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Sinkholes in Florida and Their Effect on Man's Environment

Gregory Jackson Skinner
University of Central Florida

SINKHOLES IN FLORIDA AND THEIR EFFECT ON MAN'S ENVIRONMENT

BY

GREGORY JACKSON SKINNER

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PREFACE

The primary reason for making this research study on "Sinkholes in Florida and Their Effect on Man's Environment", is an interest in learning more about this somewhat unique phenomenon and how it is likely to affect man in the future, particularly here in Central Florida. This is significant at this time in view of the large number of existing sinkholes, the frequency of occurrence, the projected population and economic growth, and the possible impact this growth may have on future sinkhole occurrences.

The research concentrated on possible causes, effects, frequencies, locations and means of predicting future sinkhole development. There is a large amount of published material on possible causes, including general agreement on some fundamental aspects. There is controversy however, among qualified experts on some of the finer points. The research revealed a small amount of data on effects and very little organized activity to collect and evaluate data on all known sinkholes as to location, frequency of occurrence, conditions found at the site, and known geological data pertaining to the area. Descriptive data on conditions is expected to include diameter, depth, size of the opening in the limestone and, if possible, characteristics of the cavern, including whether or not limestone debris was found. Several studies on possible means of predicting potential sinkhole activity were found.

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INTRODUCTION

Purpose

The purpose of this research study is to collect and present data that will be useful in creating an awareness and active concern about the possible impact of sinkholes on man's environment and to help in some way to stimulate the interests of others toward finding sufficient data and evaluating it so that mankind can gain enough knowledge to effectively cope with this natural phenomenon and reduce the probability of bad effects on the environment.

Scope

This study includes discussions of theories on how sinkholes and underground caverns are formed, examples of adverse effects upon man's environment, location of some significant sinkholes, an analysis of a sampling of known sinkholes which occurred in Orange County and Seminole County during an eleven year period, and information on techniques being used and under study in an attempt to predict sinkhole activity. In addition, the writer furnishes opinions based on this study and recommends further actions to be taken.

Discussion of Karst Topography

In Karst, Yugoslavia, on the eastern side of the Adriatic Sea, the limestone rocks are honeycombed by tunnels and openings dissolved out by ground water with much of the drainage underground. There are many large sinkholes, some of them are five and six hundred feet deep.

Numerous valleys are streamless and those that have streams often end abruptly where the streams plunge into the underground tunnels and caverns, sometimes to reappear as springs at another location. Irregular topography of this kind, developed by solution of surface and ground waters, is known as karst topography, after this type region.

In the United States there are karst regions in central Tennessee, Kentucky, southern Indiana, Alabama, Florida and Texas as reported by Flawn (1970). In addition, there are known instances of sinkholes in Ohio and Pennsylvania (Leggett, 1962) and also in New Mexico (Shelton, 1966). Leggett (1962) describes some sinkholes of unusual size, such as Culpepper's Dish (in England) which is 600 feet in diameter and 150 feet deep with sloping sides and in Jamaica, in the Cockpit Country where there are sinkholes up to 500 feet in depth.

While there are many similarities in various karst areas, there are also distinct differences such as those described in Florida Department of Natural Resources - Bulletin No. 41 (1958). This account emphasizes that the Lake Region in Florida has no counterpart in North America, for although a few small sinkhole lakes are found in other regions of karst topography, nowhere is there such an extensive zone of closely spaced solution-basin lakes. A logical explanation is presented to show why Florida karst is different from karst regions elsewhere in the United States. In the Florida karst region where lakes are very common, there is a predominately permeable sandy surface, but in other karst country where the limestones are covered with tight residual clay soils the lakes are not as numberous nor as large.

The Kentucky karst country is covered with a residual limestone soil. The surface runoff is high and the infiltration is low by comparison with the sandy Coastal Plain. There is little overland flow into sinkholes in Florida, but instead the water seeps through the sand as the rain falls. It then flows horizontally to the sinks underground. In regions of tight residual limestone soils the water table is low, not only due to the relief, but also due to the greater runoff by overland flow directly to sinkholes and thence, through caverns to surface streams. Thus the dead zones of air-filled caverns prevent widespread development of lakes.

Sinkholes are common in Orange County, Florida, largely due to the geological conditions in the area. The formations underlying Orange County include the Ocala limestone (of Eocene Age), the Hawthorn and Choctawhatchee formations (of Miocene Age), and undifferentiated Pleistocene and recent material. The Ocala limestone is the oldest formation penetrated by most wells in the county and is underlain by undifferentiated Eocene and Cretaceous sediments. Well records indicate that the top of the Ocala is from 100 to 150 feet beneath the surface. The Ocala is almost pure limestone and parts of it are porous and contain solution channels that permit free circulation of ground water. (See Figure 1 for typical cross section depicting sinkhole formations in Florida (Ardaman, 1969).)

The Ocala limestone is overlain unconformably by the Hawthorn formation, which consists of clay, sand, and marl. The Hawthorn is overlain by unconsolidated younger material, consisting principally of

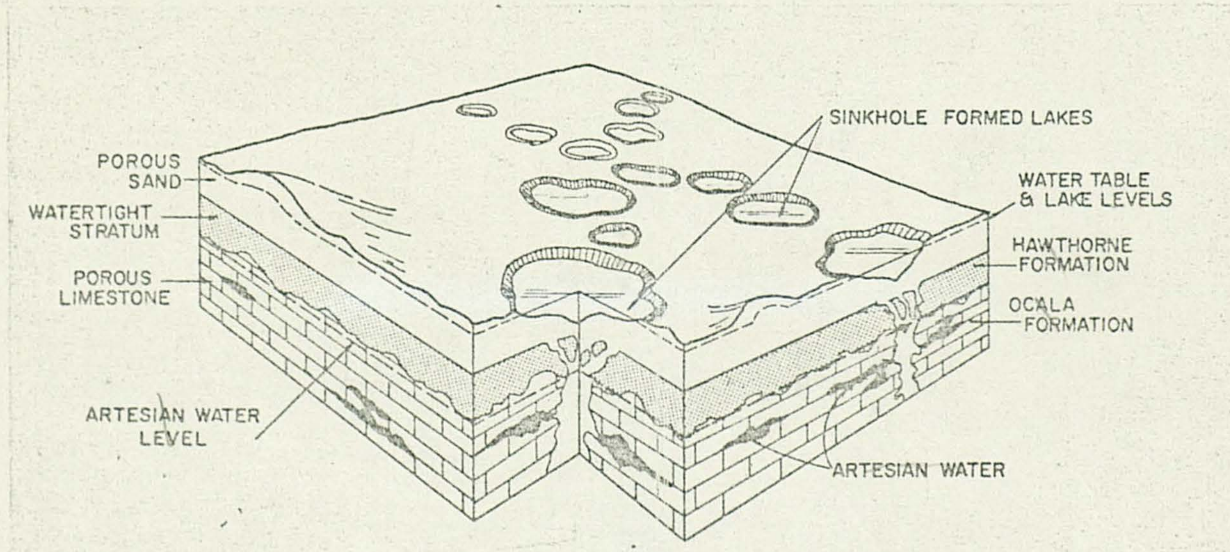

Fig. 1.--Typical cross section of Florida karst topography. Taken from article by Ardaman (1969).

sand and clay, which lie at or near the surface (Florida Department of Natural Resources - Bulletin No. 11, 1933)

The Avon Park limestone formation is generally below the Ocala formation. The Ocala formation is rated as having a "moderately high transmissibility" and the Avon Park formation is rated, "overall transmissibility very high". Many large capacity wells draw from the latter fromation, and there are a large number of wells in the Ocala formation also (Florida Department of Natural Resources - Report of Investigation No. 50, 1968.)

The interior of Florida is being carried into the ocean through Silver Springs at the rate of 890 pounds per minute, or 600 tons per day. This is based on a flow of 368,913 gpm and 274 ppm of dissolved solids. The rates of solids removed by six other streams are shown in Table 1 (Florida Department of Natural Resources - Sixth Annual Report, 1914).

TABLE 1

TOTAL SOLIDS REMOVED IN SOLUTION BY SIX SPRINGS IN CENTRAL FLORIDA

Name of Spring	County	Solids Removed (lbs./day)
Blue	Marion	469,698
Blue	Levy	59,040
Ichetucknee	Columbia	457,056
Newland	Suwannee	210,150
Weekiewachee	Hernando	273,360
White Sulphur	Hamilton	64,774
Suwannee	Suwannee	78,816

The above table is an excerpt of data contained in a tabulation shown in Sellards report entitled, "Some Florida Lakes and Lake Basins" as included in the Florida Geological Survey - Sixth Annual Report, 1914, p. 123. It lists the estimated amount of solids dissolved in the water flowing from the corresponding springs. Reference listed under "Florida Department of Natural Resources".

THEORIES ON FORMATION OF SINKHOLES

General

One of the earliest accounts of sinkholes and their formation was by Sellards in 1909. His major findings may be summarized as follows: (See Second Annual Report, Florida G.S. 1909)

a) The topography of the "Lake Region" is typical of those limestone areas which have been sufficiently elevated to permit the formation of large underground streams. Sellards stated that in order to understand the origin of sinkholes it is necessary to consider the development of the underground drainage.

b) The region is underlain, "at no great depth", by several hundred feet of porous limestone of Vicksburg Age. Where surface water bearing carbonic acid (derived from decaying organic matter and solution with carbon dioxide in the air) enters the rock, it gradually dissolves the limestone and thus forms underground channels.

c) A large amount of mineral matter is carried off by ground water to the surface, into rivers and transported to sea. Sellards estimated that Silver Spring brought 340 pounds of mineral matter per minute to the surface. (Note - this is considerably less than the estimated amount reported in the Sixth Annual Report, discussed earlier in this study.) The estimated average mineral content of the spring water was 219 ppm and on the assumption that about one-half of the rainfall entered the earth and later removed this amount of material, it was

concluded that this rate of solution was sufficient to remove, from the limestone section of Florida, about 400 tons per square mile annually. If evenly distributed this would lower the surface of the limestone about one foot in five or six thousand years. The concentration of this solution along certain beds or channels of active circulation would permit the formation of large underground passages in a comparatively short period of geological time.

d) Sellards' theory on sinkhole formation in Florida was:

i) Channels develop into large caverns, sometimes hundreds of feet in diameter and several miles long. The level surface and porous soil favor the development of caverns because most of the rainfall sinks into the earth instead of flowing off over the surface.

ii) As solution progressed, the cavern roofs weakened at various points and collapsed, forming sinkholes.

Collapse of Cavern Roofs

The fundamental concept that some sinkholes can result from collapse of cavern roofs is generally accepted by geologists and engineers. It is also recognized that other factors enter into such collapse. Some authorities also feel that the level of the water table, the type and thickness of the overburden, and the water level based on piezometric pressure can contribute toward collapse of cavern roofs. Ardaman (1969) indicated that a drop in the piezometric pressure of the water level by an amount of 20 feet is comparable to a surface loading of 1,200 pounds per square foot and a drop in the level of the water table of eight feet is comparable to adding another 500 pounds per

square foot. He further stated, "Though not always true, in a majority of cases, this differential that occurs during the months of April and May, is the prime reason we develop sinkholes--simply because the roof over the million year old cavity is not capable of supporting 1,700 p.s.f." (Ardaman 1969, p. 9).

Solution Pipes or Small Openings

There is very little published data on "solution pipes" or small openings as related to sinkholes. Some interesting information was reviewed indicating that sinkholes may occur without collapse of cavern roofs.

A sinkhole can be formed by gradual infiltration of sand through a small opening or "tunnel". This is illustrated by the formation of a sinkhole in Canton Street in Winter Park in April 1961. The sink was first noted as a depression in the graded road. By the following day a hole about six feet in diameter had formed. In the next two days the hole gradually increased in size to about 60 feet in diameter and 15 feet in depth (Florida Department of Natural Resources - Report of Investigation No. 50, 1968).

"Natural wells" and "solution Pipes" are defined as small vertical openings in the limestone, extending as much as 100 feet long. Since artesian water is under pressure and is charged with natural acid, the water will tend to move upward and by further solution activity in the limestone, new crevices or channels may develop. This may be facilitated by the increased porosity and solubility of the limestone nearer the ground surface (Florida Department of Natural Resources

Bulletin 33, 1951). Observations made of some sinkholes in Florida indicate that instead of roof collapse it appeared that the soil moved through small openings which may possibly have been "solution pipes". In many cases small round, smooth openings were observed. It was indicated that an opening as small as four inches in diameter in the limestone, over a cavern of sufficient size and with 75 feet of overburden consisting of loose sand, can result in a sinkhole 75 feet in diameter.

Impact of Man on Sinkhole Occurrence

Most of the conditions for the development of sinkholes result from processes of nature and therefore, it is presumed they already exist in some form prior to man's role in assisting sinkhole development. Some of the ways in which man can hasten the occurrence of a sinkhole appear to be by penetrating the limestone roofs over caverns and by causing significant lowering of the water table.

Sinkholes have been known to result from well drilling operations and from core drilling. An example of a sinkhole occurring during a well drilling operation is one that developed in Pine Hills in the vicinity of Orlando on August 24, 1970 (Orlando Sentinel, 1970). In other instances involving core drilling, cavern roofs have been broken sufficiently to allow sinkholes to develop rapidly and with little warning.

Man can also contribute to sinkhole occurrence sooner than it may otherwise occur by lowering the water table. This can be brought about by increasing the amount of water consumption or modifying the surface so as to increase the runoff and thereby restricting the

capability for recharging the aquifer. This is especially applicable where rainfall is the primary means for recharging the aquifer. The impact of lowering the water table as pertains to sinkhole occurrence is discussed in a subsequent section of this paper and was briefly mentioned earlier (Ardaman, 1969 and Leggett, 1962)

THEORIES ON FORMATION OF CAVERNS

General

There are many differences of opinion among leading experts in the field of geology on how caverns are formed. They agree that solution took place, but they do not agree on where it happened. They also seem to disagree on how the ground water flows through the limestone enroute to a surface outlet.

Two-Cycle Hypothesis

This theory is attributed to W. M. Davis in an account by Thrailkill (1968). Prior to 1930 when Davis presented his paper, most explanations on cave formation held that caves were dissolved in limestone meteoric water which descended from the surface, mainly along joints, and then flowed laterally to the valley of a surface stream. The lateral flow was implied to be on a less permeable (or less soluble) bed or along the top of the water table.

In 1930 Davis published his classic paper on the origin of limestone caves. He suggested that because most caves are the sites of deposition rather than solution, they may have been formed in an environment different from their present one. Because he was convinced that the caves were full of water when formed, he proposed that such caves were excavated in the phreatic zone. The decline in the water table since their formation was ascribed to rejuvenation, and thus such caves were considered to have been formed in an earlier geomorphologic cycle. Based on this he called his concept the "Two-Cycle Theory".

Vadose Water Theory

This is considered to be a modification of the prevalent thinking before Davis presented his paper in 1930. Swinnerton is a leading proponent of this theory. He placed great emphasis on the controlling factor of the water table and attributed cavern solution essentially to laterally flowing water at the level of the water table. He presented his theory to the Geological Society of America in 1928:

> In the simplest case precipitation passes more or less directly downward through the openings in the rock to the water table and then moves laterally in the fluctuating top of the water table into the surface drainage channels. Insignificant caves may occur both above and below the water table as temporary phases of the adjustment of subsurface flow to the level of the surface streams. . . . (Swinnerton 1932).

Matson also supported this theory, emphasizing that water coming fresh from the surface has much carbonic acid and attacks the limestone about the point of entrance. As it flows farther from the entrance it eventually becomes saturated and loses capabilities to dissolve rock (Swinnerton 1932).

Davis is of the opinion that Swinnerton's theory fails to explain

a) Integrated subsurface drainage systems,

b) Vertical and horizontal passages, including multiple network passages,

c) Offshore drainage outlets such as the fresh water springs off the coast of Florida,

d) The roof solution suggested by smooth ceiling markings in many caves.

Davis considers the Two-Cycle hypothesis will explain and correlate these observations (Swinnerton 1932).

Others

Roger Rhoades and M. N. Sinacori stress that initial flow through homogeneous soluble materials from an elevated water surface to a lower point of discharge will take place along curved paths which descend below the point of discharge before coming upward to the point of discharge. They indicate solution will initially be more effective along shorter paths and that continued solution lowers the water table and leads to progressive concentration of flow and solution at the higher levels and a reduced flow at greater depths (Rhoades 1941). In addition, they conclude that solution would be greatest where flow is most concentrated and that cave development began at a point of outflow to a stream and progressed horizontally away from the stream, with the flow lines adjusting continuously to an outflow (Thrailkill 1968).

For illustration on some of the theories expressed in Thrailkill's paper, see Figure 2. Also see reference (Rhoades 1941).

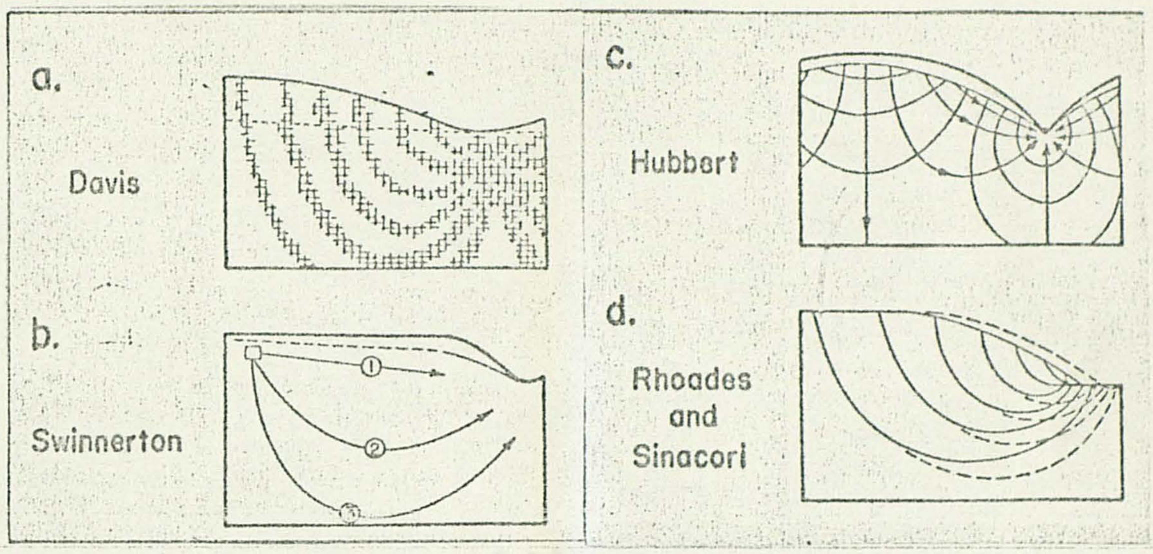

Fig. 2.--Patterns of ground water flow in limestone (Thrailkill 1968).

LOWERING THE WATER TABLE CAN AFFECT SINKHOLE ACTIVITY

Experience in Pennsylvania

An example of how sinkhole activity can be affected by lowering of the water table is indicated by the experience in the vicinity of Hershey, Pennsylvania, by Leggett (1962) and Davis and DeWiest (1967). According to Leggett, the Hershey Valley is underlain by an Ordovician limestone of the Beekmantown formation. A stone company had been operating a quarry in the area for many years and had pumped water from the working level at the rate of 3,500 gpm without serious effect. Then in May 1949, the company suddenly increased its pumping rate to 6,500 gpm in its "lower workings". Within a short time, ground water levels were affected to a varying degree throughout an area of ten square miles. Over 100 sinkholes developed, some with serious effect. After a successful recharging and grouting operation around the quarry, ground-water conditions in the area were effectively restored by May, 1950 (Leggett, 1962).

Theory on Surface Loading

As mentioned earlier in the discussion on collapse of cavern roofs Ardaman (1969) indicated that lowering of the water table could add a "ficticious" load expressed in pounds per square foot to the surface of the ground. This "ficticious" load is the increase in effective pressure which is caused by removing the buoyancy effect of the water. The unit weight for a wet sand soil, not submerged, could be assumed to

be 125 lbs./cu.ft. Under buoyant conditions the effective unit weight would be 125 - 62.5 or 62.5 lbs./cu.ft. Thus a lowering of the water table will cause an increase in effective unit weight of approximately 62.5 lbs./cu.ft. for each foot the water table is lowered. If the water table is lowered eight feet this will result in an effective pressure increase of 8 x 62.5 = 500 pounds per square foot of surface involved.

Analysis Based on Sampling of Sinkhole

Another example of possible effect of lowering of the water table on sinkhole occurrence can be found in the results of the analysis of data based on a limited sampling of sinkholes that occurred in the vicinity of Orange and Seminole Counties over an eleven year period. The analysis is covered in another section of this study.

EFFECTS ON MAN'S ENVIRONMENT

General

While there are many bad effects which can result from sinkholes, such as property damage and contamination of water sources, there are also some good effects, including the aesthetic, recreational, and food values of lakes caused by sinkholes and the capability of some sinkholes to recharge the aquifers. It is suggested that while man is enjoying the good effects of sinkholes that adequate attention be given to the detrimental effects and the need for more knowledge about sinkholes so that the adverse impact can be reduced to a minimum.

Property Damage

There are many instances of property damage resulting from sinkholes. Houses are damaged and destroyed, roads are badly damaged, and the foundations of structures can be adversely affected by sinkhole activity. Open areas can also sustain property damage from sinkholes. Examples illustrating some of these types of damage are discussed by Flawn (1970, p. 40, 41). They include:

a) Five houses were damage in the Pine Hills area west of Orlando, Florida, early in 1961 by the collapse of a large sinkhole covering about 40 acres.

b) A sinkhole 60 feet deep developed at the corner of Baker and Austin Streets in Bartwo, Florida, and endangered two residences in May, 1963.

c) Part of U. S. Highway 19 and an adjacent building at the northern limits of Chiefland, Florida, were damaged by a sinkhole about 50 feet in diameter in October, 1964.

d) In Casselberry, Florida, one house was destroyed and three were damaged by development of a sinkhole about 80 feet in diameter and 20 feet deep; cracks extended about 200 feet from the sinkhole. This occurred in May of 1965.

e) In Lexington, Kentucky, a cement truck dropped 12 feet into a limestone cavern while pouring the foundation for a house.

f) Collapse of a cavern in Ordovician Limestone (Newala and Longview formations) near Leeds, Alabama, resulted in damage to a foundation under construction for a cement plant.

Insurance for Property Damage

Based on the concern about property damage which can result from sinkholes, the State of Florida law now requires that, "every insurer authorized to transact property insurance in Florida shall be required to provide coverage for insurable sinkhole losses on dwellings of four families or less, including contents of personal property contained therein if requested by the owner or lienholder of such property." (Florida. Order Adopting Plan and Promulgating Rules, Relating to Sinkhole Insurance; Risk Apportionment Plan, Sec. 5-23.-1 (Nov. 1969)

The insurance rates from $.25 to $.06 per $100 value among four different zones. This indicates a difference in risk, which in turn may be inferred to indicate a difference in probability of sinkhole

occurrence in the separate zones. Based on the foregoing assumption it appears appropriate to list the counties in the higher rated zones. They are:

a) The zone with the highest rates include: Alachua, Hardee, Hillsborough, Lake, Orange, Pinellas, Polk, and Seminole Counties.

b) The zone with the next highest rates include: Citrus, Dixie, Gilchrist, Hernando, Jackson, Lafayette, Leon, Levy, Marion, Suwannee, Taylor, Wakulla, and Washington Counties.

c) The zone with the next highest rates include: Bradford, Calhoun, Hamilton, Highlands, Holmes, Jefferson, Okaloosa, Osceola, Putnam, Union, Volusia, and Walton Counties.

d) The last zone includes the balance of the State. (Florida Sinkhole Insurance Plan., Feb., 1970)

Possible Sources of Contamination Due to Sinkholes

One of the main hazards of sinkholes other than the damage they do when they occur is the potential for contaminating water supplies with disease bacteria, organic wastes, chemical wastes, and toxic pollutants (including pesticides). Wetterhall states; "Where the water table is higher than the piezometric surface of the artesian aquifer, water may move downward into the artesian aquifer. Such recharge of the aquifer can take place either through sinks that penetrate the confining beds or by percolation through the confining beds." (Florida Department of Natural Resources--Report of Investigation No. 39, 1965, p. 7, 8.) Meinzer points out, "Thus a sand deposit assures relative

safety, whereas a cavernous limestone may furnish no protection against pollution." (1950, p. 166)

An example of the use of sinkholes for disposal of wastewater is cited by Leggett (1962). In Bellevue, Ohio, there were approximately 1,500 sinkholes used for the disposal of all the town's sewage and drainage. As a result of a cloudburst the underground drainage filled and then overflowed spouting geysers 15 to 20 feet high covering the streets with wastewater. This happened in 1937 and in 1946 the Ohio Water Resources Board ruled that the use of any well for disposal of sewage or other material considered deleterious to the potable underground water was to be prohibited in Ohio.

An account was published by the Florida Geological Survey in 1933 on the use of drainage wells in Orlando for drainage of "surface water" and "sewage", in large quantities, into the Ocala limestone. It points out that many of the wells are located in sinkholes or other depressions and emphasizes that the water in the limestone is subject to contamination (Florida Department of Natural Resources--Bulletin No. 11, 1933). In this same reference an opinion is expressed, based on the impervious nature of the Hawthorn formation, which overlies the Ocala limestone, that only a comparatively small amount of surface water reaches the Ocala limestone locally except through sinkholes and drainage wells.

The Florida State Bureau of Geology stresses that the use of sinkholes or drainage wells to dispose of sewage or surplus surface water constitutes a threat to supply wells drawing water from the limestone. It refers to a total (existing at that time) of 132

drainage wells. Of these there were 18 sanitary wells in Orlando and vicinity; 17 owned by the City of Orlando, "are used to drain septic tanks at eleven scattered localities in the city." According to this report some of the sanitary wells range in depth from 231 to 863 feet and casings range in size from eight to 12 inches (Florida Department of Natural Resources. Report of Investigation No. 5, 1944).

LOCATION OF SOME SIGNIFICANT SINKHOLES IN FLORIDA

General

There is a lack of publications containing comprehensive data on location and characteristics of significant sinkholes in Florida. This applies to recent ones as well as those which apparently occurred long ago. This section will discuss some of the sinkholes which are mentioned in some of the available research material. See Figure 3 for typical cross section of an artesian lake (Fla. Dept. of Natural Resources--Info. Cir. 47, 1965).

Sinkholes in Lakes and Basins

In the Sixth Annual Report of the Florida Geological Survey (1914) numerous sinkholes are described along with the lakes and basins with which they are connected. Some major ones are:

a) Lake Iamonia is in Leon County and is from one to one and one-half miles wide and twelve to thirteen miles long. A large sinkhole through which the water in the lake escapes is located on the north border. It is 50 feet deep and is near an abrupt bluff of about 30 feet. A large number of smaller sinkholes occur in the vicinity of this sinkhole. Sellards states, "The formation of these is doubtless due, as previously stated, to the fact that the water entering the drainage sink spreads laterally in the underlying limestone and dissolves the rock rapidly. The result is the formation by subsidence of numerous sinks adjacent to the drainage sink. The presence of these

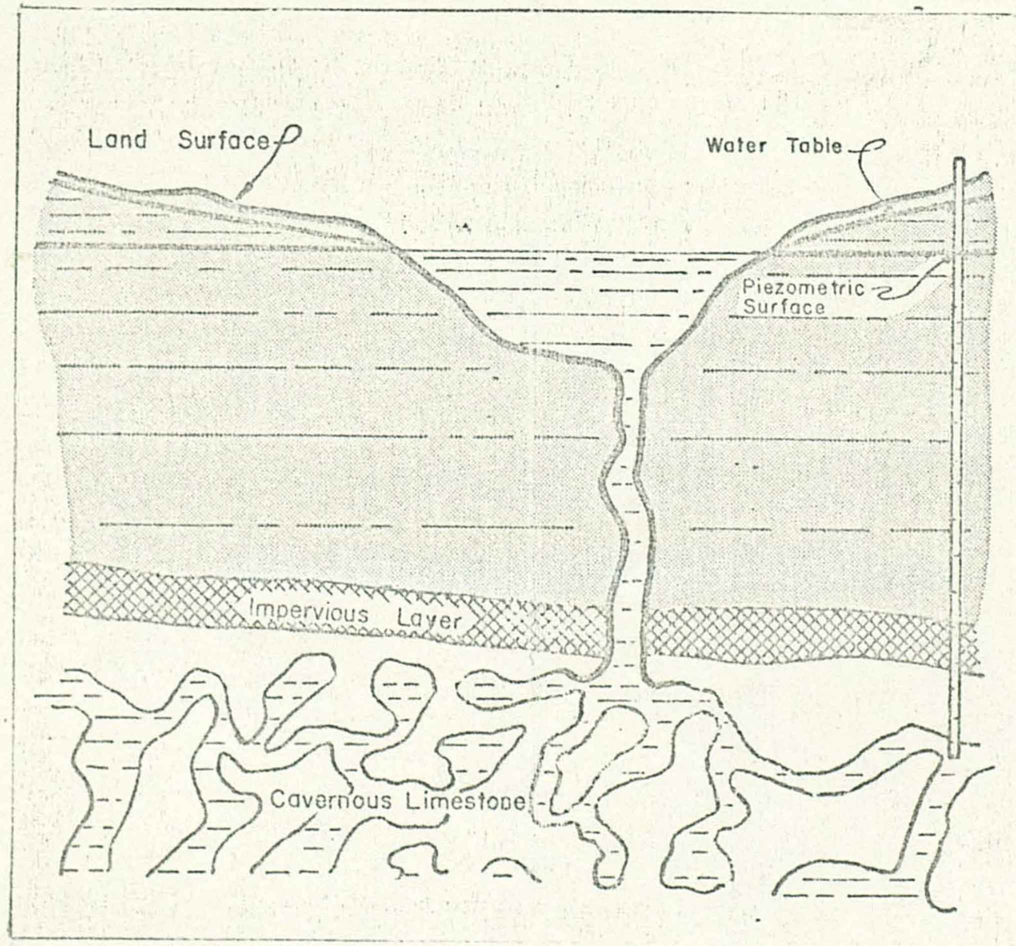

Fig. 3.--Typical cross section of an artesian lake. Taken from Information Circular No. 47, p. 9. (Ref. Fla. Dept. of Natural Resources, 1965).

sinks also indicates the manner of enlargement of the lake basin, and indicates the direction of the most rapid enlargement at the present time."

b) Lake Jackson is in the western part of Leon County. It is irregular in shape and covers about 4,500 acres. There are several sinkholes in the southern part of the lake along an "indefinitely defined broad depression" and it was noted that a new sink, 25 feet deep, occurred in 1907 along that line. Occasionally these sinkholes become unplugged and drain the lake.

c) In Lake Lafayette there is a sinkhole 75 feet deep near a bluff and another one nearby indicating the direction of enlargment of the lake basin by subsidence, due to underground solution. The lake is in the eastern part of Leon County.

d) In Lake Miccosukee, between Leon and Jefferson Counties there is one large sinkhole and several small ones near the northwest corner, bordered by a bluff, 75 to 100 feet high. Some water escapes through this sinkhole at an estimated rate of from 200 to 1,000 gallons per minute. Water also escapes through a series of sinkholes along Mill Creek toward the south.

e) There is a sinkhole in Alligator Lake, in Columbia County, through which lake water escapes and as a result it occasionally becomes a prairie.

f) Water flowing from Newnan's Lake into Alachua Lake (or Payne's Prairie) enters sinkholes, which are surrounded by bluffs , 30 to 40 feet high, at a rate, estimated in 1907, of 20,000 gallons per

minute. When the drainage sinkholes become clogged a lake is formed and remains as such until it becomes unclogged, maybe several years later. Sellards references earlier accounts of "Alachua Lake" including: Bartram in 1776, who noted that "Alachua Savannah" was a grazing ground for cattle belonging to the Indians; James Pierce in 1824; Dr. E. A. Smith in 1880, who observed it as a lake; and Dr. W. H. Dall of the U. S. Geological Survey, who gave an interesting account of the lake. Apparently, visitors used to throw logs into the sinkhole and watch them float to the center and disappear in a whirlpool. The outlet became clogged and a lake was formed in 1873 after a series of heavy rains. The lake supported an active steamer traffic for several years until it became dry again in 1891, drained by the unclogged sinkholes. Only small pools remained.

Sinkholes in West Central Florida

In a report entitled, "Reconnaiscance of Springs and Sinks in West-Central Florida", several large sinkholes in that area are described (Florida Department of Natural Resources--Report of Investigation No. 39, 1965).

a) A numbering system is established for springs and sinkholes based on location and the order in which they were inventoried within a minute of latitude and longitude. It is similar to the system for numbering wells except that an alphabetical designation is used to denote the order in which they were inventoried. For instance, Well No. 827-131-3 was the third well inventoried in the one-minute quadrangle north of 28° 27' parallel of latitude and west of 81° 31' meridian of longitude.

b) Lake Tarpon Sink (807-244-B) is in Lake Tarpon and connects the lake with Tarpon Springs through an underground conduit. It is about 250 feet by 300 feet and the west and south sides slope moderately for about 40 feet then steeply toward a small vertical hole about 20 feet deep below general bottom depth of 95 feet below mean sea level (Location--Pinellas County). Flow approached "200 to 150 cfs".

c) Blue Sink (805-246-A) is also located in Pinellas County. It is about 80 feet in diameter. The bottom slopes irregularly toward a vertical hole about 15 feet in diameter in a rock ledge. Below the rock ledge the hole expands to an undetermined diameter (a diver estimated 50 feet) to a depth of 111 feet. As much as 1,000 gpm has been pumped for a week without appreciable lowering of the water level.

d) Knights Sink (807-244-A) in Pinellas County is about 100 feet long and 80 feet wide. Sides are fairly steep from the top of the ridge that surrounds the sink to a depth of from one to 20 feet below the water surface. A nearly vertical hole extends from the rim to a depth of 60 feet. The flow is small.

e) Rocky Sink (816-239-A) in Pasco County is about 125 feet in diameter and 52 feet deep below the water surface at a stage of 13 feet above mean sea level. Flow has been measured at between 14.5 and 26 cfs. It drains five lakes and a swampy area.

f) Bear Sink (819-240-A) in Pasco County is about 100 feet wide and 150 feet long. Maximum depth is about 30 feet. At normal stage the sink drains an estimated 10 to 15 cfs and at three feet above normal it was estimated to be 41.4 cfs. It is used to drain several square miles of the Bear Creek Basin.

g) Round Sink (820-241-A) in Pasco County is about 100 feet in diameter. The sides are nearly vertical from the top of the bank to a depth of 20 to 40 feet. Near the center of the sink a vertical pipe or chimney about 20 feet in diameter bottoms at 60 feet. The cross sectional area of the conduit is estimated to be about 80 square feet. It drains the overflow from Bear Sink.

h) Hazel Sink (820-242-A) in Pasco County is about 250 feet in diameter. Just below the water surface the bottom slopes erratically toward the center. A circular opening about 100 feet in diameter near the center of the sink extends vertically from the irregular rim to a depth of 110 to 115 feet.

Miscellaneous Sinkholes

Some of these are listed as follows, but no attempt is made to make this a complete list:

a) Devil's Mill Hopper--Northwest of Gainesville--depth is approximately 115 feet--rock exposed in walls includes rock from the Vicksburg group and from the "Hawthorne" (sic) formation (Florida Department of Natural Resources--Second Annual Report, 1909).

b) Devil's Punchbowl--Northeast of Brooksville--a conical depression 100 feet in diameter and 50 feet deep (Florida Department of Natural Resources--Thirteenth Annual Report, 1921).

c) Kincaid Sinkhole--East of Bartow--125 feet in diameter and 100 feet deep; however, there is another 90 feet of water below the 100 foot depth. This indicates a total depth of 190 feet (Ardaman 1969).

d) Emerald Springs Sinkhole--Winter Park--360 feet in diameter and 55 feet in depth to a ledge and continues to about 500 feet in an hour glass shape. It is estimated to have occurred in 1880 (Orlando Sentinel, 1972). The water level is reported to be 40 feet below that of an adjoining lake (Ardaman, 1969). It is noted from separate sources that the overall depth of this sinkhole is approximately 300 feet or over (see Figure 4).

e) Little Salt Springs Sinkhole--Near North Port Charlotte--Reported to be of interest to archeologists and is estimated to be about 90 feet deep to a ledge and another 125 feet to the bottom. Date of origin unknown, but some bones removed from the sinkhole are estimated to be 10,000 years old (Orlando Sentinel, 1972).

f) There are other sinkholes mentioned previously in this study and 26 more are included in an analysis based on a sampling of sinkholes which were known to occur in Orange and Seminole Counties during the period 1961-1971 (inclusive). The analysis is in a subsequent section.

ANALYSIS OF RECENT SINKHOLES IN ORANGE AND SEMINOLE COUNTIES

General

This analysis is based on a limited sampling of sinkholes which have occurred in Orange and Seminole Counties during the eleven year period 1961-1971 (inclusive) as recorded by Ardaman and Associates, a consulting engineering firm specializing in soil sciences and materials testing, located in the Orlando area. As explained by the representative of the firm, this list may not be complete because it includes only those known by the firm as having occurred. Other sinkholes may have developed in this area during this period. A map was furnished with 27 sinkholes plotted thereon and information on date of occurrence and in some cases dimensions are given. See Figure 4. Based on this map and some supplemental data (Ardaman, 1969) and (Flawn, 1970) a tabulation was made to facilitate the analysis. See Table 2. The tabulation includes 26 sinkholes, all but one of these is on the map. Another one in Casselberry during 1965 is included as reported by Flawn (1970). Two of those on the map are not within the time frame of this study. Also very small sinkholes are neglected. The frequency of occurrence was studied and compared with the rainfall data and data on water table levels in an attempt to find if any correlation existed. There appears to be a reasonable correlation based on this limited sampling. However, caution should be exercised in reaching firm conclusions until broader samplings are made and findings reached.

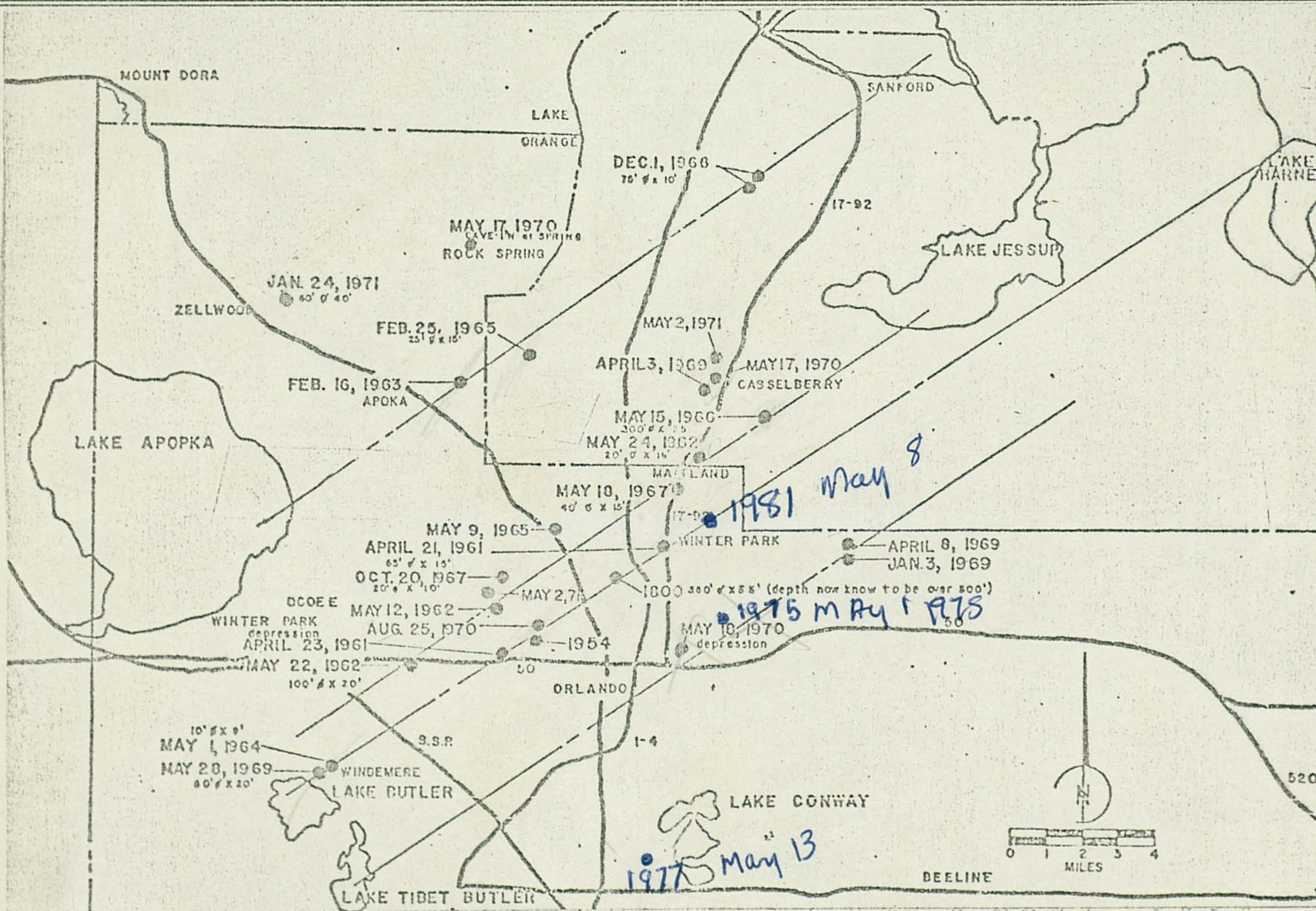

Fig. 4.--Map depicting recent sinkhole activity in Orange and Seminole Counties, showing date of occurrence and in some cases the size. This map is only a section of a larger map prepared by Ardaman & Associates, entitled, "Recent Sinkhole Activity and Their Orientation, Orange County, Florida." (undated)

TABLE 2

TABULATION OF SINKHOLES KNOWN TO HAVE OCCURRED IN ORANGE AND SEMINOLE COUNTIES

No.	Date	Location	Approximate Size Diam.	x Depth
(1)	April 21, 1961	Winter Park	65'	15'
(2)	April 23, 1961	Orange County(West)	Depression	
(3)	May 12, 1962	" " "	-	-
(4)	May 22, 1962	" " "	100'	20'
(5)	May 24, 1962	Seminole County	20'	16'
(6)	February 16, 1963	Apopka	-	-
(7)	May 1, 1964	Windemere	10'	9'
(8)	February 25, 1965	Seminole County	25'	15'
(9)	May 9, 1965	Orange County	-	-
(10)	May 15, 1965	Casselberry	80'	20'
(11)	May 15, 1966	Seminole County	300'	25'
(12)	December 1, 1966	" "	75'	10'
(13)	December 1, 1966	" "	75'	10'
(14)	May 18, 1967	Maitland	40'	15'
(15)	October 20, 1967	Orange County(West)	20'	10'
(16)	January 3, 1969	" " (East)	-	-
(17)	April 3, 1969	Casselberry	-	-
(18)	April 8, 1969	Orange County(East)	-	-
(19)	May 28, 1969	Windemere	50'	20'
(20)	May 17, 1970	Rock Spring	Cave in	
(21)	May 17, 1970	Casselberry	-	-
(22)	May 18, 1970	Orlando	Depression	
(23)	August 25, 1970	Orange County(West)	-	-
(24)	January 24, 1971	Zellwood	60'	40'
(25)	May 2, 1971	Casselberry	-	-
(26)	May 2, 1971	Orange County(West)	-	-

Above table compiled from data in map (see Fig. 4) obtained from Ardaman & Assoc. (Ardaman 1969). (Flawn).

Frequency

The frequency of occurrence of sinkholes during the period 1961-1971 is clearly illustrated in Figure 5 which shows 14 out of 26 sinkholes occurring in the month of May. The month with the next largest frequency is April and other months have either one, two or none. Based on this data 53.8 percent of the 26 sinkholes occurred in May. An effort was made to determine what if any correlation with water table levels exists for the same period.

Relationships to Water Level Tables

Record data on various wells was obtained from the U. S. Geological Survey Office in Winter Park, Florida, for review. The data included hydrographs of certain wells in different parts of Orange County. Some wells are in the Floridian aquifer and others in the non artesian aquifer.

The hydrographs show an irregular pattern during this period. For instance, the cycle of highs and lows within a given year appears to lose significance when there is an overall trend upward or downward over a period of several years. This is illustrated on the hydrographs for wells located in Southwest Orange County, near Lake Oliver. In comparing the hydrographs for two wells in this area, one in the Floridian aquifer and the other in the nonartesian aquifer, it was apparent that the patterns are similar for both. The patterns show a lowering trend from March, 1960, to December 1962, with intermittant peaks and valleys. The peaks are generally in the latter part of the third quarter or early part of the fourth quarter and the valleys are

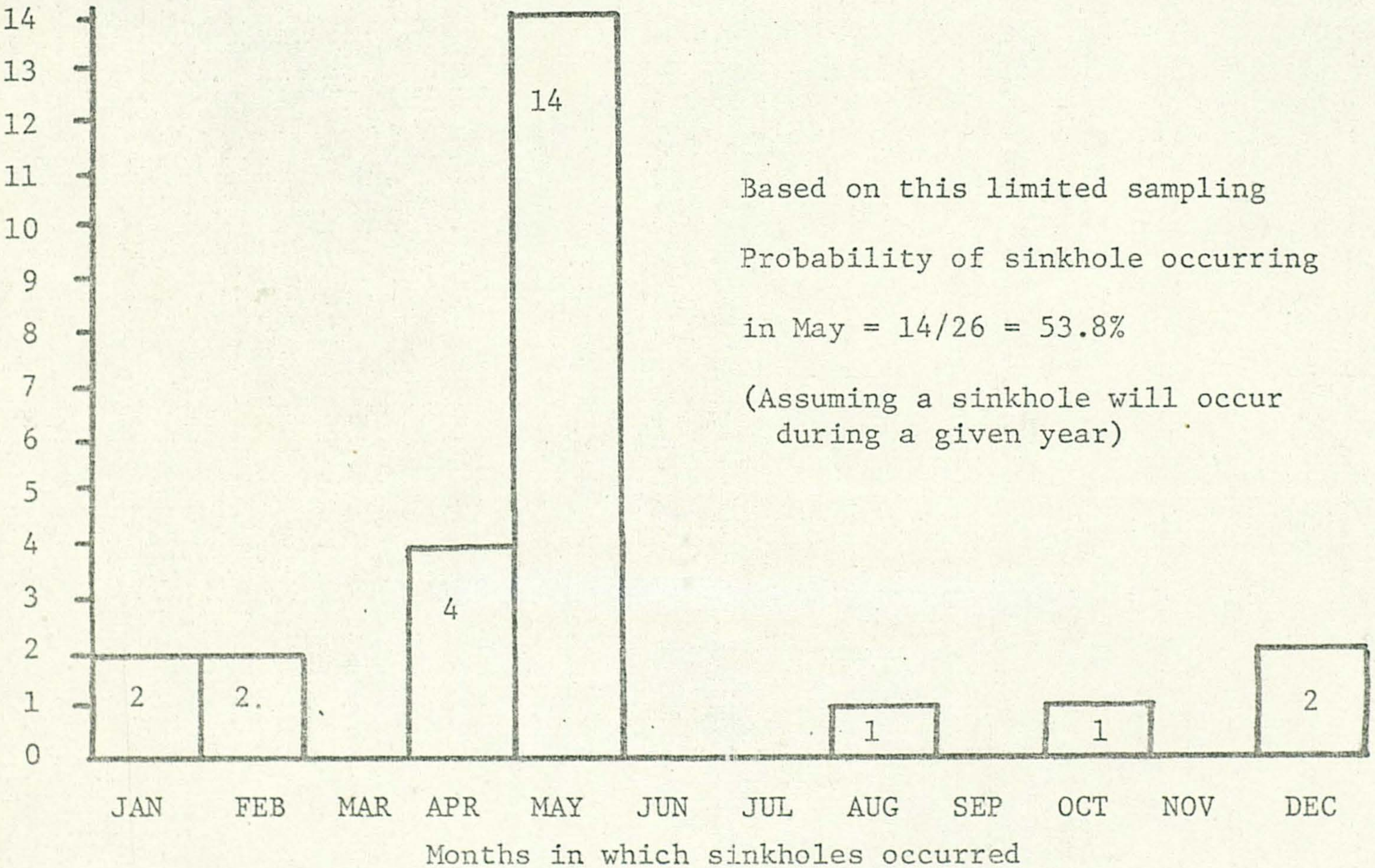

Fig. 5.--Histogram illustrating frequency of sinkhole occurrence based on a limited sampling of known sinkholes occurring in Orange and Seminole Counties during the period 1961-1971, inclusive. (Ref. Table 2 & Fig. 4)

usually in the second quarter. The level then trends upward until September of 1964, at which time it starts a downward trend until about April of 1968 and then starts another upward trend. The variations ranged only slightly more than five feet overall, for both wells. Another well, located four miles west of Orlando, dropped 20 feet from about September of 1960 to about June of 1962. It may be significant to note that two sinkholes occurred in the area west of Orlando in May, 1962. One of these was recorded as being 100 feet wide and 20 feet deep. The hydrographs discussed above are referenced under U. S. Department of the Interior, Geological Survey, 1961-1971.

In two wells near Orlando a comparison was made between rainfall and water levels. One well was artesian and the other nonartesian. The comparison shows a direct correlation and quick response of the water table to the amount of rainfall. The rainfall peaked at 12 inches above normal monthly average in July, 1960 and dropped below normal monthly average in October, 1960, and remained below average until July, 1962, except for a few months of very small above average rainfalls. They hydrographs of both wells show a dramatic drop from the latter part of 1960 to June of 1962. Both wells dropped about 20 feet during that period and showed a small peak in October in response to the above average rainfalls in July and September of 1962 (Florida Department of Natural Resources . . . Information Circular No. 48, 1966, p. 36).

In summary, the hydrographs studied appeared to be generally consistent in showing a distinct valley in April, May or June and a fairly consistent peak in September of each year. This seems to correlate with the frequency data discussed earlier.

Comparison with Rainfall Data

Rainfall data was obtained from the local Weather Bureau Office at Herndon Airport in Orlando Florida. The monthly averages for the eleven year period are generally consistent with the normal monthly averages as recorded to date by the weather bureau, with the exceptions as follows. The normal yearly average through 1971 was 51.37 inches, but the yearly average for the eleven year period was only 47.90 inches, a drop of 3.47 inches. (See Table 3.) The normal for February was 2.42 inches, but for this period it was 4.03 inches. The normal for April was 3.42 inches, but the average for this period was only 1.16 inches. Normally the two months recorded as having the lowest rainfall are November and December; but during the eleven year period the month of April was lowest of all. The rainfall peak in the normal average occurs in July with eight inches, but for the eleven year period it occurred in June with 7.72 inches. In summary, the rainfall is usually lowest at the end of the year and gradually increases to 3.57 inches in May (only 2.89 inches for this period). It then increases in June and generally levles off between six and eight inches through September when it drops off suddenly. It is difficult to draw valid conclusions based on rainfall data due to the many unknowns about what happens underground. Observations of data indicate that rainfall is relatively light from about November on. This appears to correlate with the low water table in May and with the high frequency of sinkhole occurrences in May (U. S. Dept. of Commerce, Environmental Data Service--1961-1971).

TABLE 3

TABULATION OF SUMMARY RAINFALL DATA, ORLANDO, FLORIDA, FOR COMPARISON OF NORMAL AVERAGE WITH AVERAGE FOR ELEVEN YEAR PERIOD

(From Records at WBAS--Herndon Airport)

	Months												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Normal Average (Thru '71)	2.00	2.42	3.41	3.42	3.57	6.96	8.00	6.94	7.23	3.96	1.57	1.89	51.37
Average For Period ('61-'71)	2.43	4.03	2.99	1.16	2.89	7.72	7.52	6.25	6.36	3.08	1.50	1.97	47.90

Above data expressed in inches of rainfall.

CAPABILITY OF PREDICTING SINKHOLE OCCURRENCES

General

There does not appear to be a reliable and feasible means of predicting when or where sinkholes are likely to occur. There seem to be too many unknowns. Ability to locate caverns from the surface would be very helpful in this regard. Drilling is effective but it only provides data on that precise location and a cavern could exist a few feet away. Where underground networks exist they are usually so irregular in their pattern that it is difficult to locate them. Therefore, drilling is not a practical solution for detection although it will confirm the existence of caverns detected by other means. Some other means are being studied. They include application of microwave technology and infrared imagery and study of fracture patterns and geological features.

Microwave for Detecting Caverns

Kennedy (1968) made a study in California to test his theories on use of microwave to detect subsurface voids. He selected an area of known karst topography which had been surveyed. His object was to have another means of verifying his findings. He did have some success in locating caverns 12 to 60 feet below the surface in soil containing 26 percent moisture, but he concluded that the surveys do not establish that microwave radiometry can uniquely identify subsurface voids. He pointed out that factors such as surface roughness and soil moisture can cause radiometric temperature anomalies.

Richer (1970) commented on Kennedy's paper and did not agree that microwaves can penetrate 12 to 60 feet of damp soil. He suggests

that the cold temperatures measured over the cave areas is a surface moisture and slope phenomenon rather than that of penetration.

Infrared Imagery

Sabins (1969) reviewed the technology of thermal infrared imaging and presented a previously unpublished example of imagery that provides more geological information than existing aerial photography. He discusses techniques and shows maps illustrating results. Sabins concluded that Infrared imagery provides valuable information about the thermal characteristics of the surface of the surface of the earth and that the example described in the article has greater contrast and resolution than conventional aerial photography. He does not suggest it as a replacement for aerial photography.

Fracture Patterns and Existing Sinkholes

Fracture patterns are useful in analyzing probable areas of future sinkhole activity; however, they should be used with caution. They are not true indicators of probable sinkhole activity, but may be helpful in supporting opinions based on other data. They are usually prepared by qualified geologists using aerial photos. Features are studied and based on certain indications found, fracture lines are plotted. The process is often repeated by other qualified geologists until a reliable set of fracture lines are developed. They usually occur in pairs, with two lines intersecting each other. Some professionals are of the opinion that these fracture patterns can be used to determine the probable line of future sinkhole development in an area with recently developed sinkholes. This method should be used with

caution because of the various directions possible. For instance, existing sinkholes could be lined up parallel with either set of fracture lines or with intersections of fracture lines. An example of a fracture pattern in Central Florida is shown in Figure 6. Orange and Seminole Counties are emphasized.

Special Features

There is insufficient data on which to conclude that sinkhole activity can be predicted using knowledge of certain geographical features. However, there are fairly good indicators which are useful in comparing probabilities of one region to another. This is generally observed in studying the map in Figure 7 and the larger map from which it was taken. (See U. S. Department of Interior--Geological Survey, Map, "State of Florida", 1967.) Such a map would be of limited detailed value in assisting with sinkhole prediction. Its application appears to be more appropriately applied to regions than to precise locations. The map and the definitions of the areas as shown do indicate that some areas are more likely to have future sinkhole activity than others.

Some of the more readily identifiable features which may be useful in assessing relative probabilities of sinkhole occurrence are:

a) Loose porous sandy soil providing access to limestone.

b) Piezometric level below the surface.

c) Overburden over the limestone less than or equal to 100 feet.

d) Recent sinkhole activity.

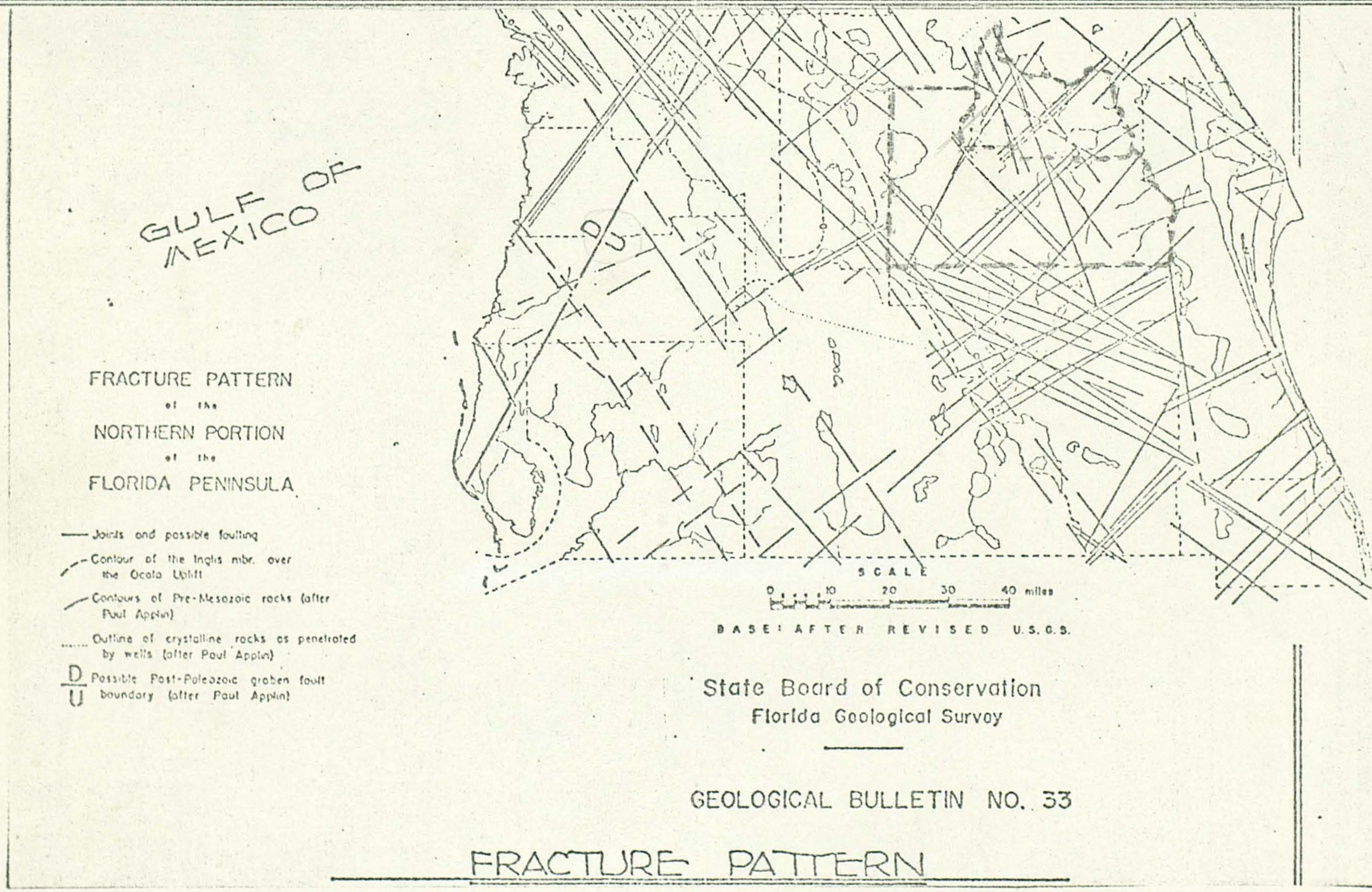

Fig. 6.--Section of a map depicting "fracture pattern" in Central Florida. Taken from larger map furnished by Ardaman & Associates, which is based on a map prepared by the State Board of Conservation, Florida Geological Survey - Geological Bulletin No. 33. (1951)

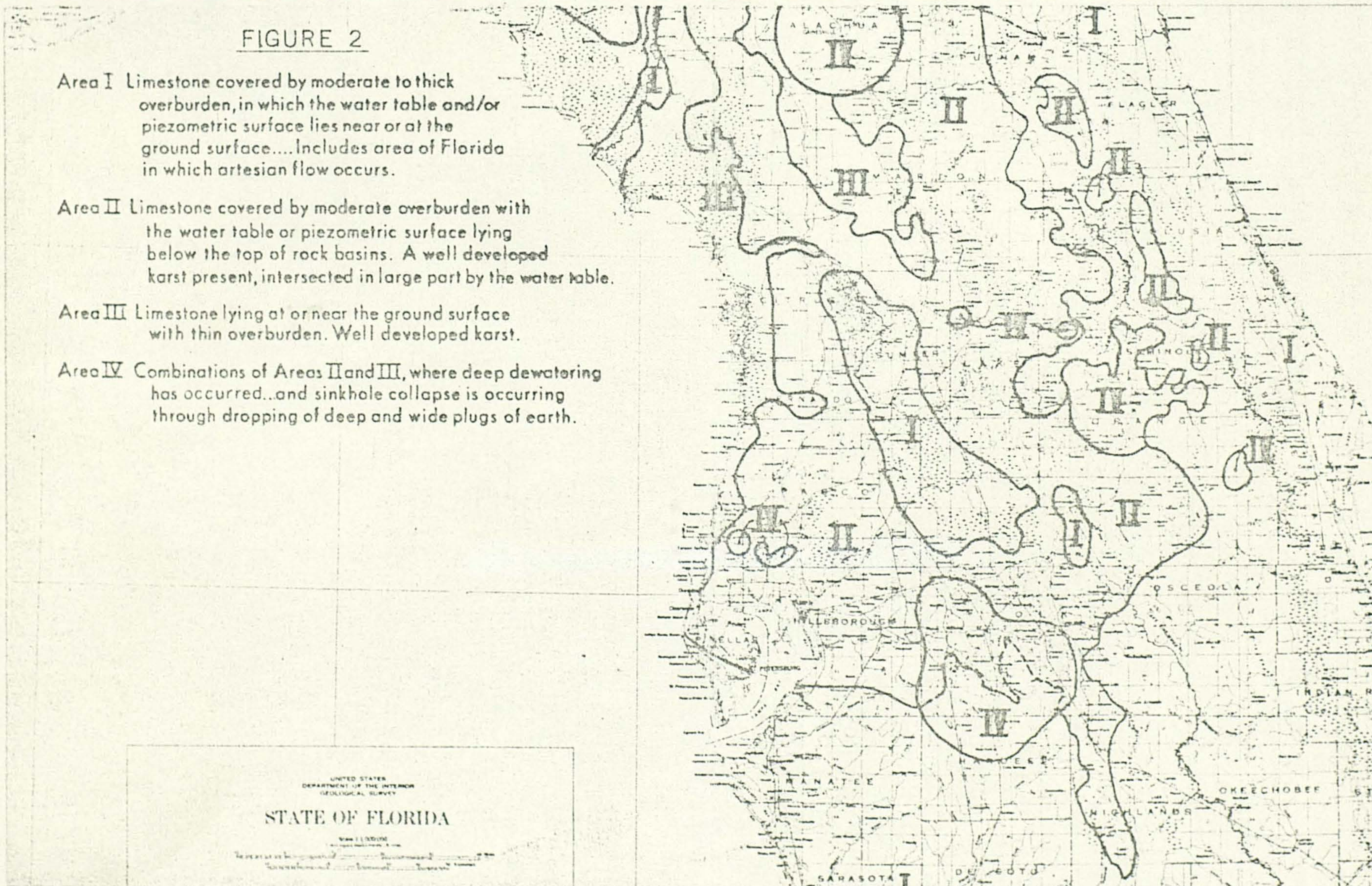

Fig. 7.--Section of a map of the State of Florida, modified to show areas of karst activity in relation to certain geologic features. Print from which this map was taken was furnished by the Florida Bureau of Geology. As shown, the original map was prepared by the U. S. Geological Survey.

When the above indicators are combined with significant lowering of the water table, the probability of sinkhole occurrence is assumed to be relatively high.

CONCLUSIONS

The conclusions reached based on material researched and analysis of data are summarized as follows:

a) Sinkholes do have adverse effects on man's environment as well as some good effects.

b) There is not sufficient data collected and available for study to provide the depth of knowledge required to substantially reduce the adverse effects of sinkholes on man's environment in Florida.

c) Professional opinions on sinkhole behavior, except for certain basic fundamentals, are stated with much caution.

d) Some fundamental principles are known and generally agreed upon concerning how caverns are formed and various ways in which sinkholes can occur.

e) Little is known on how to reliably detect existence of underground caverns and determine size and shape.

f) There appears to be a correlation between water table levels and sinkhole occurrences.

g) Substantially more sinkholes occur in May than in any other month, based on data in Central Florida.

h) Recharge of aquifers through existing sinkholes is vital to maintaining adequate water table levels in Central Florida.

i) Lowering of water tables can increase likelihood of sinkhole activity.

RECOMMENDATIONS

The following recommendations are made based on the research conducted and the findings:

a) One single agency, preferably a State agency, utilizing geologists and engineers, be given responsibility for:

i) Collecting all known data on existing and future sinkholes.

ii) Compiling and analyzing the data continuously.

iii) Categorizing sinkholes by type and probable cause.

iv) Publishing documentation on findings periodically and making it readily available.

b) Measures be studied to control drainage and disposal of wastes into sinkholes in order to reduce possibility of contamination.

c) Further continuous research be undertaken by qualified geologists and engineers. Examples of the topics for the research include:

i) Analyze geological features and determine which most likely indicate high probability of sinkhole activity.

ii) Compile comprehensive listing of known sinkholes and note significant features.

iii) Analyze frequency of occurrence of recent sinkholes and predict future trends.

iv) Study effects of artesian and nonartesian water table levels and their relationships to sinkhole activity.

v) Determine trends in water table levels, based on all known data available.

vi) Determine extent to which sinkholes are being used for disposal of contaminants, including organic wastes, chemical wastes, and toxic wastes (including pesticides).

vii) Study techniques for predicting sinkhole occurrence.

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