Case History No. 9.11. Alabama, U.S.A., by J. G. Newton, U.S. Geological Survey, Tuscaloosa, Alabama

9.11.1 INTRODUCTION

Sinkholes in Alabama are divided into two categories defined as "induced" and "natural." Induced sinkholes are those related to man’s activities whereas natural sinkholes are not. Induced sinkholes are further divided into two types: those resulting from a decline in the water table due to ground-water withdrawals and those resulting from construction. Those resulting from a decline in the water table, the subject of this case history, far outnumber those resulting from all other causes. Information presented here consists of excerpts taken from five reports by the author. These reports, approved for publication by the Director, U.S. Geological Survey, are listed with the references cited in this case history. They resulted from investigations by the U.S. Geological Survey made in cooperation with the Geological Survey of Alabama and/or the Alabama Highway Department.

9.11.2 GEOLOGIC AND HYDROLOGIC SETTING

The terrane used to illustrate sinkhole development is a youthful basin underlain by carbonate rocks such as limestone and dolomite (Figure 9.11.1). The basin contains a perennial or near-perennial stream. This particular terrane is used because it is very similar to that of 10 active areas of sinkhole development in Alabama that have been examined by the author. Factors related to the development of sinkholes that have been observed in these areas are generally applicable to other carbonate terranes. The terrane illustrated differs from those examined only in the inclination of beds, which is shown as horizontal for ease of illustration.

The development of sinkholes is primarily dependent on past and present relationships between carbonate rocks and water, climatic conditions, vegetation, and topography, and on the presence or absence of residual or other unconsolidated deposits overlying bedrock. The source of water associated with the development of sinkholes is precipitation which, in Alabama, generally exceeds 1,270 mm annually. Part of the water runs off directly into streams, part replenishes soil moisture but is returned to the atmosphere by evaporation and transpiration, and the remainder percolates downward below the soil zone to ground-water reservoirs.

Water is stored in and moves through interconnected openings in carbonate rocks. Most of the openings were created, or existing openings along bedding planes, joints, fractures, and faults were enlarged by the solvent action of slighly acidic water coming in contact with the rocks. Water in the interconnected openings moves in response to gravity from higher to lower altitudes, generally toward a stream channel where it discharges and becomes a part of the streamflow.

Water in openings in carbonate rocks occurs under both water-table and artesian conditions; however, this study is concerned primarily with that occurring under water-table conditions. The water table is the unconfined upper surface of a zone in which all openings are filled with water. The configuration of the water table conforms somewhat to that of the overlying topography but is influenced by geologic structure, withdrawal of water, and variations in rainfall. The lowest altitude of the water level in a drainage basin containing a perennial stream occurs where the water level intersects the stream channel (Figure 9.11-1). Openings in bedrock underlying lower parts of the basin are water filled. This condition is maintained by recharge from precipitation in the basin. The water table underlying adjacent highland areas within the basin occurs at higher altitudes than the water table near the perennial stream. Openings in bedrock between the land surface and the underlying water table in highland areas are air filled (Figure 9.11.1).

The general movement of water through openings in bedrock underlying the basin, even though the route may be circuitous, is toward the stream channel and downstream under a gentle gradient approximating that of the stream. Some water moving from higher to lower altitudes is discharged through springs along flanks of the basin because of the intersection of the land surface and the water table. The velocity of movement of water in openings underlying most of the lowland

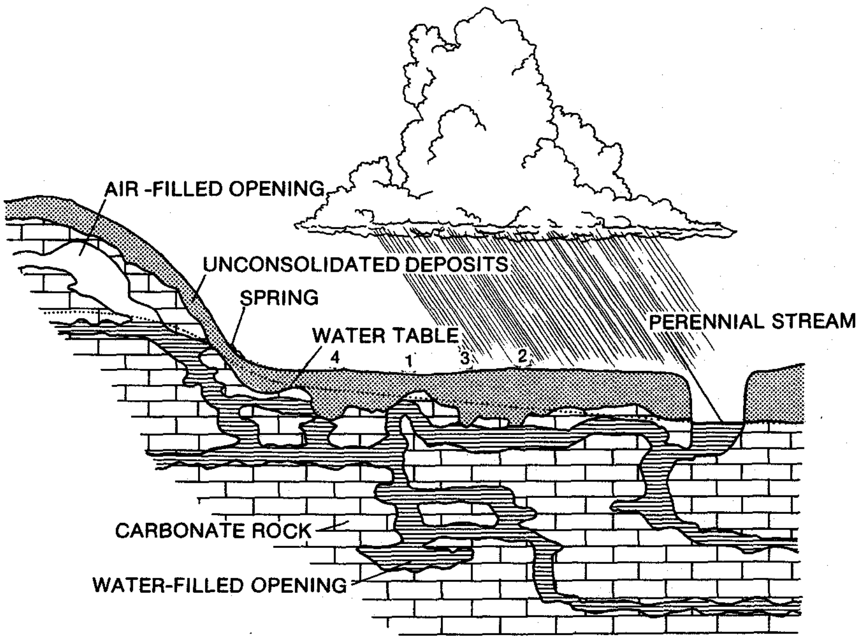

Figure 9.11.1 Schematic cross-sectional diagram of basin showing geologic and hydrologic conditions. (Numbers apply to sites described in report.)

area is probably sluggish when compared to that in openings at higher altitudes.

A mantle of unconsolidated deposits consisting chiefly of residual clay (residuum), that has resulted from the solution of the underlying carbonate rocks, generally covers most of the bedrock in the typical basin described. Alluvial or other unconsolidated deposits often overlie the residual clay. The residuum commonly contains varying amounts of chert debris that are insoluble remnants of the underlying bedrock. Some unconsolidated deposits are carried by water into openings in bedrock. These deposits commonly fill joints, fractures, or other openings enlarged by solution that underlie the lowland areas. The buried contact between the residuum and the underlying bedrock, because of differential solution, can be highly irregular (Figure 9.11.1).

9.11.3 CAUSE

A relationship between the formation of sinkholes and high pumpage of water from new wells was recognized in Alabama as early as 1933 (Johnston, 1933). Subsequent studies in Alabama (Robinson and others, 1953; Powell and LaMoreaux, 1969; Newton and Hyde, 1971; Newton and others, 1973; and Newton, 1976) have verified this relationship. Dewatering or the continuous withdrawal of large quantities of water from carbonate rocks by wells, quarries, and mines in numerous areas in Alabama is associated with extremely active sinkhole development. Numerous collapses in these areas contrast sharply with their lack of occurrence elsewhere.

Two areas in Alabama in which intensive sinkhole development has occurred and is occurring have been studied in detail. Both areas were made prone to the development of sinkholes by major declines of the water table due to the withdrawal of ground water. The formation of sinkholes in both areas resulted from the creation and collapse of cavities in unconsolidated deposits caused by the declines (Newton and Hyde, 1971; Newton and others, 1973). The growth of one such cavity in Birmingham has been photographed through a small adjoining opening (Newton, 1976).

Previous reports have described only indirectly or in part the hydrologic forces resulting from a decline in the water table that create or accelerate the growth of activities that collapse and form sinkholes. These forces, based on studies in Alabama (Newton and Hyde, 1971; Newton and others, 1973), are (a) a loss of support to roofs of cavities in bedrock previously filled with water and to residual clay or other unconsolidated deposits overlying openings in bedrock, (b) an increase in the velocity of movement of ground water, (c) an increase in the amplitude of water-table fluctuations, and (d) the movement of water from the land surface to openings in underlying bedrock where recharge had previously been rejected because the openings were water filled. The same forces creating cavities and subsequent collapses also result in subsidence. The 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 (Donaldson, 1963).

To demonstrate forces that result in the development of cavities and their eventual collapse, a schematic diagram is shown in Figure 9.11.2 that illustrates changes in natural geologic and hydrologic conditions previously described and shown in Figure 9.11.1. A description of the forces triggered by a lowering of the water table follows.

The loss of buoyant support following a decline in the water table can result in an immediate collapse of the roofs of openings in bedrock or can cause a downward migration of unconsolidated deposits overlying openings in bedrock. The buoyant support exerted by water on a solid (and hypothetically) unsaturated clay overlying an opening in bedrock, for instance, would be equal to about 40 per cent of its weight. This determination is based on the specific gravities of the constituents involved. Site 1 on Figure 9.11.1 shows the unconsolidated deposit overlying a water-filled opening in bedrock. Site 1 on Figure 9.11.2 shows the decline in the water table and the resulting cavity in the deposit formed by the downward migration, of the unconsolidated deposit caused by the loss of support.

The creation of a cone of depression in an area of water withdrawal results in an increased hydraulic gradient toward the point of discharge (Figure 9.11.2) and a corresponding increase in the velocity of movement of water. This force can result in the flushing out of the finer grained unconsolidated sediments that have accumulated in the interconnected openings enlarged by solution. This movement also transports unconsolidated deposits migrating downward into bedrock openings to the point of discharge or to a point of storage in openings at lower altitudes.

The increase in the velocity of ground-water movement also plays an important role in the development of cavities in unconsolidated deposits. Erosion caused by the movement of water through unobstructed openings and against joints, fractures, faults, or other openings filled with clay or other unconsolidated sediments results in the creation of cavities that enlarge and eventually collapse (Johnston, 1933; Robinson and others, 1953).

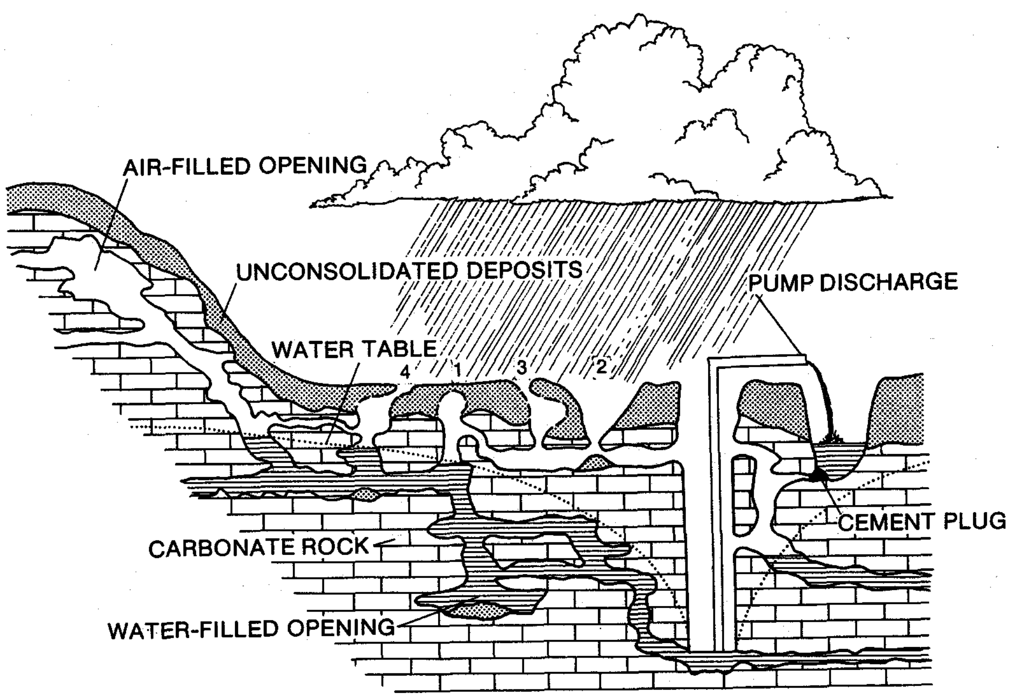

Figure 9.11.2 Schematic cross-sectional diagram of basin showing changes in geologic and hydrologic conditions resulting from water withdrawal. (Numbers apply to sites described in report.)

Pumpage results in fluctuations in ground-water levels that are of greater magnitude than those occurring under natural conditions. The magnitude of these fluctuations depends principally on variations in water withdrawal and on fluctuations in natural recharge. The repeated movement of water through openings in bedrock against overlying residuum or other unconsolidated sediments causes a repeated addition and subtraction of support to the sediments and repeated saturation and drying. This process might be best termed "erosion from below" because it results in the creation of cavities in unconsolidated deposits, their enlargement, and eventual collapse. Fluctuations of the water table against the roof of a cavity in unconsolidated deposits near Greenwood, Alabama, have been observed and photographed through a small collapse in the center of the roof. These fluctuations, in conjunction with the movement of surface water into openings in the ground, resulted in the formation of the cavity and its collapse (Newton and others, 1973).

A drastic decline of the water table in a lowland area (Figure 9.11.2) in which all openings in the underlying carbonate rock were previously water filled (Figure 9.11.1) commonly results in induced recharge of surface water. This recharge was partly rejected prior to the decline because the underlying openings were water filled. The quantity of surface water available as recharge to such an area is generally large because of the runoff moving to and through it from areas at higher altitudes.

The inducement of surface-water infiltration through openings in unconsolidated deposits interconnected with openings in underlying bedrock results in the creation of cavities where the material overlying the openings in bedrock is eroded to lower altitudes. Repeated rains result in the progressive enlargement of this type cavity. A corresponding thinning of the cavity roof due to this enlargement eventually results in a collapse. The position of the water table below unconsolidated deposits and openings in bedrock that is favorable to induced recharge is illustrated in Figure 9.11.2. Sites 2, 3, and 4 on Figure 9.11.2 illustrate a collapse and cavities in unconsolidated deposits that were formed primarily or in part by induced recharge. The creation and eventual collapse of cavities in unconsolidated deposits by induced recharge is the same process described by many authors as "piping" or "subsurface mechanical erosion" where it has been applied mainly to collapses occurring on noncarbonate rocks (Allen, 1969).

In an area of sinkhole development where a cone of depression is maintained by constant pumpage (Figure 9.11.2), all of the forces described are in operation even though only one may be principally responsible for the creation of a cavity and its collapse. For instance, the inducement of recharge from the surface (site 2 on Figure 9.11.2) where the water table is maintained at depths well below the base of unconsolidated deposits, can be solely responsible for the development of cavities and their collapse. In contrast, a cavity resulting from a loss of support (site 1 on Figure 9.11.2) can be enlarged and collapsed by induced recharge if it has intersected openings interconnected with the surface. In an area near the outer margin of the cone (site 4 on Figure 9.11.2), the creation of a cavity and its collapse can result from all forces. The cavity can originate from a loss of support; can be enlarged by the continual addition and subtraction of support and the alternate wetting and drying resulting from waterlevel fluctuations; can be enlarged by the increased velocity of movement of water; and can be enlarged and collapsed by water induced from the surface.

9.11.4 MAGNITUDE AND AREAL EXTENT

It is estimated that more than 4,000 induced sinkholes, areas of subsidence, or other related features have occurred in Alabama since 1900. Most of them have occurred since 1950. Almost all have resulted from a decline in the water table due to ground-water withdrawals.

Dewatering or the continuous withdrawal of large quantities of water from carbonate rocks by wells, quarries, and mines in numerous other areas in Alabama is associated with extremely active sinkhole development. Numerous collapses in these areas contrast sharply with their lack of occurrence in adjacent geologically and hydrologically similar areas where withdrawals of water are minimal. For example, in five areas examined by the author in north-central Alabama in Jefferson and Shelby Counties, an estimated 1,700 collapses, areas of subsidence, or other associated features have formed in a total combined area of about 36 km^2.

In Alabama, most induced sinkholes related to water withdrawals from wells, except those drilled specifically for dewatering purposes, were found within 150 m of the site of withdrawal. The yield of these wells commonly exceeds 22 l/s. Most sinkholes related to quarry operations were found within 600 m of the point of withdrawal; those related to mining operations can occur several kilometres from the point of withdrawal.

Recent collapses forming sinkholes in Alabama in areas in which large quantities of ground water are being withdrawn generally range from 1 to 90 m in diameter and from 0.3 to 30 m in depth. The largest, located in a wooded area in Shelby County, apparently occurred in a matter of seconds in December 1972. The collapse was about 90 m in diameter and 30 m deep (Figure 9.11.3).

9.11.5 ECONOMIC IMPACT

Costly damage and numerous accidents have occurred or nearly occurred in Alabama as a result of collapses beneath highways, streets, railroads, buildings, sewers, gas pipelines, vehicles, animals, and people. Unfortunately, no inventory of costs or loss in property values has been made. The maintenance and protection of highways in sinkhole prone areas indicate costs resulting from their development. The cost of filling collapses, leveling pavement and monitoring subsidence along less than a kilometre of Interstate Highway 59 in Birmingham, Alabama, during the period 1972-77 is estimated to have exceeded $250,000 (L. Lockell, oral commun.). The estimated cost of bridging a, part of this area, and planned safety measures for highways crossing two similar areas near Birmingham exceeds $4,660,000 (C. Kelly, oral commun.). The need for these protective measures is well illustrated by the damage to a warehouse in 1973 (Figure 9.11.4) that resulted from a collapse adjacent to Interstate Highway 59 in Birmingham.

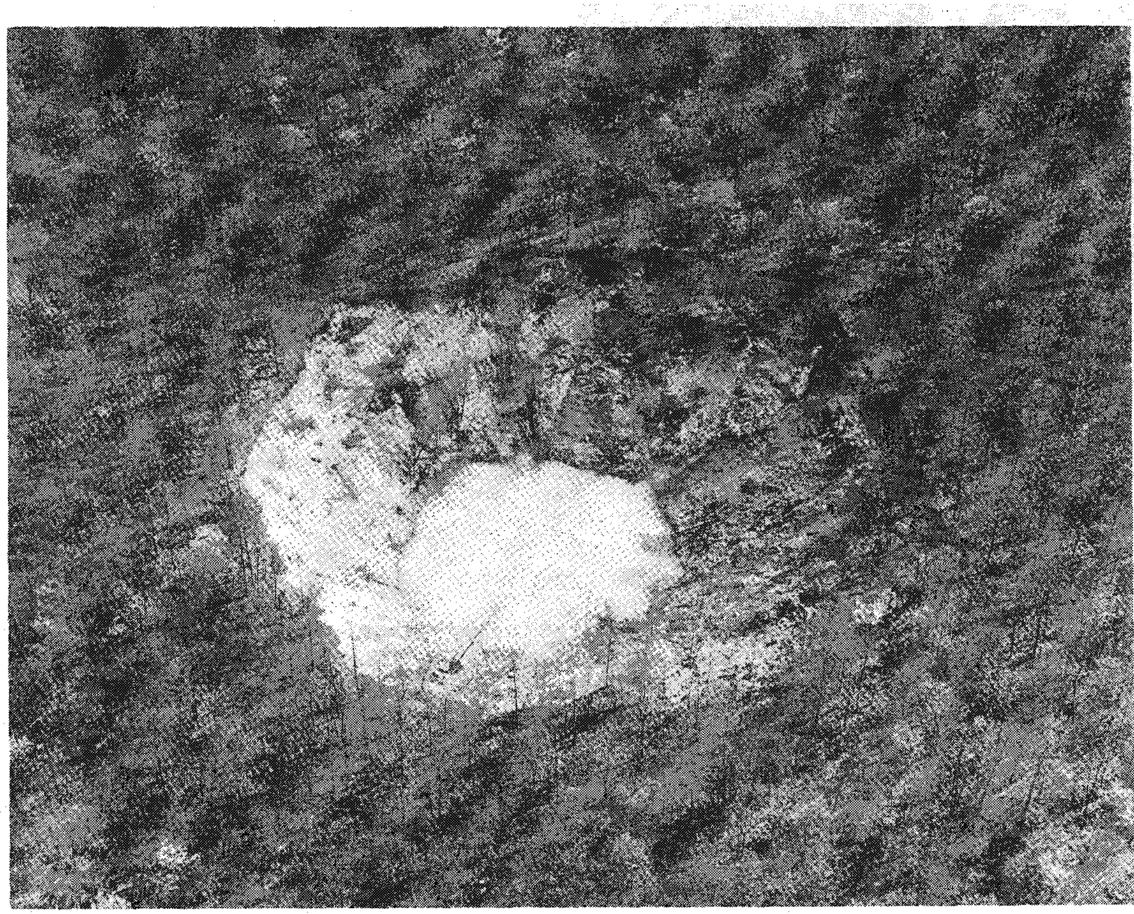

Figure 9.11.3 Sinkhole resulting from collapse near Calera in Shelby County, Alabama (photograph by Curtis Frizzell).

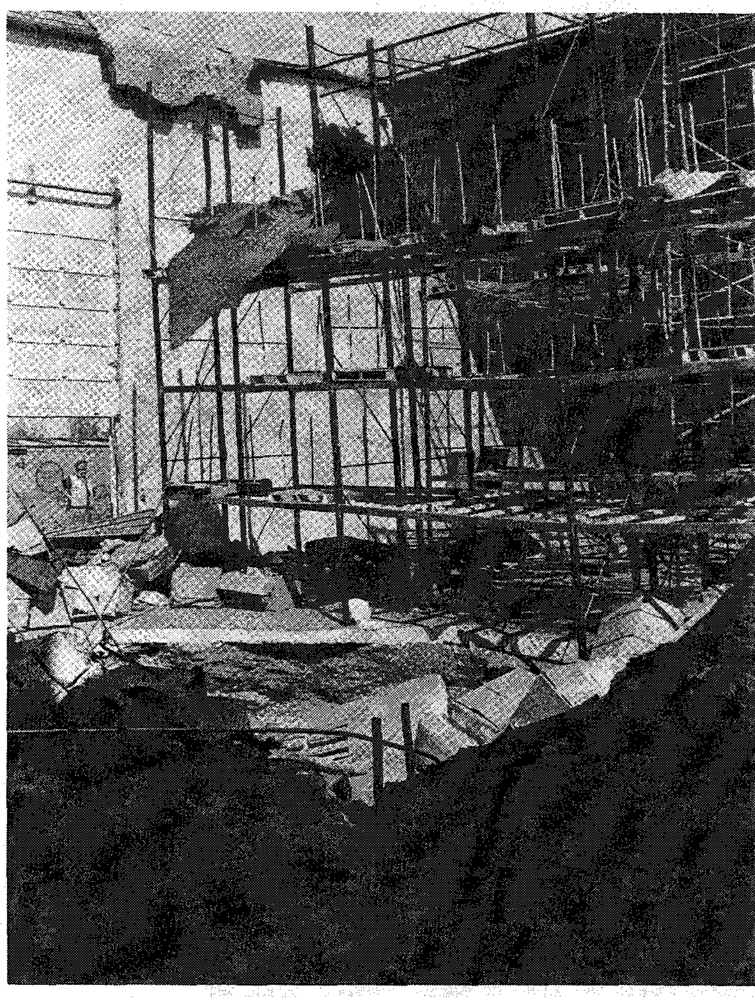

Figure 9.11.4 Collapse in warehouse near Interstate Highway 59 in Birmingham, Alabama (photograph by T. V. Stone).

9.11.6 CORRECTIVE MEASURES

Ideally, the development of sinkholes can be eliminated or minimized by ceasing the pumpage that causes the decline of the water table. The cessation of or drastic decrease in sinkhole activity following a recovery of the water table has been recognized previously (Foose, 1953; Newton and Hyde, 1971; Newton, 1976). Most efforts in Alabama have been directed toward measures minimizing sinkhole development and eliminating potential hazards and damage to structures rather than dealing with the cause. The measures that have been or will be utilized include bridging, adding additional support, the removal of unconsolidated deposits overlying bedrock, grouting, minimizing the diversion of natural drainage, and the construction of flumes and other impermeable drainage systems.

9.11.7 REFERENCES CITED

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