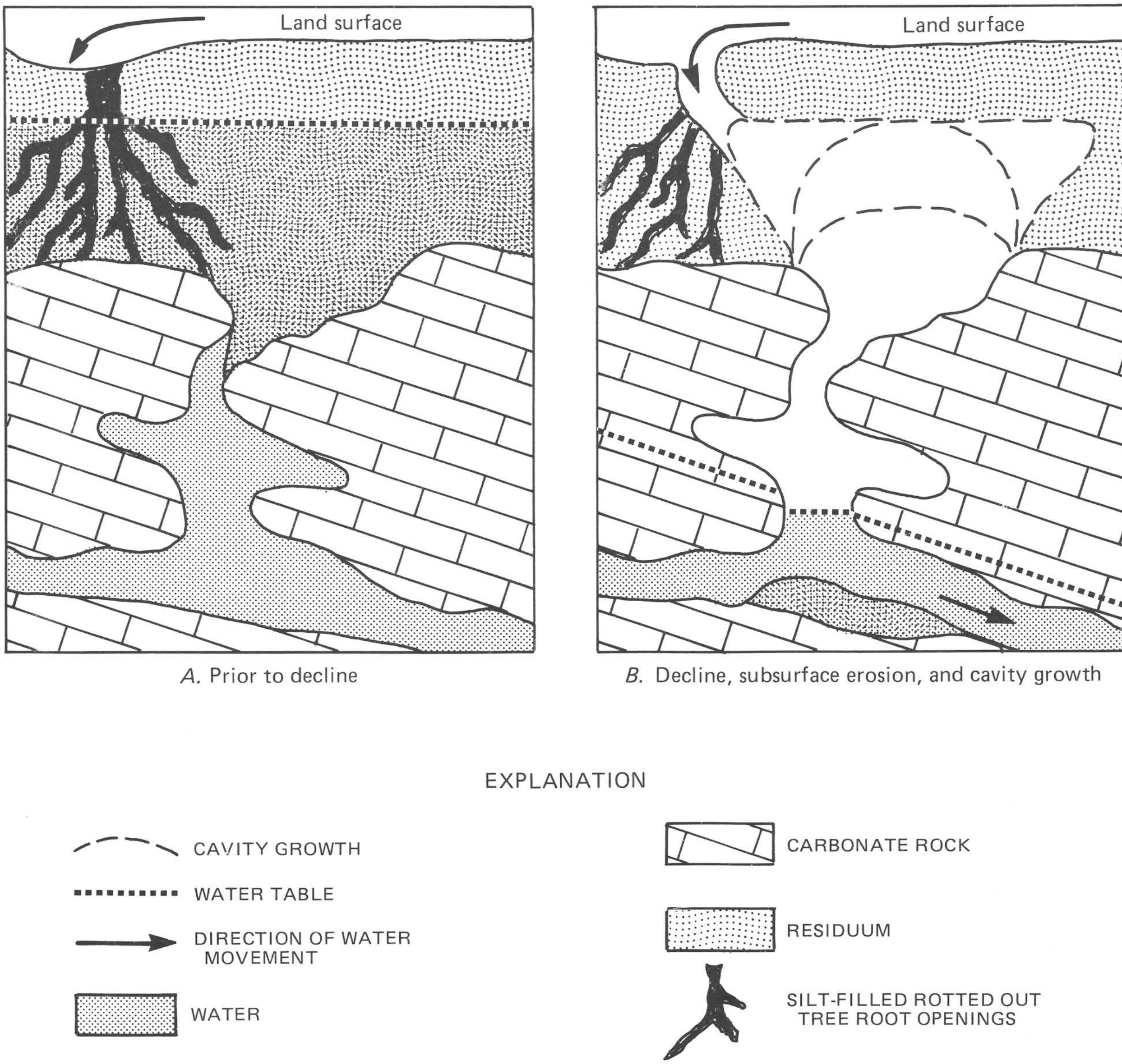



FIGURE 20.—Subsurface erosion (piping) resulting from water-level decline.

streamflow until the underlying opening in bedrock was sealed.

Areas in the interior terrane especially vulnerable to collapses due to induced recharge are near streams that have ceased flowing because of a decline in the water table. Precipitation on such an area results in intermittent streamflow that discharges from the streambed into the subsurface and forms sinkholes (Newton and others, 1973, p. 21). Large numbers of collapses also occur in adjacent lowland areas during flooding.

Declines in the potentiometric surface in the carbonate-rock aquifer of the coastal terrane (fig. 14*B*) result in induced or increased recharge from the shallow sand aquifer through the confining bed. As discussed previously, this recharge would be diffused and would probably not contribute to sinkhole development. Increased velocity accompanying the increased recharge through breaches in the confining bed would contribute to sinkhole development, however, and is described under that mechanism.

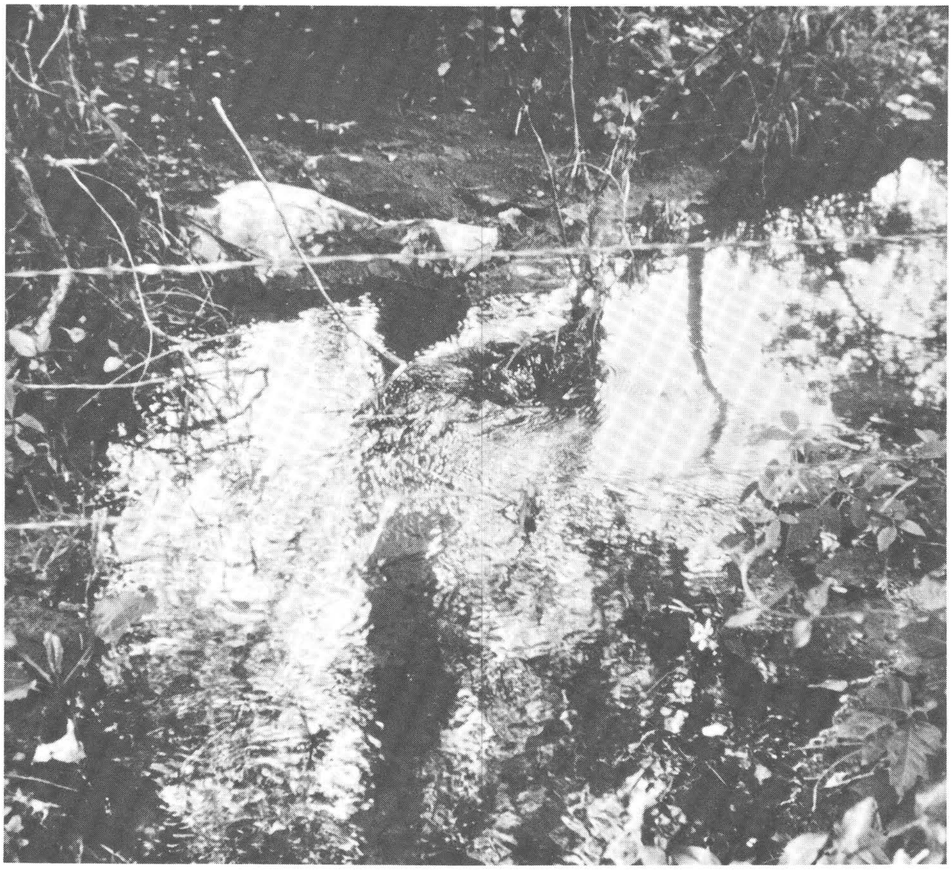


FIGURE 21.—Induced recharge forms vortex in stream in Shelby County, Ala.

### OCCURRENCE AND SIZE

Sinkhole development due to water-level declines in the interior terrane is confined largely to lowlands in basins containing perennial or near-perennial streams or to areas where the water table was above or near the top of bedrock prior to pumpage. The position of the water table with respect to the irregular residuum-bedrock contact prior to and during withdrawals determines whether the area is prone to sinkhole development. The activity is confined to the cone of depression, where the mechanisms described affect unconsolidated deposits, or, rarely, to the roofs of cavities in bedrock. In the Eastern United States, sinkhole activity due to water-level declines is confined to areas that generally vary in size from a few feet around the point of water withdrawal to about 10 square miles (site 27 in table 1). Where the water table is maintained below the top of bedrock, the location of collapses is predictable to some degree. Many occur where surface water concentrates or where man has disturbed the land surface (e.g., by timber removal, ditching, laying of drains and pipelines) sufficiently to increase the downward movement of recharge. In one small open area in Shelby County, Ala. (fig. 23), for instance, 26 of 33 collapses are located in an area from which timber was removed after 1950, or are within 50 feet of structures which include a highway, its drain, and a gas pipeline (Newton, 1976a). Most of the others are in natural drainageways and on the flood plain of a nearby stream. Available data for the interior terrane indicate that most sinkhole activity has been related to rainfall, especially deluges (Newton and Hyde, 1971, p. 18–20).

Limited data are available relating to sinkhole size. Most sinkholes are described as being "small." Of 42 collapses described in South Carolina (Spigner, 1978), the largest was about 20 feet in diameter and the greatest depth was about 10 feet. The largest of 64 collapses near Tampa, Fla.,

FIGURE 22.—Collapse and loss of streamflow in Shelby County, Ala.

was reported to have the same dimensions. Collapses in Alabama range from 3 to 340 feet in diameter and from 1 to 100 feet in depth. An inventory of 243 collapses in areas in Birmingham and Greenwood (Newton and Hyde, 1971; Newton and others, 1973) showed that the average sinkhole in the Birmingham area was 12 feet long, 10 feet wide, and 8 feet deep and the average sinkhole in the Greenwood area was about 20 feet long, 13 feet wide, and 7 feet deep. In Shelby County, Ala. (figs. 1, 28), six collapses had diameters approaching or exceeding 100 feet. Generally, collapses with diameters ranging from 25 to 50 feet were common. Some observed near Sylacauga, Ala., have surface dimensions of 30 to 100 feet. In Hershey Valley, Pa., 100 new sinkholes were reported to be 1 to 20

FIGURE 23.—Collapses in open area in Shelby County, Ala. (white areas are repaired collapses). (Photograph by T.V. Stone.)

feet in diameter and 2 to 10 feet deep (Foose, 1969). Although data are limited, larger collapses have occurred in Pennsylvania.

## CONSTRUCTION

The term "construction" applies not only to the erection of a structure but to any modification of the land surface and the diversion and impoundment of surface water. Diversion of drainage includes any activity that results in changes in the downward percolation or movement of recharge to the water table. These activities include removal of timber and drilling, coring, and augering where pumpage is not involved.

Construction practices often "set the stage" for sinkhole occurrence. In the interior terrane, grading removes the upper tough or cohesive weathered residual soils and exposes the underlying less cohesive clay. Loading on this horizon can cause collapses during or after construction. This results from placing additional weight on thinned roofs of existing cavities in residual clay or on roofs of shallow bedrock openings. The occasional collapse beneath heavy equipment during construction is attributable to this cause (site 21 in table 1). Differential compaction caused by the weight of a structure on unconsolidated deposits overlying the irregular surface of the top of bedrock results in subsidence and foundation problems. Rainfall and saturation of roofs of cavities in residual clay after grading can also result in roof failure. Sinkholes that result from grading and loading in the coastal terrane (fig. 14*A*) are probably rare in comparison to the interior terrane. Existing near-surface cavities would not be present in the noncohesive sand in the shallow aquifer.

Shocks or vibrations resulting from blasting or other causes can also contribute to the failure of cavity roofs in bedrock and unconsolidated deposits. Some collapses identified in Missouri have been attributed to these causes (Williams and Vineyard, 1976). Similarly, shock waves or vibrations from cable tool drilling may have contributed to sinkhole development in Florida (C.H. Tibbals, U.S. Geological Survey, oral commun., 1983). Tibbals reported that multiple sinkholes occurred after installation of surface casing to bedrock when wells were being deepened. This type of activity has resulted in a temporary ban on drilling in Longwood, Fla. (Sentinel Star Metro Newspaper, July 27, 1973). Sinkholes in the same area have also been attributed to well construction where casing was not seated in bedrock (Jammal and Associates, 1982, p. 10–4).

### DIVERSION OF DRAINAGE

Sinkholes caused by diversion of drainage are those resulting from any concentration of drainage relating to man's activities that exceeds, at a site, the concentration occurring in the natural state. Included as sources of drainage concentration are sewers, storm drains, water lines, and similar facilities. Collapses due to leakage from these sources are common. Concentration of water increases the quantity of recharge transmitted through residuum to underlying openings and also causes saturation and weakening of roofs of cavities in unconsolidated deposits. The creation or enlargement of cavities resulting from the movement has been described by Newton (1976a) as being the same as the piping process. Moore (1980) identified piping as being responsible for most collapse failures along highways in Tennessee.

Sinkholes that result from diversions of drainage are most common in areas where the water table is located below the top of bedrock because the erosive energy of water is dissipated when the water table is located above bedrock (fig. 20*A*). In some areas, the water table is below the top of bedrock during dry periods and above it during wet periods. In these areas, most subsurface erosion or piping due to the diversion of drainage would occur during the dry season and at the beginning of the wet season.

A diversion of drainage, resulting piping, and development of cavities and a tunnel in sand near Centreville, Ala. (fig. 24), have been described by Newton (1976b). The sand, crossbedded and containing some ferruginous cemented layers, overlies carbonate bedrock. The grading of a timber trail resulted in the diversion and discharge of water into a surface opening connected with an opening in the underlying bedrock (fig. 24*A*). The water moved downward about 25 feet and laterally about 50 feet, and discharged down through an opening in sandy clay to a cavity in bedrock. A cavity developed on top of the sandy clay (fig. 24*B*) and, with continued subsurface erosion, the route along which the water moved enlarged back toward the surface, forming a tunnel (fig. 24*C*). A second vertical cavity formed as the erosion approached the surface, and the collapse of its roof enlarged the opening into which water discharged (fig. 24*D*).

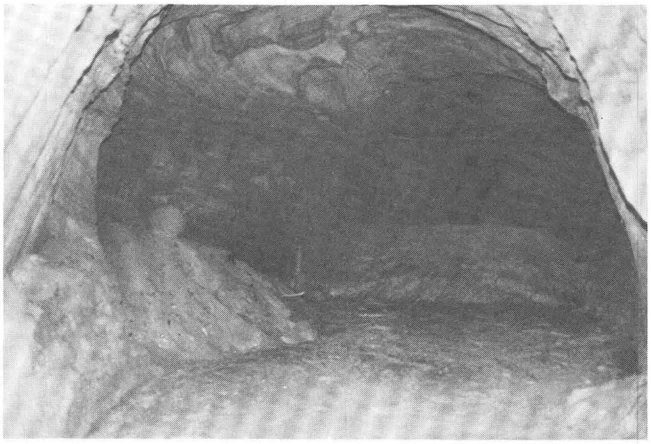
Sinkholes caused by leakage from pipes or similar structures result from the piping process, saturation, and loading. Saturation causes loss of cohesion of the residual clays and also causes loading because of the additional weight of the water. The result is the downward migration of the clay into an opening and the formation of a sinkhole. Examples of leakage resulting in subsidence or the beginning of collapses are summarized at sites 26 and 28 in table 1.

Drilling, augering, and coring can result in collapses where surface water gains access to uncased or unsealed drill holes. The piping process is generally responsible. An example is a collapse that occurred beneath a bridge over Piscola Creek near Barwick in Thomas County, Ga., in 1975 (site 42 in table 1). An additional example where water gained access to a drill hole is given at site 22 in table 1.

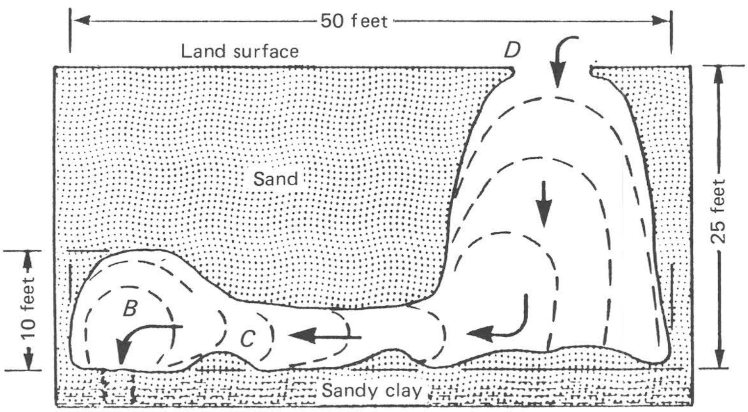
Sinkholes can also form in any terrane where drilling penetrates, successively, a perched sand aquifer, an impermeable or leaky confining bed such as the residual clay in the coastal terrane, and openings in bedrock. Where the water level or the potentiometric surface in the bedrock aquifer is lower than that in the perched aquifer, the downward drainage and transport of sand through the drill hole could result in a collapse or subsidence at the surface. Although unsubstantiated, this could account for some unexplained collapses beneath drill rigs.

### IMPOUNDMENT OF WATER

Collapses caused by impounding water occur, in part, in the same manner as those due to diversion of drainage. The impounding of water causes saturation and loss of cohesiveness of unconsolidated deposits overlying openings in bedrock. This, accompanied by loading due to the weight of impounded water, can result in the collapse of unconsolidated deposits into the bedrock opening and a draining of the impoundment (Aley and others, 1972, p. 18). If the impoundment is located



*B.* Cavity resulting from subsurface erosion

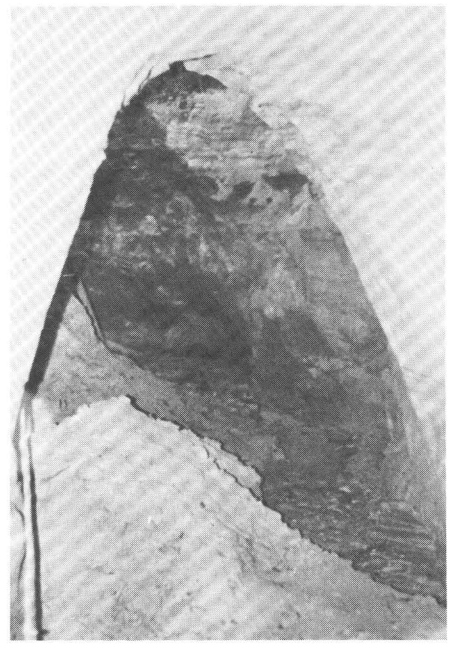



*A.* Growth and collapse of cavity

EXPLANATION:

BOUNDARY DESIGNATING CAVITY GROWTH

DIRECTION OF MOVEMENT OF WATER



*C.* Tunnel resulting from subsurface erosion

*D.* Collapse where water enters opening at surface

FIGURE 24.—Growth and collapse of cavity due to piping near Centreville, Ala.

FIGURE 25.—Collapse beneath sewage lagoon in Bibb County, Ala., in 1972.

where the water table is naturally below the top of bedrock and openings at the surface are connected with those in bedrock, a collapse can result from the piping process. Collapses due to saturation and piping causing the draining of sewage treatment ponds in Alabama have been described by Warren (1974). One of these is shown in figure 25.

The development of sinkholes by piping can also occur when water is impounded on unconsolidated deposits where the water table was originally above the top of bedrock. On the floor of the impoundment, water moving through openings in the deposits into openings in underlying carbonate rocks can form and collapse cavities in the deposits. This occurs where there is considerable pressure exerted by the impounded water and where openings in the underlying carbonate rocks have a discharge point outside of the impoundment at a lower elevation. The increase in water velocity through openings in unconsolidated deposits into openings in bedrock, caused by the pressure, would probably have sufficient erosive capacity to create and collapse cavities in the deposits. This action is probably responsible for the formation of some sinkholes in an impoundment on the Coosa River in Alabama (Newton, 1976a) (site 34 in table 1). Of the numerous sinkholes occurring in this impoundment, many undoubtedly resulted from saturation of unconsolidated deposits, loading, and erosion and turbulence caused by increased water velocity against clay-filled openings in bedrock. Additional examples of sinkhole activity associated with impoundments are given for sites 14, 20, 31, 37, 41, and 45 in table 1.

Sinkholes resulting from the impoundment of water in the coastal terrane would probably be rare and would probably result from loading. An increase in velocity resulting from raising the water level, thereby increasing head differential between the water table and the potentiometric surface, might cause a collapse where a breach in the confining bed (location 3 in fig. 14*A*) is present beneath the impoundment.

#### OCCURRENCE AND SIZE

Sinkholes that result from diversions of drainage have occurred in most States in which active subsidence has been reported. Numerous sites have been inventoried in Alabama and Georgia. Sinkholes associated with highway construction in Missouri are due to water-related changes (Williams and Vineyard, 1976). Sinkholes attributable to diversions of drainage along highways in Tennessee have been described and illustrated by Moore (1980). Similarly, sinkholes forming beneath drains in Pennsylvania (site 6 in table 1) and Kentucky are attributed to this cause. About 20 sinkholes resulting from construction and concentration of drainage at one site in Pennsylvania have been described by Knight (1970).

Collapses due to concentrations of water caused by leakage from pipes and sewers have occurred at several sites in Alabama. Sowers (1956) described sites of occurrence in Tennessee. Numerous collapses in Allentown, Pa. (site 3 in table 1), were commonly associated with leaks from pipes, sewers, and similar structures.

Sinkholes that have resulted from the impounding of water have occurred in numerous States in which active subsidence has been reported. Impoundments affected extend from Florida to Minnesota (site 1 in table 1). Some of the large impoundments are in Alabama, Arkansas, Georgia, Kentucky, Missouri, and North Carolina. Case histories for several impoundments drained by collapses in Missouri have been described by Aley and others (1972).

Most collapses classified here as being due to construction are relatively small. Most in Alabama are less than 15 feet in diameter; the largest surface area involved was about 60 feet in diameter and the greatest depth about 25 feet. The largest reported in Missouri was about 75 feet long, 35 feet wide, and 25 to 30 feet deep (Aley and others, 1972). Data for collapses caused by construction are not available for other areas; however, most are probably small, and the largest are probably similar in size to the largest described above.

## ASSESSMENT OF PROBLEM

Recognition of potential sinkhole problems can result in avoiding or minimizing damage and hazards involved in sinkhole development. Because most sinkhole activity in many areas is induced, identification of the cause can provide alternatives that will stop or minimize further development. Assessment of a problem or potential problem at a site requires an understanding of the different types of sinkholes and initiating mechanisms described in this report. It also requires recognition of features associated with sinkhole development, site evaluation, and an awareness of predictive capabilities to define available alternatives.

### RECOGNITION

The physical features and range in size of collapses forming natural and induced sinkholes are essentially the same. Natural collapses, except in the more active carbonate terranes, tend to be relatively rare and widely spaced singular occurrences that are associated with older sinkholes. Many induced sinkholes, especially those resulting from water-level declines, are associated with other similar collapses and with nearby wells, dewatering quarries, or subsurface mines.

Many induced sinkholes develop with little or no advance warning; others are preceded by recognizable features. Many of these features indicate development of some natural sinkholes. Unfortunately, some features, like the fracturing of clay soils that results from drying, can also be attributed to other common causes. Recognition of several features is sometimes necessary for positive identification of sinkhole development. These features, most described by Newton (1976a), are as follows:

1. Circular and linear cracks or fractures in soil, asphalt (fig. 26), paving, floors, walls, and foundations resulting from subsidence. These features are often accompanied in buildings by jammed doors and windows. Loud, sharp cracking noises in or under a structure often accompany foundation damage.
2. Formation of depressions in soil or pavement that commonly result in the ponding of water (fig. 27).
3. Slumping, sagging, tilting, or warping of highways, rails, fences, curbings, pipes, poles,

FIGURE 26.—Circular fracture in asphalt.

sign boards, and other vertical or horizontal structures, including the downward movement of small-diameter vertical structures such as poles or posts (fig. 28).

4. Holes that form in the ground in a relatively short period of time. Enlargement beneath the land surface is sometimes observable.
5. Discharge of drainage into small holes or fractures in the ground that do not fill and overflow. Scouring or erosion around openings (fig. 19) sometimes occurs in drains and flood plains.
6. Sudden muddying of water from a well that has been producing clear water. Occurrence is often associated with precipitation.
7. Sudden draining of a well or a large decline of water level where there is no history of large declines.
8. Water spouts erupting from openings in soil during rainstorms in basins adjacent to highland areas. This occurs when underlying bedrock openings are sealed by the downward migration of residual clay. Subsurface recharge from a highland area temporarily discharges at the surface due to blockage of the cavity system.
9. Anomalous variations in vegetative vigor due to lack or excess of water.
10. Stream discharging into openings in the ground. Where streamflow exceeds water loss into the ground, small whirlpools (fig. 21) accompanied by sucking or draining noises are sometimes present.
11. Sudden draining of a surface water impoundment or inability of a new impoundment to hold water.

FIGURE 27.—Ponding of water in depression.

12. Depressions in a wooded area where collapses have occurred but where the root zone maintains soil and leaf cover. The ground moves when stepped on, and it feels as if one is walking on a net or sponge.
13. Sound of running water in the subsurface being emitted through small openings at the land surface.
14. Sporadic muddying or discoloration of discharge below a dam when the water in an impoundment is clear.

## SITE EVALUATION

Most site evaluations are initiated by developers to assess an area for a particular land use. Others are made by land users after the occurrence of sinkholes to identify causes, to evaluate the potential for additional occurrence, or to assess damage and the need for repairs. Additional evaluations are made to obtain information for litigation or to identify areas prone to sinkhole development for insurance purposes.

Approaches, procedures, and methods used to evaluate sites vary greatly because of (1) the innumerable differences in geologic and hydrologic conditions in the many carbonate terranes, (2) variations in the types and magnitudes of problems prompting assessments, (3) variations in the land uses planned, and (4) funding and time limitations. No specific approach is recommended here because these factors often dictate what, when, and how much work is done.

Site evaluations, while they vary in detail and method, basically require the same approach. An orderly examination of readily available information can reduce greatly the amount of field observation or work required. The primary sources are (1) geologic maps and reports, (2) topographic maps, (3) aerial photographs, and (4) published and unpublished water records. Information available from the first three sources, acquired from a series of investigations in Alabama (Newton, 1976a, p. 52–67), is given in table 2 (at end of report).

A geologic map showing the distribution of carbonate and noncarbonate rock units aids in deter-

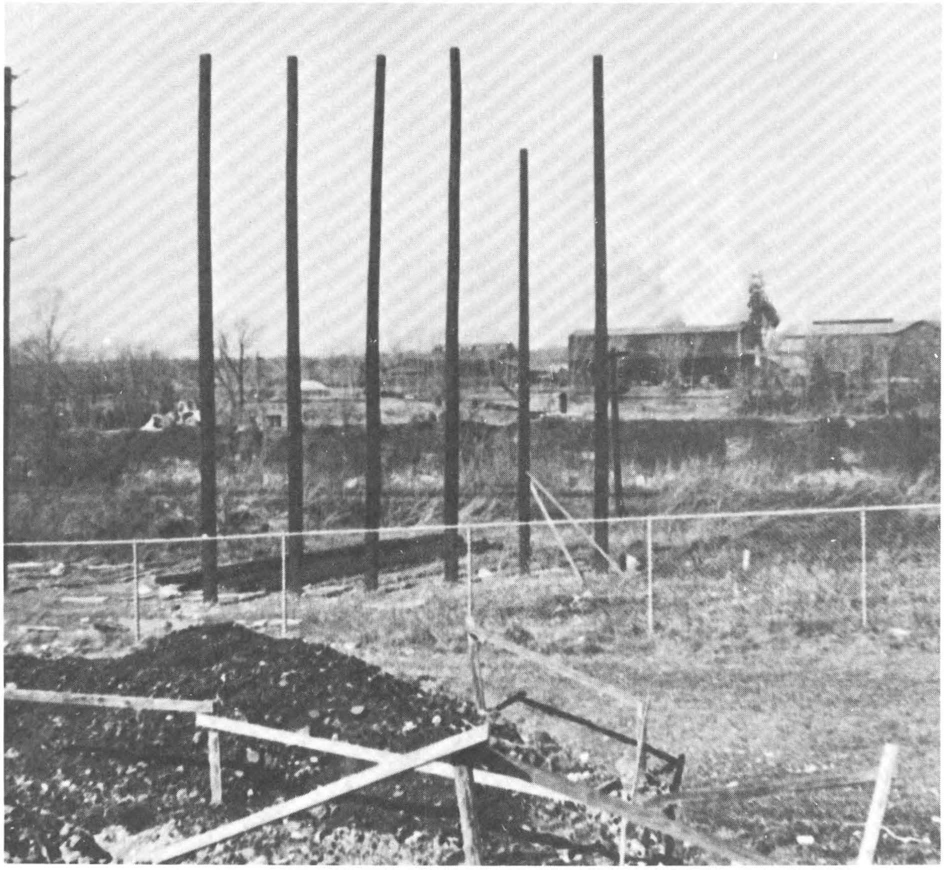


FIGURE 28.—Downward movement of signpost.

mining whether all or part of the area being evaluated requires examination. It may also show the location of geologic structures such as faults and folds. Geologic reports may provide additional information such as the orientation of fracture systems, descriptions of overburden, and well logs.

Information on topographic maps complements that on geologic maps. By superimposing sinkholes shown on topographic maps on the geologic map showing the distribution of carbonate rock units, a map showing areas in which sinkholes have occurred and can occur can be constructed. The concentration and alignment of sinkholes may also indicate orientation of bedding planes, location of faults or fractures, and areas that are least stable. Other valuable information on topographic maps includes locations of industries, mines, and quarries from which information can be acquired during field inspection.

Aerial photography aids in locating depressions, small natural sinkholes, and recent natural and induced collapses not shown on topographic maps. Their identification, whether from photographs or field inspection, is a necessity. Recent photography also updates or identifies land use changes occurring since publication of topographic maps.

Water records can provide a basis for determining why active sinkhole development has occurred or is occurring, and its significance. Records for wells in the area may be available from Federal and State Geological Surveys. These agencies will also be aware of other potential sources of information.

The next and often final stage of site evaluation is field observation, during which the findings from the evaluation of available information are verified. The site is examined for features associated with sinkhole development; existing sinkholes and depressions are examined for recent movement; pertinent water withdrawal and water level data are acquired; and a history of active sinkhole development in the area, if any, is obtained. Historical sinkhole data are obtained from interviews with landowners, county and municipal waterworks, street, and sanitation department officials, county and State highway engineers, agents with the U.S. Soil Conservation Service, drillers, and others. The results are generally sufficient to complete evaluations for many land uses. The investigator, when recommending a site for a particular use, should always consider practices that minimize the initiation of sinkholes. These include avoiding or minimizing alterations of the land surface and natural drainage.

Site development involving active sinkholes (fig. 29), heavy construction, or proposed land uses possibly associated with the triggering of induced sinkhole development will require additional information. Information includes water-level measurements and aquifer characteristics, thickness of the overburden, foundation adequacy, and the presence or absence of openings in bedrock and overburden obtained by drilling and pumping, augering, and coring. Sealing of test holes and wells drilled during data collection might prevent piping that could result in induced sinkholes (sites 22 and 42 in table 1).

In areas where drilling is not feasible, information is sometimes obtained with subsurface geophysical techniques such as gravity, seismic, electrical resistivity, and ground-penetration radar surveys. These surveys yield information relating to the overburden-bedrock interface, the location of caverns or large subsurface openings, and other anomalies that may be significant. Airborne remote sensing, especially multispectral photography, can also be used to identify features associated with active sinkhole development and other beneficial information (table 2).

Evaluation of sites during and following data collection can determine the feasibility of that site for specific land uses. Some proposed uses may be feasible and others may present problems that, with engineering, are acceptable. Some sites may be unsuitable for their intended use. In areas that have been damaged or are being threatened by sinkholes (figs. 23, 29) or where the intended land use may initiate sinkhole occurrence, the site evaluation may require some degree of prediction to provide alternatives that will help avoid, stop, or minimize sinkhole development.

## PREDICTION

Sinkholes resulting from man's water activities, in contrast to those resulting from natural processes, are predictable in some instances—but predictable only in the sense that they will occur within a particular area, not when, to what extent, and so forth. This predictive capability is also restricted to certain terranes. It would not, for instance, relate to possible sinkhole occurrence in most terranes altered by glaciation. Similarly, prediction in the coastal terrane is very limited because of large variations in the thickness of the confining bed and because of a lack of information relating to conditions and the amount of stress that initiates sinkhole development.

Predictive capabilities are most useful for the interior terrane, with many being applicable to other terranes. The position of the water table in relation to the top of bedrock, for instance, determines whether a triggering mechanism will be activated by a water-level decline or whether piping can result from a diversion of drainage.

Determining the position of the water table in relation to the top of bedrock aids in predicting whether sinkholes will occur. The most predictable sinkhole development is that resulting from water-level declines due to dewatering by subsurface mines and quarries. This occurs where the water level, previously located above the top of bedrock during all or most of the year, is maintained below the top of bedrock by pumping. All mechanisms affecting overlying unconsolidated deposits that initiate sinkhole development are activated by this decline. Conversely, unconsolidated deposits are not affected where the water level fluctuates below the top of bedrock prior to dewatering.

Sinkhole development following dewatering by subsurface mining occurs more rapidly and is more widespread than that resulting from quarrying. Because of the depth of dewatering, cones of depression are relatively large (sites 4, 7, and 27 in table 1). Pit quarrying begins at the top of bedrock, with progressive deepening occurring over a period of years. Sinkhole development begins after water-bearing openings are penetrated. When this occurs at shallow depths, sinkhole development is generally confined to the immediate vicinity. Sinkholes occur farther away as the cone of depression enlarges owing to the deepening of the quarry and the accompanying dewatering (Newton, 1976a, p. 23–27).

Many sinkholes in a dewatered area will occur where concentrations of surface water are greatest, such as streambeds, natural drains, or poorly drained areas. Large numbers occur where natural drainage has been altered or where recharge has been increased as a result of activities such as timber removal and grading. Most occur during or immediately after periods of rainfall, especially deluges, when hydrologic stresses to overburden such as piping, saturation, and loading are greatest.

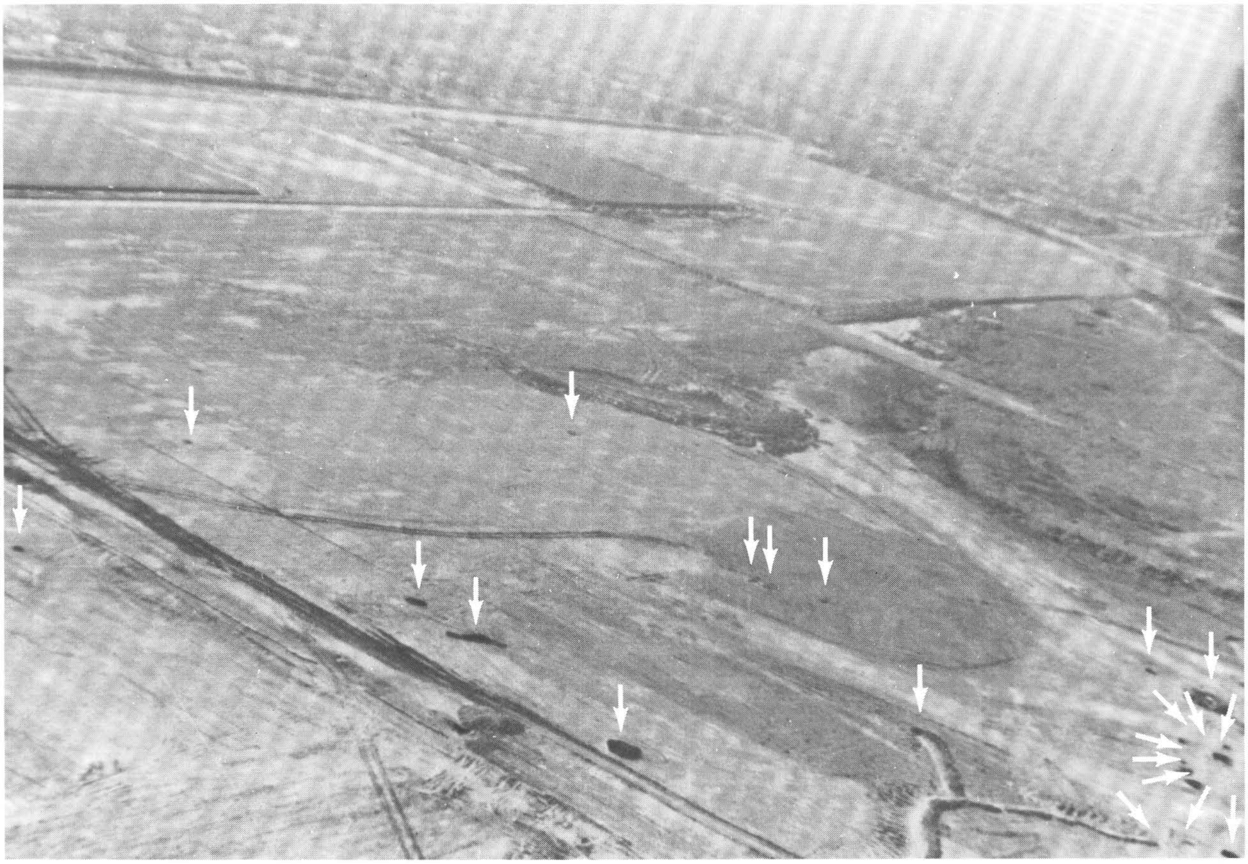


FIGURE 29.—Construction of warehouse and office complex in area of active sinkhole development in Birmingham, Ala., in 1966. (Photograph by James Walters.)

Sinkhole development from dewatering by wells, like that from dewatering by mining, results from prolonged continuous pumping. Wells involved generally yield large supplies that periodically become muddy. This water may be used for purposes other than human consumption such as fire protection, cooling, and washing (Newton, 1976a, p. 74, 75) (sites 24 and 33 in table 1). Prolonged pumpage from new wells to "clear up" turbidity problems (sites 15, 30, 35, and 40 in table 1) also belongs in this category.

Prediction of sinkholes resulting from pumpage by wells is greatly enhanced by site evaluations and case histories that pinpoint other activities and conditions that contribute to sinkhole development. Development of a high-capacity well in or adjacent to an area of large withdrawals where sinkholes have occurred or are occurring (site 38 in table 1) would be a risk. Unusually close well spacing to obtain more water from a limited area (site 8 in table 1) would be a greater risk. Similarly, a high-capacity well located in the immediate vicinity of foundation auger holes (site 33 in table 1) would have to be considered a potential problem owing to induced recharge and piping. Locations of wells near manmade impoundments (sites 39 and 47 in table 1) also pose some risk where cones of depression extend to or beneath impoundments.

The most predictable collapses due to well construction or development occur at sites where the water table is near land surface, saturated overburden is thin, and mud-filled openings are at or near the top of bedrock. During well development, air pressure or pumping is used to increase yields by removing natural accumulations of mud and sediment in openings in bedrock. The "mining" of overburden through openings connected with the top of bedrock is often masked by this procedure. The likelihood of collapses increases with the amount of sediment removed. Although most collapses result from shallow openings, the removal of large quantities of mud from openings as deep as 300 feet have resulted in collapses (S. Graves, Graves Drilling Co., Sylacauga, Ala., oral commun., 1983).

Prediction of sinkhole development due to construction can be made in some instances. Sinkholes associated with major impoundments are predictable to some degree because all mechanisms associated with sinkhole development are triggered by this type of construction. Fortunately, detailed site evaluations and engineering practices minimize hazards to dams and allow time for corrective and safety measures where problems arise (sites 14, 31, 34, and 37 in table 1).

Areas most prone to sinkhole development are those where the water table is located below the top of bedrock and overlying unconsolidated deposits are thin. Further thinning of overburden by grading would enhance piping. Areas with thick overburden would have lower risk, especially where the water table is above bedrock. This position of the water table would eliminate piping as a mechanism in most instances. Some sinkhole risk would accompany significant diversions of drainage such as irrigation or the construction of sizable ponds or impoundments. Alteration of the land surface to construct a pond in a natural sinkhole (site 23 in table 1), for instance, would be considered a risk. In contrast, grading to construct impoundments in areas without natural sinkholes or a history of their development might be considered acceptable, but may result in multiple collapses (site 21 in table 1). In a few instances, prediction is obvious. One example is the construction of a holding pond on or adjacent to numerous auger holes and a large-capacity well in an area with a history of sinkhole development (site 33 in table 1). In most instances, prediction is limited to weighing the magnitude and type of land-use change to be made against geologic and hydrologic conditions at the site involved.

### AVOIDING OR MINIMIZING PROBLEMS

Alternative courses of action that avoid or minimize hazards associated with sinkhole development are available, in some instances, to those making site evaluations. Most alternatives relate to induced sinkhole development and their occurrence in the interior and similar terranes. To benefit from available alternatives, awareness of sinkhole or potential sinkhole activity that can be associated with wells, quarries, and mines is necessary. Alteration of the land surface in such an area can increase the severity of sinkhole development. Identifying these areas during site evaluation allows several alternatives: select another site and avoid the problem, use engineering practices to protect structures and minimize hazards, or accept risks and potential consequences. Engineering practices used to minimize problems include placing foundations on bedrock, grouting openings in bedrock, paving parking lots, and diverting surface runoff through impermeable drains. Impermeable drains, bridging, removal of overburden and replacement with riprap, and installation of reinforcing steel in pavement are used to minimize problems in highway construction.

Courses of action available decrease greatly when sinkhole problems associated with water withdrawals are discovered during or after construction. After initial stages of construction, costs of protective engineering practices could restrict alternatives to the management of surface runoff or abandonment.

The most common alternative to minimize sinkhole problems that may result from groundwater withdrawals from wells is to control water-level declines by regulating pumping rates and well spacing. When these alternatives are used, water withdrawals by adjacent land users should always be considered.

Limited alternatives are available where the new land use is the mining or quarrying of carbonate rocks or valuable minerals in these rocks or other rocks interconnected with them. Dewatering of carbonate rock quarries and mines is commonly accompanied by some sinkhole activity. Minimizing potential sinkhole impact is accomplished in most instances by locating sites in undeveloped areas and, where feasible, minimizing depth of dewatering, sealing openings dewatered, and grouting. Because the mining commonly continues for decades, many problems arise where conflicting land uses are developed in and adjacent to impacted areas (fig. 29). Warren (1976, p. 41) stated that the logical alternative to eliminate most hazards would be zoning that would require the coordination of mining companies, local planning agencies, and developers. Land use in and adjacent to impacted areas would be restricted to those less prone to hazards such as forests and pasture. Housing and other high-density development would be avoided.

Alternative courses of action involving induced sinkholes due to construction are generally limited because of the lack of predictability. Where site evaluation indicates a degree of risk for the intended land use, there is the choice of selecting another site with less risk or using engineering practices that will eliminate or minimize the problem. Most of these alternatives or precautions involve foundation design, surface-runoff management, and impoundment-engineering practices such as compaction and lining. Where a degree of risk cannot be assigned, the land user's most protective measure is the minimizing of landform and drainage alterations.

## SUMMARY AND CONCLUSIONS

1. Thousands of sinkholes have formed in the Eastern United States since 1950. Most of these were induced by man's activities changing the hydrologic environment. Collapses forming natural sinkholes are rare in many terranes.
2. Sinkhole development was identified in 19 of 31 States in the study area. More than 850 sites were inventoried; it is estimated that more than 6,500 sinkholes or related features have occurred at these sites. Extensive inventories are available only for Alabama and Missouri. The Alabama inventory, the most comprehensive, was used as a guide in this study.
3. Total cost of damage and associated protective measures is unknown. Costs reported during the limited inventory amounted to about $170 million, expended almost entirely after 1970. Of this, about $140 million was expended for protective measures at five dams or impoundments in Alabama, Georgia, Kentucky, and North Carolina, and to repair or protect highways in Alabama and Tennessee.
4. Available information shows that the impact of sinkholes has been most significant in Alabama, Florida, Georgia, Missouri, Pennsylvania, and Tennessee. States with the least impact are located in areas formerly covered by glaciers.
5. Loss of life resulting from sinkholes is rare. Fatalities resulting from or associated with sinkholes have been reported in Florida, Missouri, and Pennsylvania. Injuries have been reported in Alabama, Florida, and South Carolina.
6. The sudden development of sinkholes results from the collapse of the roof of a cavity or cavern in rock, or from the downward migration of unconsolidated deposits into solutionally enlarged openings in the top of bedrock. Cavities in unconsolidated deposits form when the deposits migrate downward into bedrock openings. The occurrence of roof collapse in bedrock, compared with that of roofs of cavities in unconsolidated deposits, is rare.
7. Mechanisms that initiate most natural and induced sinkholes are the same.
8. Most induced sinkholes related to water activities, if these activities had not stressed the system, either (1) would not have occurred, (2) would not have occurred during a man's lifetime, or (3) would, under natural conditions, have occurred as subsidence rather than collapse.
9. Induced sinkholes are separated into those resulting from a decline in water level and those resulting from construction. Construction includes erection of structures, grading, blasting, and any other activities that result in the alteration of the land surface and the diversion and impoundment of drainage. Diversion of drainage includes any activity that changes rates of recharge, such as the removal of timber and drilling, coring, and augering where pumpage is not involved. Diversion and impoundment of drainage account for most sinkholes resulting from construction.
10. Mechanisms that trigger induced sinkhole development resulting from a decline in water level are (1) loss of buoyant support, (2) increase in velocity of ground-water movement, (3) increase in magnitude of water-level fluctuations, and (4) movement of water from the land surface to openings in bedrock where recharge had previously been largely rejected.
11. Mechanisms that trigger induced sinkhole development resulting from construction include (1) loading, (2) saturation, (3) piping, and (4) shocks or vibrations. Sinkholes resulting from shocks and vibrations are rare.
12. Assessment of existing or potential sinkhole problems requires recognition of features associated with sinkhole development, site evaluation, and an understanding of triggering mechanisms.
13. Most site evaluations are made to assess an area for a particular land use, to identify sinkhole development, to evaluate potential for additional sinkhole occurrence, or to

assess damage and the need for repairs. Available information includes geologic maps and reports, topographic maps, aerial photographs, and water records. Field observation is made to acquire other data and to determine what additional information is needed. Additional information is commonly acquired by drilling and pumping, augering, and coring. Depending on need, information may also be obtained by airborne remote sensing, subsurface geophysical, and other techniques.

14. Where and when natural sinkholes will occur is not predictable. Induced sinkholes resulting from water activities are predictable in some instances, but only in the sense that they will occur within a particular area. This predictability is restricted to certain terranes and is dependent on the degree and type of impact to be exerted. Prediction is enhanced by site evaluation and case histories. The most predictable induced development is that resulting from dewatering by wells, quarries, and mines.
15. Alternatives that allow avoiding or minimizing sinkhole hazards are most numerous when a problem or potential problem is recognized during site evaluation. The number of available alternatives declines after site development begins.
16. Where sinkhole development is predictable, zoning of land use can minimize hazards.

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TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]

[Site numbers correspond to numbers in fig. 4]

| Site number | Source(s) of information | Number of collapses | General dimensions in feet 2/ | | | Descriptions |
|---|---|---|---|---|---|---|
| | | | Width | Length | Depth | |
| 1 | E. Scherbring, municipal employee, oral communication, 1981. | 1 | 10 | 10 | 20 | Sewage treatment holding pond at Altura, Minnesota, was put into full operation about 1975. Collapse in 1979-80 resulted in the draining of effluent from a 10 acre pond. Problem was being evaluated by State and Federal agencies in 1981. |
| 2 | Allentown Call Newspaper, January 17, 1981; unpublished data in files of the Pennsylvania Geological Survey | 1 | -- | -- | -- | Development of sinkhole on January 15, 1981, at West Catasauqua, Pennsylvania, occurred in street beneath gas and water lines. A large explosion resulted in one fatality and heavily damaged three homes. Previous subsidence at or near the site reportedly damaged sewer, water and gas lines on April 28, 1979. Reported cost of street repair at site of 1981 sinkhole exceeded $48,000. |
| 3 | The Morning Call Newspaper, Allentown, Pennsylvania, November 16, 1951; January 10, 1952; and January 17, 1952. Unpublished data in files of U.S. Geological Survey | 19+ | -- | -- | -- | Numerous sinkholes or sites of subsidence developed in Allentown, Pennsylvania during the period 1949-52. Many occurring in streets or beneath structures were associated with the downward leakage of water from sewers, water mains, or cesspools. Sinkhole development was also associated with a large gas explosion and rupture of a major water main in 1949. Reported expenditures resulting from their occurrence exceeded $135,000. To alleviate the problem, more than 5,000 cesspool-users were given 90 days on March 21, 1952 to connect their waste lines to city sanitary sewers. The estimated cost per user was $100 to $500 or more. |
| 4 | Miller (1941); Wood and others (1972); Pennsylvania Department of Transportation (1971); Longwill, Stanley M., U.S. Geological Survey, written communication, 1961; unpublished data in files of U.S. Geological Survey. | 153+ | -- | -- | -- | Active sinkhole development near Friedensville, Pennsylvania in area of large ground-water withdrawals. Water level in lowland areas prior to withdrawals was generally at a depth of less than 30 feet. Depth to top of bedrock exceeds 30 feet in numerous areas. Dewatering for mining was begun 1953. Rates of withdrawal between 1953 and 1977 varied between 10 and 30 million gallons per day. Cone of depression in 1967 exceeded 4 square miles in size. Records indicate that 128 sinkholes formed around dewatering site during period 1953-57. Twenty-five new sinkholes occurred from October 1970 to January 1971. Number occurring during the intervening 13 years and since 1971 not inventoried. |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5 | Goughnour and others, (1979); Wilshusen (1979). | 5 | 5-40 | 15-40 | 15-30 | Five sinkholes developed in and near U.S. Highway 202 adjacent to an abandoned quarry in Bridgeport, Pennsylvania, between January and May 1970. A temporary roadway constructed around the problem area was in use for more than 4 years. Repairs to 1100 feet of roadway was accomplished at a reported cost of 2 million dollars. |
| 6 | Shuster (1973); observation, photography. | 2 | 10 | 10 | -- | Two sinkholes formed adjacent to Highway 114 near Mechanicsburg, Pennsylvania, in 1973. Sinkhole in ditch adjacent to highway was attributed to diversion of runoff. Subsidence of this sinkhole required additional leveling in 1981. |
| 7 | Foose (1953). | 100+ | 1-20 | 1-20 | 2-10 | Large increases in mine pumpage near Hershey, Pennsylvania, in 1949 lowered ground-water levels over an area of 10 square miles. About 100 new sinkholes formed entirely within the area where there was a drastic lowering of the water table. Recovery of water levels to nearly normal conditions in 1950 was accompanied by a cessation of sinkhole development. |
| 8 | Unpublished data in files of the U.S. Geological Survey. | 7 | 6-10 | 6-10 | 3-60 | Installation of well at Westminster, Maryland, in 1940 was associated with a collapse in the floor of a nearby building. In 1948, the well was replaced by two new wells located 40 feet apart. Both wells were pumped simultaneously, one at 500 to 550 gallons per minute and one at 450 to 500 gallons per minute, during a 72-hour test. Cracks reportedly formed in two nearby buildings at this time. On May 7, 1948, a sinkhole formed near the wells. Four additional sinkholes formed in the same vicinity in 1971. |
| 9 | Carrol County Times Newspaper; December 9, 1980. | 5 | -- | -- | 11 | New well being developed in Westminster, Maryland, in 1980 was abandoned because muddy water could not be cleared up and because of the occurrence of four nearby sinkholes. An additional sinkhole formed in the vicinity several months later. |
| 10 | Court of Appeals of Maryland (1968). | -- | -- | -- | -- | Multiple collapses resulted in damage to 35 acres in Wakefield Valley in Carroll County, Maryland. Reported dewatering to depth of 80 feet. Water table in areas of collapses prior to dewatering was described as being at a depth of 5 feet. Depth to the top of rock underlying soil mantle was reported to vary between 17 and 30 feet. |

1/ Includes sites of active subsidence

2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]—Continued

| Site number | Source(s) of information | Number of collapses | General dimensions in feet[2/] Width | Length | Depth | Descriptions |
|---|---|---|---|---|---|---|
| 11 | Aley and others (1972, p. 12). | 2 | 6 | 6 | 6 | Catastrophic collapse in Republic, Missouri, sewage lagoon on October 29, 1968, resulted in an estimated 4 million gallons of sewage entering ground water system during 24-hour period. On October 31, 1968, an additional collapse occurred. Sewage and dye reappeared in two wells as much as 1.5 miles from the lagoon. |
| 12 | Aley and others (1972, p. 13). | 2 | 17 | 17 | 10-20 | Collapses occurred in sewage lagoon at West Plains, Howell County, Missouri, in 1964 and was repaired. Collapse in larger nearby lagoon cell in 1966 resulted in 136 acre-feet of effluent draining out within 52 hours. |
| 13 | Aley and others (1972, p. 17). | 4 | 10-35 | 10-75 | 6-30 | Group of collapses was induced by construction at Norton Dam south of Winona, Shannon County, Missouri. After impoundment, four collapses occurred in or near impoundment about 1968-69. Dam unsuccessful in producing permanent lake. |
| 14 | U.S. Army Corps of Engineers (1974); M. Simmons, U.S. Army Corps of Engineers, oral communication, 1981, 1983. | 59 | 1-13 | 1-15 | 1-10 | Wolf Creek Dam on Cumberland River in Russell County, Kentucky. After 16 years of operation, wet areas materialized near downstream toe of dam embankment. First sinkhole was discovered in August 1967. Potential problem involving foundation seepage was recognized and detailed assessment was begun. Muddy flows and continuous development of sinkholes followed. Remedial work and continuous surveillance continued until 1972 when it was determined that course of action would not assure complete safety. Concrete diaphragm wall constructed through dam and underlying solution openings in bedrock during 1974-79 eliminated sinkhole activity and potential foundation problems. Reported cost 96 million dollars. |
| 15 | C. R. Burchett, Hydrologist, U.S. Geological Survey, oral communication, 1981. | 1 | 34 | 34 | 18 | U.S. Geological Survey test well 1.5 miles west of Dickson, Tennessee. Residuum about 80 feet thick, opening in limestone at depth of 172 feet, static water level at depth of about 50 feet. Well pumped continuously for two weeks at rate of 200 to 250 gallons per minute to eliminate turbidity (mud) problem. Two weeks after pumping ceased in May 1981, collapse occurred next to well during or following about 2 inches of rain. |

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| 16 | Donald Rima, U.S. Geological Survey, oral communication, 1981. | 1 | 20 | 20 | 2 | U.S. Geological Survey test well near north limit of Franklin, Tennessee. Collapse occurred in small depression where discharge of about 600 gallons per minute from well ponded. |
| 17 | J. Lovell, Murphreesboro, Tennessee, Water Superintendent, oral communication, January 27, 1981. | 9 | 8-80 | 8-80 | 2-10 | Sinkholes in Murphreesboro, Tennessee, resulted from greater than average pumpage from two municipal wells during prolonged drought in 1941. Wells were 10 and 12 years old. Sinkhole activity ceased at end of drought accompanied by decrease in pumpage. Problem was avoided thereafter by regulating pumpage and water-level decline that triggered the previous activity. One large site of subsidence that formed in a street during the activity was leveled with as much as 2 feet of asphalt. Unfortunately, an underlying sewer was apparently broken and is believed to have been a source of pollution to the underlying aquifer. The problem was discovered only after a sinkhole developed at the site of the break about 10 years later. |
| 18 | Kenneth Gentry, Miller Drilling Company, oral communication, 1981; Wiley Harris, Tennessee Valley Authority, written and oral communication, 1981; unpublished data in files of U.S. Geological Survey. | 3 | 20 | 20 | -- | Collapse beneath sewer in Chattanooga, Tennessee, occurring in December 1979 exposed large cavern. One 15 foot section of 8-inch sewer pipe missing. Located about 800 ft from new well being developed at rate of about 2,000 gallons per minute. After repairs, the sinkhole recollapsed two times in response to further well development and pumping test. Well abandoned. Well drilled to furnish Tennessee Valley Authority cooling system in new building. Cost of well, observation wells, well field design and associated engineering estimated to be $400,000 to $500,000. |
| 19 | R. Amos, Amos Construction Company, oral commun., 1981. | 1 | 5-10 | 5-10 | 10 | Pond and 2 miles of pipeline were constructed near Tuscumbia, Alabama in the early 1960's to remove process water from vinyl tile factory after nearby inhabitants objected to its direct discharge into streams. Immediately after first process water entered pond, collapse resulted in draining of the pond. A pump installed to deliver water through the pipeline to a distant stream when water in the pond reached a certain stage, was never used. The collapse, because no one objected to discharging the water into the subsurface, was never repaired. Process water was allowed to enter the collapse for years until the company ceased operation because of bankruptcy. Original construction costs of installation $40,000 to $50,000. |

1/ Includes sites of active subsidence
2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]—Continued

| Site number | Source(s) of information | Number of collapses | General dimensions in feet[2] Width | Length | Depth | Descriptions |
|---|---|---|---|---|---|---|
| 20 | J. Bond, oral communication, 1981; R. Amos, Amos Construction Company, oral communication, 1981. | 4+ | 2-20 | 2-20 | 8 | Two 5-acre cells of a sewage lagoon were constructed near Leighton, Alabama in late 1960's. Collapse draining first impoundment occurred about 1970-71. After repair, repeated collapses draining first cell continued for 2 to 3 years. Repairs were made following each collapse. Pipelines were then diverted to second cell which had not been used previously. Similar collapses resulting in draining occurred in the second cell. System was abandoned about 1976-77. Estimated cost of repairs and loss $115,000. |
| 21 | P. Moser, Geological Survey of Alabama, oral communication, 1982. | 2 | 5-10 | 5-10 | 15 | At old airport west of Courtland, Alabama. Collapse occurred under large pan during excavation of sewage lagoon. Another collapse occurred nearby at a later time. Both resulted from collapse of roofs of cavities in unconsolidated deposits. No evidence of natural subsidence in area. |
| 22 | W. Warren, Geological Survey of Alabama, written communication, 1976; C. R. Bossong, U.S. Geological Survey, oral communication, 1981. | 1 | 15 | 15 | 6 | Drilling of new well begun near Madison, Alabama on February 10, 1976 was discontinued when bedrock at a depth of 50 feet was encountered. Drill rig was left on uncased open hole. Heavy rain on following day, which prevented further drilling, ponded and entered the drill hole. On the morning of February 12, the drill rig was found in a collapse that occurred during the night. |
| 23 | T. Moffit, oral communication, 1981; F. V. Meter, written communication, 1981; Birmingham News, November 24, 1981. | 3 | 8-16 | 8-16 | 4-18 | Fishing lake constructed in natural sinkhole near Triana, Alabama. After grading, three collapses occurred. Collapses were treated and walled off from area to be impounded. Construction was completed, water impounded, and lake was dedicated on November 23, 1981. |
| 24 | Observation; unpublished data in files of U.S. Geological Survey. | 50 | 1-50 | 1-50 | <10 | Wooded swamp area along planned corridor of Interstate Highway 59 near Brighton, Alabama. Area of active subsidence in 1974. Number of sinkholes estimated. Most were small with surface dimensions less than 15 feet, largest was general area of subsidence. Activity confined to circular area with diameter of about 1,000 feet with an industrial well located at the center. The well reportedly was 109 feet deep and was pumped 24 hours per day at 600 to 700 gallons per minute. |

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| 25 | Newton (1976a). | 46 | -- | -- | -- | Repetitive photography used to illustrate migration of collapses away from dewatering operation at Pelham, Alabama. One possible collapse observable during early stage of dewatering in 1950; 11 open collapses observable in 1959; and 34 open collapses observable in 1967. Total distance of migration about 0.4 mile. Distinct hazard to highways, structures, and a railroad. Damage not inventoried. Sinkhole activity ceased with cessation of pumpage and recovery of water level prior to 1967. Industrial and urban complex built on former area of sinkhole activity after 1967. |
| 26 | B. Bailey, oral communication, 1974; R. Kelly, oral communication, 1974; observation. | 1 | 60-70 | 60-70 | 0.5-1 | Significant subsidence at Montevallo, Alabama bounded by radial fractures occurred on November 4 and 6, 1974 resulting in damage to one unit of housing project. Leakage from damaged fireplug discharged into ground beneath sidewalk inside of area of subsidence for a period of about three months prior to collapse. Small root-like openings in soil zone reported when area was graded off during construction of housing unit. |
| 27 | Newton (1976a); Warren, 1976. | 1000 | 1-300 | 1-325 | 1-100 | Estimated number of collapses west of Calera, Alabama include sites of subsidence, fracturing and significant piping. Area dewatered by wells, quarries, and an underground mine. Cone of depression in October 1973 was about 10 square miles in size. Pumpage at that time exceeded 14,000 gallons per minute. Significant sinkhole development began about 1964. Greatest hazards in rural area were collapses beneath highways and major gas pipelines. Part of area still active in 1981. |
| 28 | Earnest Bailey, oral communication, 1974. | 1 | 20 | 20 | <1 | General subsidence beneath home and patio near Calera, Alabama resulted in large fractures in concrete and inside and outside walls. Occurred during extended period of drought but attributed to long term leakage from corroded water line leading to home. Leakage from small openings in pipe entered bottom of covered ditch 25 feet from home, moved downslope through the ditch, and entered the subsurface beneath it. Total failure of pipe occurred in March or April 1981 resulting in the discharge of water at the land surface in the front yard. |
| 29 | S. Graves, Graves Drilling Co., written communication, April 1, 1975. | 1 | 6-8 | 6-8 | 42 | Collapse 45 feet from a new public supply well near Calera, Alabama during initial development and pumping test. |

1/ Includes sites of active subsidence
2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]—Continued

| Site number | Source(s) of information | Number of collapses | General dimensions in feet[2/] Width | Length | Depth | Descriptions |
|---|---|---|---|---|---|---|
| 30 | B.C. Spigner, Geological Survey of Alabama, written and oral communications, 1972 and 1981; observation; photography. | 13+ | 4-10 | 4-20 | 4-8 | In July-August 1972, public supply well at Moody, Alabama, muddied up and failed. This occurred while new well located about 1,200 feet away was being developed. The former had a history of "mud" problems. The latter, drilled in 1971, required pumping for more than a year before mud problem cleared up. Water table and top of pinnacled bedrock near land surface. Collapses and subsidences started about the same time as the failure of the older well. They occurred beneath driveway, drain, culvert, homes, and yards. Two homes vacated. Estimated damage $75,000. |
| 31 | A. B. Martin, city of Birmingham, written and oral communication, 1976 and 1981; observation. | 4 | -- | -- | -- | Lake Purdy in Shelby and Jefferson Counties, Alabama. Concrete dam and lake were constructed in 1909. As part of corrective measures to eliminate leakage in 1916, clay blanket was placed on upstream face of dam. Between 1916 and 1927 failures in blanket resulted from burrowing crawfish. Dam was raised in 1927 and grouting was accomplished to minimize leakage. Two sinkholes in the lake were discovered in 1954. Another was discovered later in the land surface near the dam. In December 1974, leakage became muddy and increased. Two sinkholes formed in the land surface near the north end of the dam in 1976. Grouting program was begun in 1979 to eliminate leakage and associated problems. Program was highly successful. Leakage was reduced from about 4,400 to 70 gallons per minute. Reported cost was $550,000 to $600,000. |
| 32 | Powell and LaMoreaux (1969); J. Palmer, oral communication, 1981. | -- | -- | -- | -- | Multiple sites of subsidence and collapse at Columbiana, Alabama in 1968 damaged several buildings, numerous units in a housing project, a concrete filter plant, endangered an elevated water storage tank, broke water lines, and severed tracks of a railroad. Related occurrence to water levels, pumpage, and muddying of withdrawals. Suggested discontinuing pumping of all wells in area of subsidence. Replacement of municipal well system in 1969 reportedly cost $180,000 to $200,000. Problem ceased with corrective action. |

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| 33 | Observation; W. B. Clow, Clow Corporation, oral communication, 1972; photography; unpublished data in files of U.S. Geological Survey. | 4 | 5-18 | 5-18 | 15+ | Extensive augering at industrial site in Lincoln, Alabama in 1966. Development moved to adjacent site due to potential foundation problems. Development of well at site in 1967 resulted in a collapse next to it. Collapse repaired and holding pond was excavated next to well in area on or adjacent to auger holes. Well supplied about 300 gallons per minute to pond. Water circulated from well to pond and back to well through openings in overburden. Cessation of pumpage would result in draining of pond. Collapses in and around pond and well due to piping occurring in 1972 were repaired and walled off from remainder of pond. Process water used by industry muddied occasionally. |
| 34 | Alabama Power Company, written communication, 1981; J. Weinfordner, oral communication, 1981; the Birmingham News, November 25, 1979; observation. | 150+ | -- | -- | -- | Logan Martin dam used for power generation on Coosa River near New London, Alabama was completed in 1964. "Boils" or leakage appeared downstream as impoundment was being filled. A "chimney" sinkhole appearing in east dike of dam on April 9, 1968 was repaired immediately. Sinkholes forming in impoundment were filled with more than 185,000 tons of sand, gravel, and stone during the period October-November 1968. Initiated grouting and surveillance program in March 1972 to minimize and monitor problem. A "bolster" or second dam was built behind parts of the original dam to eliminate potential problems. Regular computerized sonar surveys locate collapses beneath impoundment. These are filled with stone deposited by barge. Cost of repair and safety measures prior to 1980 reported to be 19 million dollars. |
| 35 | Unpublished data in files of U.S. Geological Survey; observation; photography. | 3 | 12-16 | 12-16 | 2-18 | Test well drilled in Childersburg, Alabama in 1969. Top of bedrock was 33 feet below land surface, static water level was 22 feet below land surface. Continuous pumping for 5 months failed to clear turbidity. Well reconstructed in 1972. Continuous pumping at 280 to 393 gallons per minute from October to November 1972 with maximum drawdown of 137 feet. Sinkholes within 400 feet of well reportedly formed in October 1971 and in October and November 1972. Collapses occurred in street and beneath railroad. |

1/ Includes sites of active subsidence

2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]—Continued

| Site number | Source(s) of information | Number of collapses | General dimensions in feet[2/] Width | Length | Depth | Descriptions |
|---|---|---|---|---|---|---|
| 36 | G. Swindel, U.S. Geological Survey and Alabama Geological Survey, written and oral communication., 1956 and 1981; unpublished data in files of U.S. Geological Survey. | 40 | -- | -- | -- | As many as 40 collapses forming sinkholes in downtown Sylacauga, Alabama occurred during a prolonged drought in 1953-56. The largest was as much as 30 to 40 feet in diameter and 30 to 40 feet in depth. Collapses occurred under streets, water lines, drains, and other structures including a church and football field. Activity ceased with recovery of water table at end of drought. Limited activity occurred briefly in 1981 during similar decline in water table. Some water withdrawals contributed to declines during both periods. |
| 37 | J.H. Bryan, J. McFadden, and J. Baer, U.S. Army Corps of Engineers, Mobile District, oral communications, 1981. | 60+ | 4-10 | 4-10 | 1-5 | The formation of sinkholes occurred during 1967-81 in the vicinity of Walter F. George Lock and Dam on the Chattahoochee River near Fort Gaines, Georgia. Five or more sinkholes generally form each year in downstream areas within 600 feet of the dam. In contrast, one sinkhole generally forms every two years in upstream areas within 600 feet of the dam. The sinkholes result from leakage from the impoundment to downstream areas. Grouting has minimized the problem. The first segment of a concrete sleeve to be constructed through the dam and carbonate rocks to insoluble rocks to eliminate problem is scheduled for 1982. Estimated expenditures on the problem and expenditures on the first segment of the sleeve are estimated to be about 8.6 million dollars. |
| 38 | R. Clarke, President, and J. Taylor, Rossville Development Company, Incorporated, oral communication, 1981; R. Cressler, U.S. Geological Survey; unpublished data in files of U.S. Geological Survey. | 18+ | 2-35 | 2-100 | 3-79 | Sinkholes formed in Rossville, Georgia, and adjacent area in Tennessee during 1978-80. Large ground-water withdrawals associated with problem. Numerous small sinkholes not included in inventory. Fluctuations in water level during early part of period, based on those recorded in U.S. Geological Survey test well, generally ranged from 10 to 70 feet per day. During latter part of period, reduced pumpage resulted in fluctuations generally ranging from 25 to 45 feet per day. Largest collapse involved four segments of a warehouse in Tennessee. Damage was estimated to be 1.4 million dollars. Daily "surges" or fluctuations in water level observed in collapse reported to range between 15 and 30 feet. |

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| 39 | Vernon Rogers, U.S. Soil Conservation Service, oral communication, 1981. | 4 | -- | -- | -- | Impoundment at Chatsworth, Georgia, constructed about 1974. New well was located near site to supply water. Collapses occurred during or after filling. Stopped pumping for repair. A collapse occurred beneath a construction vehicle during repair. After filling and compacting collapses, impoundment was filled with water. No problems have been experienced since repair. Attributed collapses to well pumpage. |
| 40 | Mrs. Robert White, oral communication, 1981. | 1 | 25 | 25 | -- | New well drilled near Rockmart, Georgia about 1946. It yielded muddy water and was pumped overnight to clear up discharge. Collapse occurred in backyard near home during the night. Estimated that 15 truckloads of fill were used to level area. |
| 41 | D. Wilson, Georgia Geological Survey, written communication, 1981; T. Driggers and Associates, oral communication, 1981; observation. | 7+ | 2-10 | 2-10 | -- | Sewage lagoons at Fort Gaines, Georgia drained into subsurface through a collapse in 1974. Repeated collapses necessitated repairs on several occasions. Abandoned. Cost of facility was about $100,000 and cost of replacement treatment system was about $230,000. |
| 42 | A. Maxwell, Thomas County Highway Superintendent, oral communication, 1981; D. Wilson, Georgia Geological Survey, written communication, 1981; J. Freeman, property owner, oral communication, 1981; photography. | 1 | 35 | 40 | 50 | Collapse beneath bridge over Piscola Creek near Barwick, Georgia in 1975. Two-inch foundation hole was cored in intermittent streambed to a depth of 85 feet. Based on reported data for nearby well, the water table should have been at a depth of about 120 feet. No openings were penetrated in the core hole. Property owner discovered large whirlpool or vortex "making noise" in creek 3 days later. On fourth day, sagging bridge and the stream discharging into small collapse were discovered. Steady growth of opening and collapse of bridge into it were observed on same day. Leveled collapse and relocated stream and bridge to avoid area. |
| 43 | R. Shiver, North Carolina Department of Natural Resources and Community Development, written communication, 12-1-81. | 1 | 1-24 | 1-30 | 2-8 | Collapse in lagoon at poultry processing plant between Rose Hill and Magnolia, North Carolina, occurred on July 20, 1974. About 5.4 million gallons of wastewater drained into the subsurface and discharged as a spring in a quarry wall about 200 feet from the lagoon. The rate of discharge was estimated to be 1,000 gallons per minute. The quarry, mined for aggregate, was about 40 feet deep. Collapse was excavated to bedrock and sealed with clay. |

1/ Includes sites of active subsidence
2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 1.—*Records of selected sinkholes forming in the Eastern United States since 1940*[1]—Continued

| Site number | Source(s) of information | Number of collapses | General dimensions in feet[2/] Width | Length | Depth | Descriptions |
|---|---|---|---|---|---|---|
| 44 | W. D. Bingham, North Carolina Department of Transportation, written communication, 1981; R. Shiver, North Carolina Department of Natural Resources, written and oral communication, files of U.S. Geological Survey. | 18+ | 4-30 | 4-40 | 1-18 | Sinkhole activity occurred along planned highway corridor near Castle Hayne, North Carolina in 1980-81. Sites of occurrence were under pavement of existing road and in or adjacent to right-of-way near dewatered quarry. Four occurred during torrential rains in August 1981. Estimated cost of planned protective measures including construction of impermeable drain along new highway was $700,000. |
| 45 | R. Siesem and E. Titcomb, U.S. Army Corps of Engineers, oral communication, 1981; H. LeGrand, written communication, 1977; C. Davis, oral communication, 1981. | 8+ | -- | -- | -- | Boiling Springs Lake, North Carolina. Lake with 310-acre surface area impounded behind earth fill dam. Construction completed in 1961. Repairs made in 1964 and 1969 to plug sinkholes in lakebed. Sinkhole in upstream slope of dam partially drained lake in 1976. Problem posed a hazard to a railroad downstream from dam. Sinkholes also occurred in and near railroad route in vicinity. Cost of repairs and (or) safety measures to lake and dam, including grouting, reported to be $168,000 and those for railroad reported to be about one million dollars. |
| 46 | Spigner (1978). | 42 | 1-19 | 1-25 | 1-10 | Ground-water withdrawals from two quarries in the Jamestown, South Carolina area resulted in 42 sites of subsidence and collapse in 1976-78. Pumpage was estimated to be periodically in excess of 36 million gallons per day causing a water-level decline of over 35 feet. About 20 feet of unconsolidated sands and clays overlie the cavernous limestone being mined. |
| 47 | B. C. Spigner, Soil and Material Engineers, Incorporated, written communication, 1981. | 4+ | -- | -- | -- | Two pond failures and collapses on residential property occurred at Santee Lakes Resort northeast of Moncks Corner, South Carolina. Collapses occurring in 1978 were attributed to ground-water withdrawals from wells. |
| 48 | J. Cagle, oral communication, 1981; J. Foster, oral communication, 1981-83; photography. | 1 | 20 | 20 | 15 | Collapse at U.S. Geological Survey test well near Keystone Heights, Florida, in 1959-60 buried drillers' helper to depth of 30 feet and partially buried geologist. Drilling at time was at depth of about 80 feet near contact between surficial and underlying limestone aquifers. Water level in shallow aquifer reportedly higher than that in underlying aquifer. Well being drilled was replacement for another recently completed and abandoned well located about 12 feet away. Blasting in abandoned well to increase yield had damaged bottom of casing set at depth of about 80 feet. Casing was removed prior to drilling of new well. |

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| 49 | Rutledge (1982). | 9 | -- | -- | -- | Collapse forming sinkholes near Pierson, Florida occurred during period 1973-79. All sinkholes formed in cone of depression created by ground-water withdrawals. Most are known to have occurred during periods of drawdown caused by irrigation for freeze protection. The remainder formed in secluded locations but were discovered soon after periods of freeze protection. |
| 50 | Observation: Jammel and Associates (1982); J. Litton, H. Owens, and other City of Winter Park officials, oral communications, 1981. | 1 | 350 | 350 | 100 | Sinkhole formed at Winter Park on May 8-13, 1981 (fig. 2). Occurred beneath home and other buildings, water mains, streets, automobiles and swimming pool. Occurred during a major drought when water levels in observation wells in general area reached record lows. Declines resulted from long-term less than average precipitation and pumpage. Top of carbonate rocks is at a depth of about 150 feet. Wells within a mile of the site tapping openings about 450 feet below this horizon yield as much as 3,300 gallons per minute. Water related activities and changes at site were restricted to those involving the swimming pool. Leakage from the pool occurred during the preceding year and it was filled on date of collapse. Between May and October 1980, leakage amounted to about 16,250 gallons per day. Borings through floor of pool located small 4-inch void resulting from compaction of sand caused by leakage. Cost of damages, services, and safety measures estimated to range between 2 and 4 million dollars. |
| 51 | Sinclair (1982) | 115+ | -- | -- | -- | Sinkhole activity resulting from ground-water withdrawals occurred at six sites in same general area near Tampa, Florida. The largest number occurred when pumpage in a well field was increased from about 5 to 11 million gallons per day in March 1964 and, ultimately, to 14 million gallons per day in April 1964. By May 1964, landowners reported 64 new sinkholes within a 1-mile radius of well field. |

1/ Includes sites of active subsidence
2/ Ranges represent minimum and maximum dimensions in area of multiple collapses.

TABLE 2.—*Sources of information used to evaluate sinkhole problems in Alabama.*

[Modified from Newton, 1976a, p. 76, 77]

| Information needed to evaluate problem | Geologic map | Topographic map | Standard U.S. Department of Agriculture photography scale 1:20,000 | Multispectral photography scale 1:6,000 or less | Remarks |
|---|---|---|---|---|---|
| Distribution of geologic units containing carbonate rocks. | x | | | | Defines area in which sinkholes can occur. |
| Geologic structures (faults). | x | | | | Generally associated with solutionally enlarged openings in subsurface. |
| Location and size of natural sinkholes. | | x | x | x | Defines potential problem areas and distribution of existing sinkholes. |
| Location and size of induced sinkholes and small unmapped natural sinkholes. | | | x | x | Defines a problem area and distribution of active sinkhole development. Best results obtained from low altitude photography. |
| Linear trends along which most sinkhole activity has occurred. | | x | x | x | Alignment of sinkholes indicates areas most prone to their development where solution of carbonate rocks in subsurface has been greatest. |
| Linear features indicating locations of unmapped geologic structures (faults, joints, or fractures). | | | x | x | Indicates where openings may exist in subsurface where the movement of ground water and solution of carbonate rocks is or has been significant. Depending on magnitude and nature of structure, high altitude photography may yield best results. |
| Water loss where streams discharge into ground. | | x | | x | Generally associated with development of sinkholes. Best results from remote sensing are obtained during the nongrowing season. |
| Vegetative stress or anomalous vigor in open areas. | | | | x | May indicate potential site of collapse in area of induced sinkhole development. |
| Scour holes or other small openings in soil zone. | | | | x | Associated with active development of sinkholes. |
| "Tree kills" or vegetative stress in wooded areas where induced sinkholes are occurring. | | | | x | Potential location of sites of collapse obscured by vegetative cover. Where cavity in subsurface has developed and root damage and weakening of trees has resulted in infestation by insects, this may indicate potential site of collapse. |
| Filled sinkholes and areas of subsidence in and along highways, streets, and railroads that have required leveling. | | | x | x | Locates problem area. |
| Location of nearby industries, quarries, and mines. | | x | x | x | Potential sites of large ground water withdrawals that may make area prone to the development of induced sinkholes. |



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