

KARST HYDROGEOLOGY
IN THE
UNITED STATES OF AMERICA

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21st Congress of the International Association of Hydrogeologists
Karst Hydrogeology and Karst Environment Protection



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by Dallas L. Peck, Joseph W. Troester, and John E. Moore

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ABSTRACT

Karst hydrogeology has been the subject of much study in the United States. About 15 percent of the conterminous United States has carbonates, gypsum, or other soluble rocks at the land surface. Dissolution of these rocks has formed karst topography at the surface and karst features in aquifers that are a major source of drinking water. Carbonate aquifers, however, are commonly vulnerable to contamination from the land surface. In 1985, about 25 million cubic meters of water per day was withdrawn from carbonate aquifers in the United States. Three fields of current karst research in the United States are water-resources management, sinkhole formation, and carbonate geochemistry and geomorphic consequences. Examples of karst fields where these areas of research are continuing, include Alabama, Florida, and Puerto Rico.

INTRODUCTION

The United States Geological Survey (USGS) strongly promotes participation in international meetings, such as this Congress in Guilin. At these meetings, USGS scientists learn new techniques from their colleagues and they share the results of their latest research with others. USGS scientists work closely with other earth scientists worldwide to improve understanding of natural resources, so that the resources can be developed for the benefit of mankind, and at the same time, be protected for future generations. Hydrology of karst terrane and karst-environment protection are a major subject of study in the United States mainly because of the importance of carbonate aquifers associated with karst.

The geographic setting of the United States is similar to that of China (fig. 1). In general, the two countries are about the same size and roughly lie in the same latitudes. Because of this, it might be expected that problems associated with karst areas are similar in both countries (Yuan, 1987).

About 15 percent of the conterminous United States has carbonate, gypsum, or other soluble rocks at or near the land surface. Karst areas are widespread in the United States, and can be regionally categorized as follows (LeGrand and others, 1976): (1) the carbonate rocks in the Tertiary Coastal Plain in South Carolina, Georgia, Florida, Alabama, and the northern coast of Puerto Rico; (2) the folded belt of carbonate Paleozoic rocks from Pennsylvania to Alabama; (3) the nearly flat-lying carbonate Paleozoic rocks in Alabama, Tennessee, Kentucky, Ohio, Indiana, Illinois, Wisconsin, and Missouri; (4) the carbonate Cretaceous rocks in Texas; (5) the evaporite-bearing and carbonate Permian rocks in New Mexico; and (6) the carbonate Paleozoic rocks in South Dakota and Wyoming. In addition, there are other scattered karst areas of various ages in the Western United States. The generalized distribution of these regions is shown in figure 2. Because of the wide differences in climate and topography across the United States, the karst regions have a broad range of topographic and hydrologic features (LeGrand and others, 1976).

The exposed karst areas of the United States have long been recognized as fragile environments that are vulnerable to degradation by man's activities. These areas are characterized by the constraints of thin soils, marked differences in the availability of water supplies, and susceptibility to ground-water contamination inherent in karst areas throughout the world. However, for various hydrogeologic and demographic reasons, the United States has not been forced to deal with many complex environmental and engineering problems that occur in many karst regions of the world. For example, even though deforestation has caused soil erosion in many parts of the United States, the country has not suffered the consequences of extensive denudation, such as has occurred in parts of China and in areas around the Mediterranean Sea. The limited extent of economic mineral deposits in carbonate rocks has not necessitated extensive dewatering of aquifers, such as is done for bauxite mining in Hungary. The lack of high elevation and high relief of most of the carbonate areas of the United States prevents catastrophic flooding, such as that which occurs in the Dinaric karst of Yugoslavia. The United States does not have dam sites that cause problems in construction of large hydroelectric projects in permeable carbonate rocks, such as in Turkey. Lack of high karstic mountains eliminates the need for construction of tunnels and underground dams for flood prevention and the interbasin transport of water, such as in France and China.

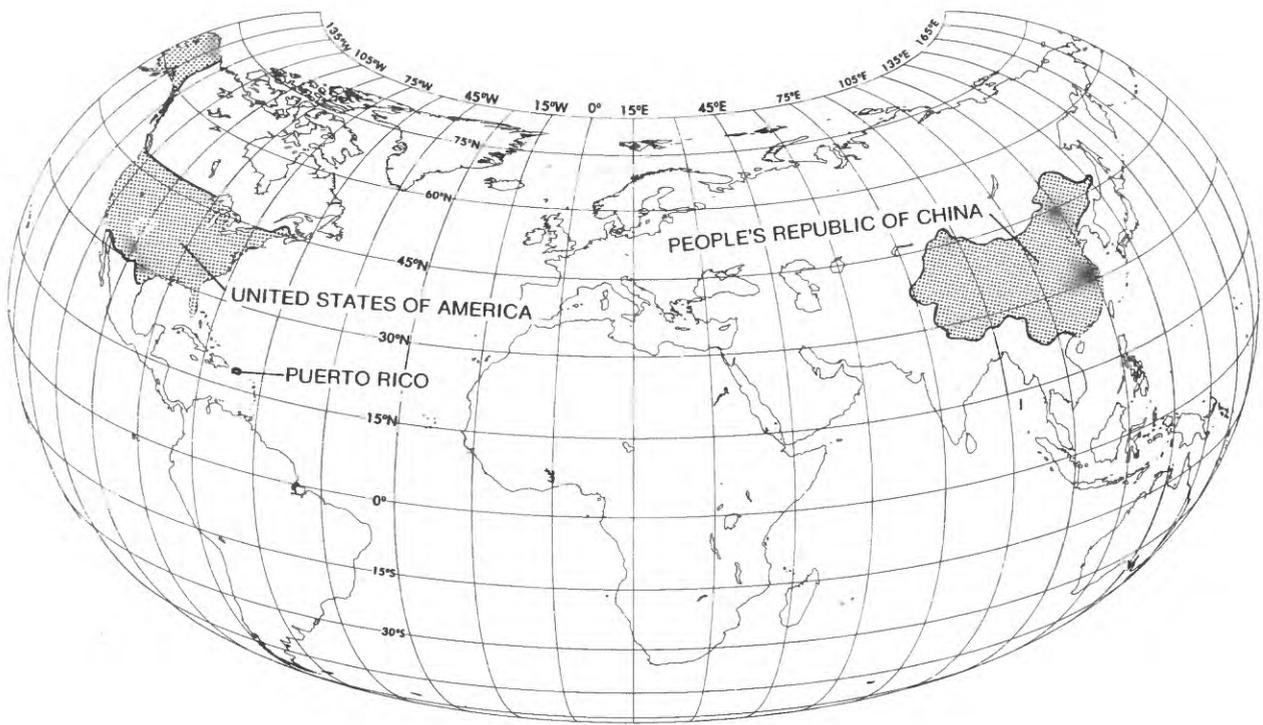


Figure 1. World map showing the similarities in size and latitudes of China and the United States.

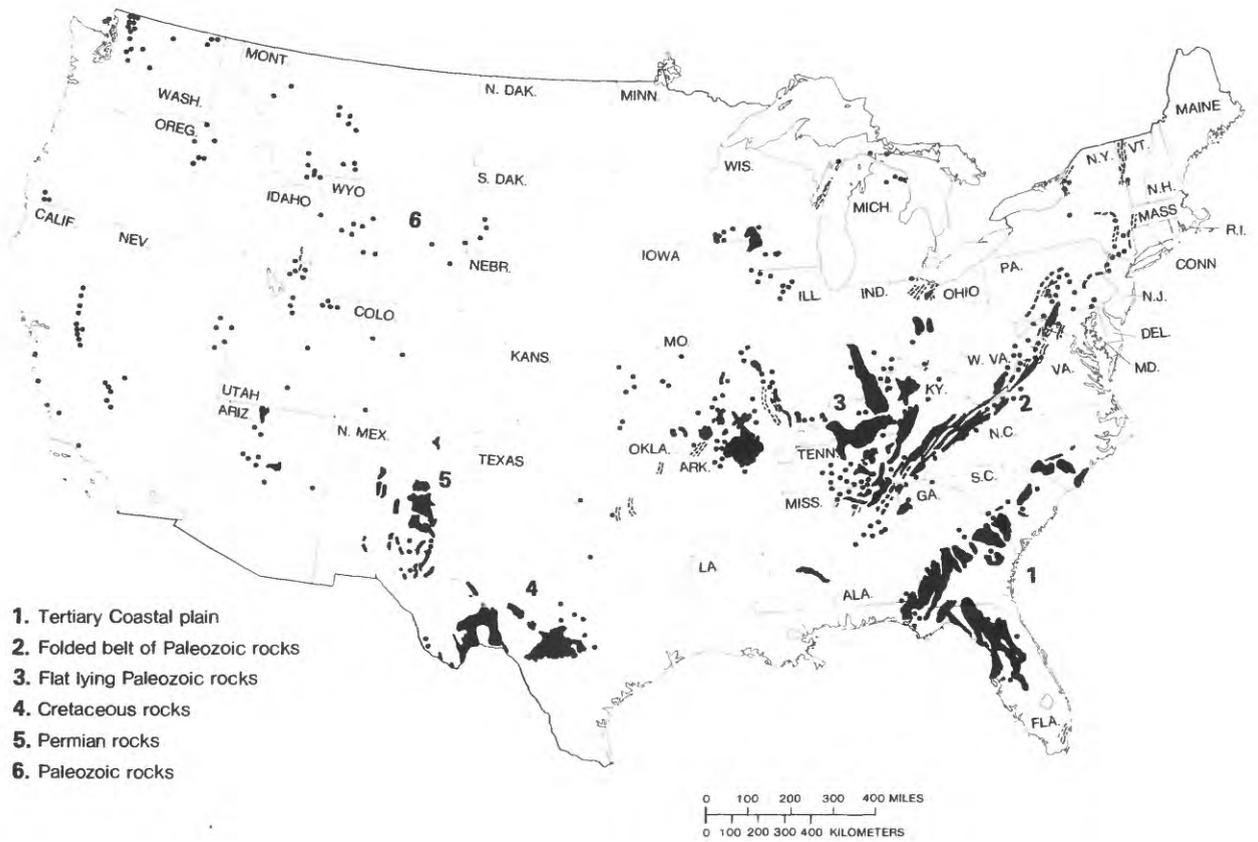


Figure 2. Map showing the general distribution of karst areas of the United States (U.S. Geological Survey, 1970).

Because of the United States' relatively fortunate circumstance, most of the work done by the USGS in hydrology of carbonate rocks has focused on evaluation of geologic factors that control the occurrence, movement, and chemical character of water for water supplies and management of wastes.

One significant environmental problem associated with karst in the United States is the formation of sinkholes. This problem has increased in response to population expansion and relocation. Because of the relatively minor geographic extent of exposed or thinly-covered karst regions, these areas have tended to remain largely rural. Increased urbanization in karst areas is now drawing attention to the problem of sinkhole formation. In particular, the development of additional water supplies, installation of water-supply and sewer lines, and construction of foundations for high-rise apartments and offices requires site evaluation of the susceptibility for sinkhole formation.

Industrial and municipal expansion in karst areas also draws attention to the problem of ground-water contamination and waste disposal. In some karst areas waste is being disposed through deep-well injection; the environmental consequences of this activity is largely unknown at the present time. In all karst areas, increased pressure for suitable waste disposal sites requires definition of regional and local flow systems as potential pathways of waste migration.

Rather than trying to summarize research on all karst hydrogeology in the United States, this paper emphasizes current activities of karst research conducted by the USGS on (1) water-resource management, as exemplified by work done in Florida, (2) development of sinkholes, based on work done in Alabama, and (3) geochemistry of ground water and its geomorphic consequences, as demonstrated by work done in Puerto Rico.

SELECTED RESEARCH TOPICS ON KARST HYDROGEOLOGY IN THE UNITED STATES

Water-Resources Management

The USGS has conducted numerous investigations that provide hydrologic information needed for water-resources management in karst areas. One such series of investigations is the Regional Aquifer-System Analysis (RASA) Program that evaluates and analyzes the Nation's important aquifers, including near-surface and deep carbonate aquifers. This program uses computer simulation based on observed data to determine recharge and discharge areas, quantify ground-water flow, assess changes in water chemistry along flow paths, and predict aquifer response to changes in ground-water development. Other aspects of the investigations involve use of tracers, isotopes, and other geochemical means for field determination of ground-water flow velocity, ground-water recharge and discharge areas, and understanding mechanisms of formation of sinkholes and other karst features affected by human activities.

The major carbonate aquifer systems investigated as part of the RASA Program are shown in Figure 3. These aquifer systems are important sources of ground-water supply in the United States. In 1985, about 9 percent (25 million cubic meters per day) of ground-water withdrawals in the United States came from carbonate aquifers. Some of the largest withdrawals were from carbonate aquifers in Florida.

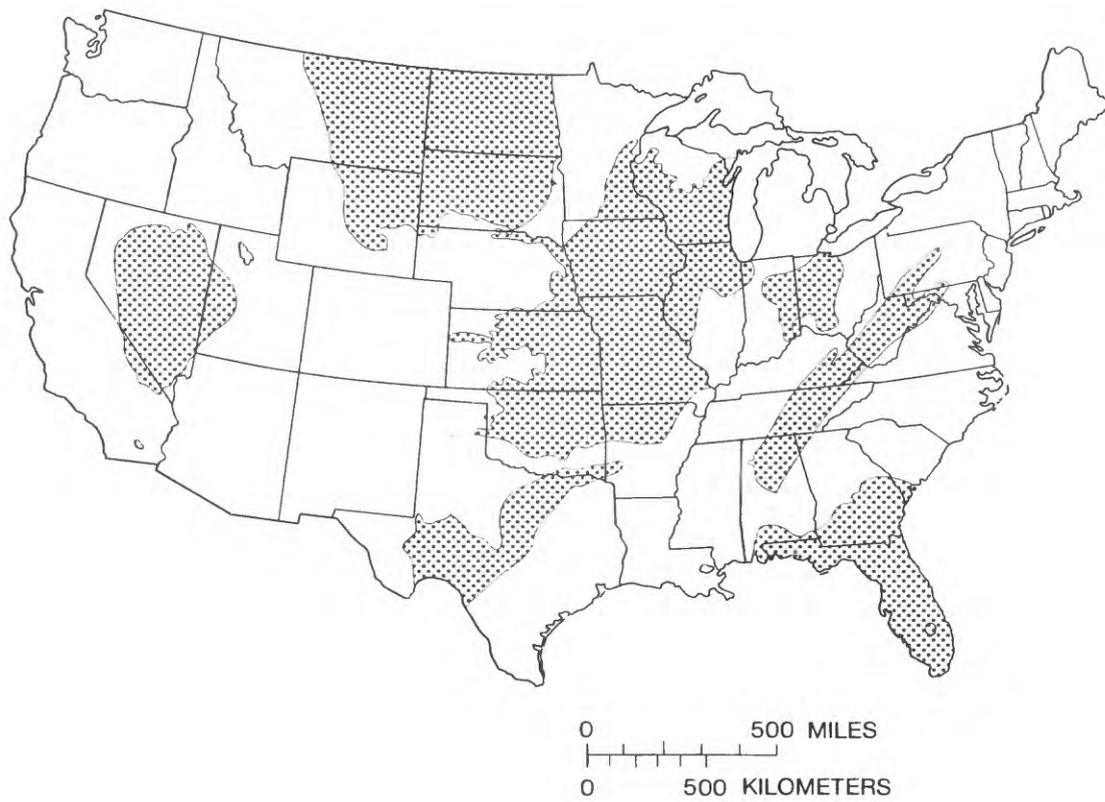


Figure 3. Regional Aquifer System Analysis (RASA) study areas where carbonate rocks are important aquifers.

Florida is on the eastern Coastal Plain of North America. The Coastal Plain generally has low relief and is almost completely mantled by unconsolidated to poorly consolidated sediments that overlie a 3,500-foot-thick sequence of limestone and dolomite. This sequence of carbonate rock comprises the Floridan aquifer system (fig. 4), which is one of the most productive sources of water in the United States. The system extends across all of Florida and parts of several adjacent States (Johnston and others, 1986; Johnston and Miller, 1988). At the southern end of the Florida Peninsula, the Floridan aquifer contains saline water.

Florida has abundant ground-water resources available from the carbonate aquifers in most parts of the State. The State also has 27 of the 78 springs in the United States that discharge more than 3 cubic meters per second (Heath and Conover, 1981, p. 131). Because of its abundance and availability, ground water accounted for more than half the 320 cubic meters per second of freshwater used in Florida in 1985. About 90 percent of Florida's population depends on ground water for its drinking water. In 1985, Florida ranked sixth among all States in total fresh ground-water withdrawals (Solley and others, 1988). Withdrawals of ground water continue to increase, because of the State's growing industry and growing population.

Ground-water withdrawals have exacerbated sinkhole development, lowered water levels below land surface or below sea level, diminished flow of springs and size of wetlands, and caused seawater intrusion in parts of Florida. These problems, which principally occur in urban coastal areas, have led to implementation of water management alternatives for development and protection of ground-water resources in the State of Florida.

The USGS, in cooperation with state and local agencies, has studied the carbonate Floridan aquifer since the early 1900's and has produced more than 350 reports on ground water in Florida. The USGS currently produces a potentiometric surface map of the entire Floridan aquifer annually (Barr, 1987). From these data and maps, the USGS documents the changes that occur as a result of increasing development, calibrates and verifies computer ground-water models, and assesses potential effects of future development on the carbonate aquifer.

Because of the importance of ground-water resources and the vulnerability of the carbonate aquifers to contamination, waste-disposal alternatives are intensively studied in Florida. The USGS has evaluated deep-well injection of wastes into the saline part of the Floridan aquifer in the northern, west-central, and southeastern parts of the State (Miller, 1979; Hickey, 1982; Meyer, 1984; Hickey and Vecchioli, 1986). At one site near Pensacola, in the northwestern part of the State, highly acidic liquid waste has been injected below a thick clay confining bed since 1963 (Vecchioli, 1979). Since then, there has been no measurable migration of these wastes into overlying freshwater zones. Other waste-injection sites have also been operating for shorter periods of time, but again no measurable migration of waste has been observed.



Figure 4. Hydrogeologic map of Florida (U.S. Geological Survey, 1985).

Sinkhole Formation

Another field of current research on karst environmental problems concerns the mechanism of sinkhole formation. A map from a recent study in the Eastern United States (Newton, 1987) identifies more than 850 areas of active sinkhole formation (fig. 5) having more than 6,500 associated sinkholes or related features. Most of the sites are in the Southeastern United States. Few sinkhole problems are present in the Northeast because the soluble carbonate rocks there are mantled by thick glacial deposits. The total cost of damage and associated protective measures from sinkholes in the United States is estimated to be tens of millions of dollars annually. Although sinkhole formation is widespread, comprehensive research related to this problem has been done by the USGS mainly in Alabama (Newton, 1984 and 1987; Newton and Tanner, 1987). In Alabama, carbonate rocks are present in both the coastal plain aquifers and in the Floridan aquifer (fig. 6). Carbonate rocks of Paleozoic age also are present in northern Alabama, where most of the sinkholes in the State are found.

Sinkholes occur naturally or may be induced by man's activities. They result suddenly from the collapse of a cave or cavity roof, or gradually from the downward migration of water through unconsolidated deposits into solutionally enlarged openings in the underlying rock. The number of sinkholes that result from roof collapses is small in comparison with sinkholes that result from downward migration of water through unconsolidated deposits.

Induced sinkholes result from either water-level declines associated with ground-water withdrawals or from construction. Sinkholes resulting from water-level declines are caused by loss of buoyant support in the soil zone, increase in erosion of soil particles caused by water percolating through the soil, water-level fluctuations, and induced recharge (fig. 7). Most induced sinkholes that result from construction are caused by the diversion of surface drainage to areas underlain by rocks containing solution cavities. Sinkhole formation mechanisms also include loading, soil saturation, and piping of water through the soil zone.

Assessment of existing or potential sinkhole problems requires recognition of features associated with sinkhole development and knowledge of causative mechanisms. Natural sinkhole development generally is not predictable. In some instances, induced sinkhole development that result from dewatering quarries and mines by wells is predictable, but only in the sense that it may occur in a particular area. Obviously, the exact time and location of sinkhole formation is difficult to predict.

The USGS has identified some actions which can help avoid sinkhole formation. These include thorough site evaluation, management of ground-water withdrawals, and control of surface runoff (Newton, 1984 and 1987). The number of alternatives that minimize development of sinkhole hazards is largest when a problem or potential problems are recognized during site evaluation. The number of alternatives is less after development begins. Where sinkhole development is probable, zoning of land use can be used as a management alternative.



Figure 5. Map showing areas of active sinkhole development in the Eastern United States (Newton, 1987)

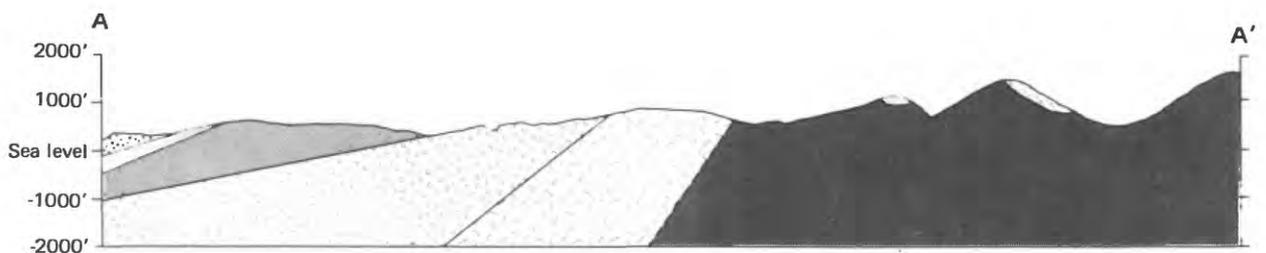
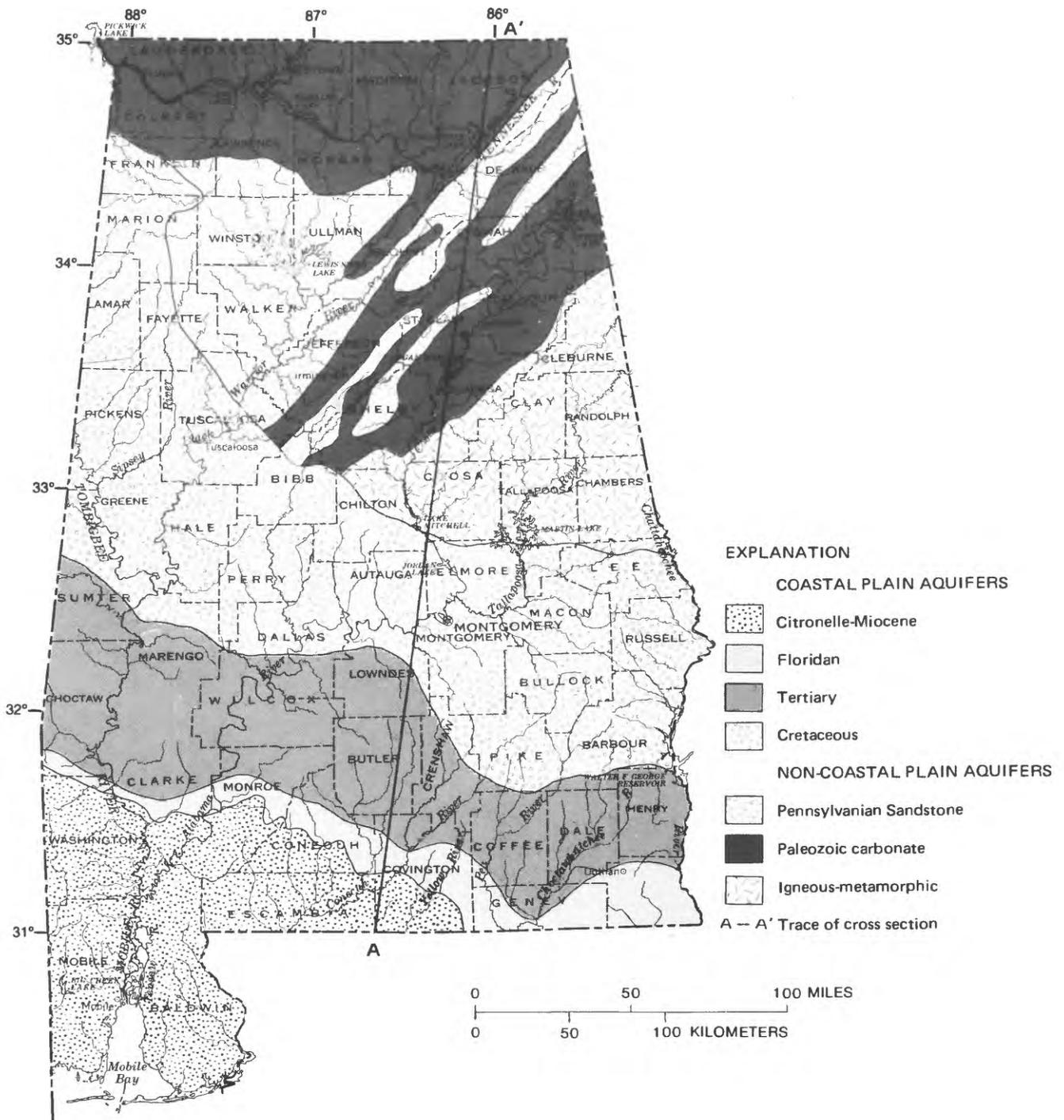


Figure 6. Hydrogeologic map of Alabama (U.S. Geological Survey, 1985)

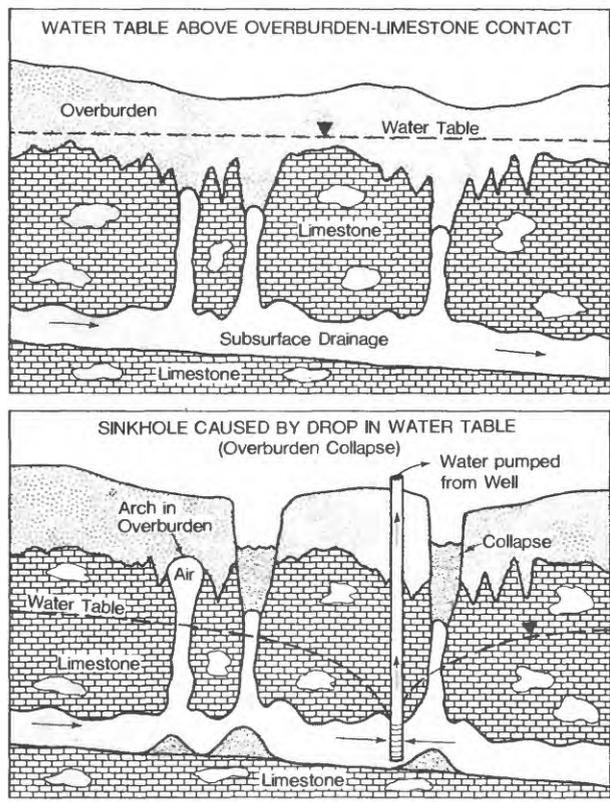


Figure 7. Schematic cross sections of karst terrane showing water-level decline and resulting sinkhole development (U.S. Geological Survey 1986).

Carbonate Geochemistry and Geomorphic Consequences

Because the solubility of the carbonate rocks is the basic physical characteristic of karst terranes, geochemical reactions have a more dominant role in the geomorphic development of karst terranes than in terranes of other lithology. The amount of dissolution and rates of reactions are the primary factors that control the development of karst features. Solubility of carbonate rocks is being studied by the USGS in laboratory experiments, by theoretical analyses, and in field investigations. Laboratory experiments are being done to determine the rate of dissolution of carbonate minerals (Plummer and others, 1978). Rates of dissolution are being incorporated into geochemical models, such as those developed by Plummer and others (1983), to determine rates of dissolution of caves and other karst features, and to determine rates of precipitation of calcareous deposits. Laboratory-determined rates of dissolution also are being evaluated and verified by use of carbon-14 analyses in field investigations. Information on the ages of water determined by carbon-14 analysis combined with hydraulic-gradient data can be used to determine (1) the velocity of ground-water flow, and (2) the time that the water has been in contact with the rocks. Similarly, chemical analyses of water can be used to determine the quantity of dissolved constituents and, therefore, the quantity of calcite dissolved during the time that ground water moves from areas of recharge to areas of discharge.

To understand the controls of ground-water geochemistry on dissolution of limestone and formation of karst landforms, researchers are using ion-speciation models, such as WATEQ (Truesdell and Jones, 1974) and its various modified versions (Plummer and others, 1976, Ball and others, 1980). These computer models calculate the concentrations of all ion species in solution and the saturation indexes of minerals to determine which minerals are dissolving and which are precipitating. The models are used to calculate the saturation index of calcite and the partial pressure of carbon dioxide in equilibrium with the water, which are two of the most useful parameters to help explain karst processes.

Much research on the geomorphic consequences of these geochemical reactions in the karst areas of Puerto Rico has been conducted. Because of the geologic conditions and the climate, many classic karst features are more developed in Puerto Rico than in other parts of the United States.

Puerto Rico, a Commonwealth of the United States, is an island 1,600 km east-southeast of Florida (fig. 1). Limestone underlies about 25 percent of the island; the remainder of the island is mostly underlain by volcanic and volcanoclastic rocks. The largest area of limestone is along the northern coast of the island (fig. 8). These middle Tertiary rocks dip gently northward and compose the northern karst belt (Monroe, 1976 and 1980) and the North Coast limestone aquifer (Giusti, 1978). The area, which has a wet, tropical climate (average annual precipitation is about 2,000 mm and average annual temperature is about 25° C), contains some of the most spectacular tropical karst landforms in the western hemisphere, including cone karst and tower karst areas. Cone karst (also known as Kegelkarst and cockpit karst) is characterized by many closely spaced cone- or tower-shaped hills separated by deep sinkholes and little level ground. Tower karst (also known as Turmkarst and mogote karst) is characterized by isolated limestone hills separated by areas of alluvial deposition.

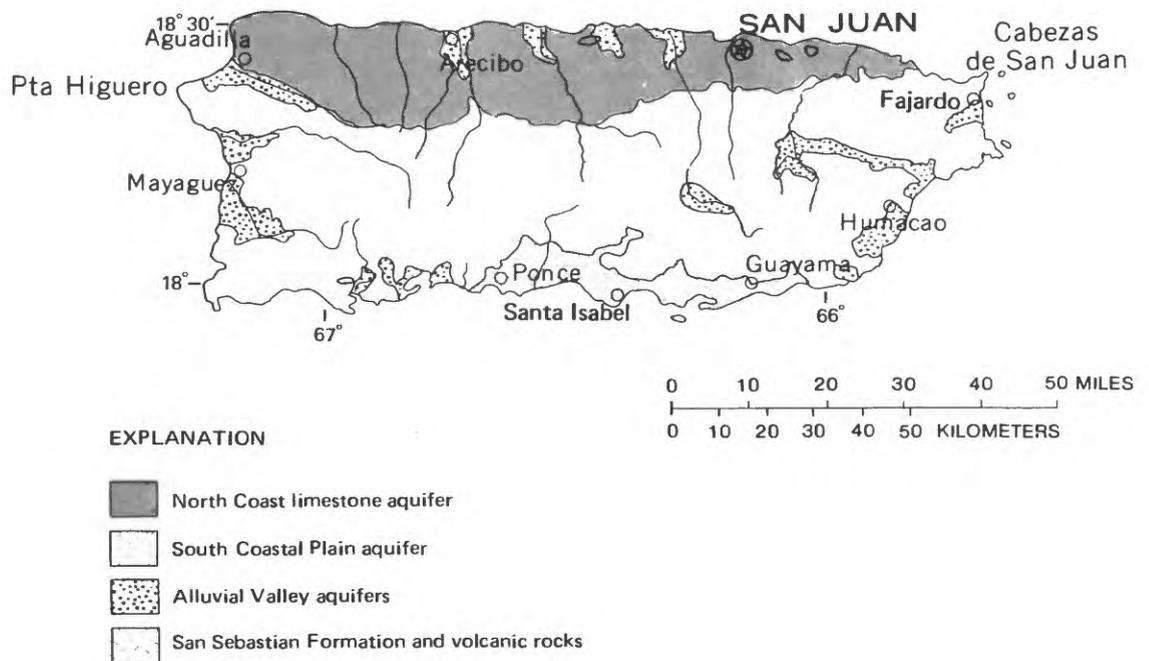


Figure 8. Hydrogeologic map of Puerto Rico (U.S. Geological Survey, 1985).

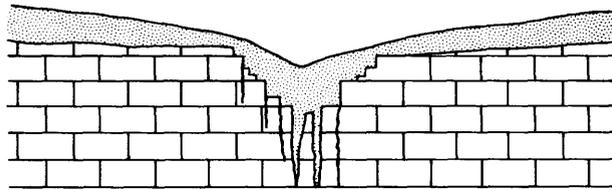
These landforms are distinctively different from other karst areas in the United States, both in scale and shape (White, 1984; Troester and others, 1987). For example, the average depth of sinkholes in Kentucky near Mammoth Cave is 5.4 meters, whereas the average depth of sinkholes in the northern karst belt of Puerto Rico is 19 meters (Troester and others, 1984). Figure 9 shows some of the differences between a typical sinkhole in a temperate climate area and a typical sinkhole in a tropical climate area. Sinkholes in temperate areas are usually more shallow and have a more complete soil cover than sinkholes in tropical areas. Sinkholes in tropical areas are deeper and have steeper slopes and less or no soil on the sides of the sink than those in temperate areas.

At one time it was thought that the great depths of sinkholes in tropical areas were due to high concentrations of carbon dioxide in soils. However, the calculated partial pressure of carbon dioxide in equilibrium with water from monthly samples of springs and measurements of carbon dioxide in the atmosphere of caves (Troester and White, 1984, and 1986) in karst areas with different climates indicates that the concentration of carbon dioxide in soils in tropical areas is similar to those in temperate areas. However, the part of the year when carbon dioxide in soil is available to form carbonic acid and, thus, to dissolve limestone, is greater in tropical areas than in temperate areas. This difference in the availability of carbon dioxide, combined with torrential tropical rains is sufficient to cause greater dissolution of limestone in tropical areas compared to temperate areas (White, 1988).

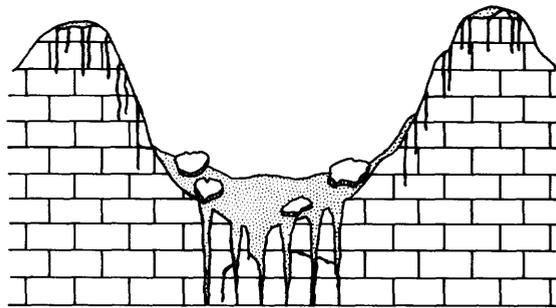
A LOOK TO THE FUTURE

Research in karst hydrogeology will continue in the United States because of the importance of carbonate aquifers as sources for water supply and because of the high vulnerability of these aquifers to contamination from surface sources. The widespread reliance on karst aquifers for water supply is commonly accompanied by problems of water-level declines, increased potential for saline-water intrusion, and increased concerns about potential contamination. Although the demand for waste-disposal sites is competitive with the need for water supply, research in the engineering geology of karst sinkhole development and research on the geochemistry and formation of karst features have proceeded somewhat more rapidly than that on water-supply management; the results of these research efforts are extremely useful in identifying potential contamination mechanisms and probable paths of contamination movement in karst terrane.

These research efforts will continue in the future but will be based on a more interdisciplinary approach. The advent of powerful, computer-based geographic information systems and the development of data display techniques on supercomputers will enhance the researcher's capabilities to use results on ongoing research outside of their principal field of expertise. The formation of teams with multidiscipline scientific expertise to investigate processes in all the earth sciences, including karst, will allow the USGS to focus results from these fields to help solve problems attendant to development in karst. In the future, as in the past, the USGS role will be to concentrate on process research and National programs, while cooperating with local authorities to provide the scientific basis for solving specific problems.



TEMPERATE CLIMATE SINKHOLE



TROPICAL CLIMATE SINKHOLE

Figure 9. Schematic cross sections of typical sinkholes in temperate and tropical climates.

REFERENCES

- Ball, J.W., Nordstrom, D.K., and Jenne, E.A., 1980, Additional and revised thermochemical data and computer code for WATEQ2--A computerized chemical model for trace and major element speciation and mineral equilibria of natural waters: U.S. Geological Survey Water-Resources Investigations 78-115, 109p.
- Barr, G.L., 1987, Potentiometric surface of the Upper Floridan aquifer in Florida, May 1985: Florida Bureau of Geology Map Series No. 119, scale 1:2,000,000.
- Giusti, E.V., 1978, Hydrogeology of the karst of Puerto Rico: U.S. Geological Survey Professional Paper 1012, 68p.
- Heath, R.C., and Conover, C.S., 1981, Hydrologic almanac of Florida: U.S. Geological Survey Open-File Report 81-1107, 239p.
- Hickey, J.J., 1982, Hydrogeology and results of injection tests at waste-injection test sites in Pinellas County, Florida: U.S. Geological Survey, Water-Supply Paper 2183, 42p.
- Hickey, J.J., and Vecchioli, John, 1986, Subsurface injection of liquid waste with emphasis on injection practices in Florida: U.S. Geological Survey Water-Supply Paper 2281, 25p.
- Johnston, R.H., Bush, P.W., and Miller, J.A., 1986, Hydrology of the Floridan Aquifer System: in Vecchioli, John, and Johnson, A.I, eds., Regional Aquifer Systems of the United States, Aquifers of the Atlantic and Gulf Coastal Plain: American Water Resources Association Monograph Series no.9, p.153-166.
- Johnston, R.H., and Miller, J.A., in press, Carbonate aquifers of the southeastern United States: Geologic Society of America, DNAG (Decade of North American Geology) O-2, Hydrogeology.
- LeGrand, Harry, Stringfield, V.T., and LaMoreaux, P.E., 1976, Hydrologic feature of United States Karst Regions: Karst Hydrology and Water Resources, Proceedings of the U.S.-Yugoslavian Symposium, Dubrovnik, June 2-7, 1975, Volume 1, Karst Hydrology, Yevjevich, Vujica, ed., Water Resources Publications, Colorado State University, Fort Collins, Colorado, p. 2-1 to 2-16,.
- Meyer, F.W., 1984, Disposal of liquid wastes in cavernous dolostones beneath southeastern Florida: in Burger, A. and Dubertret, L., eds., Hydrogeology of karstic terrains: case histories: International Contributions to Hydrogeology, v.1, International Association of Hydrogeologists, p.211-216.
- Miller, J.A., 1979, Potential subsurface zones for liquid-waste storage in Florida: Florida Bureau of Geology Map Series No. 94, scale 1:2,000,000.
- Monroe, W.H., 1976, The karst landforms of Puerto Rico: U.S. Geological Survey Professional Paper 899, 69p.
- Monroe, W.H., 1980, Geology of the middle Tertiary formations of Puerto Rico: U.S. Geological Survey Professional Paper 953, 93p.

- Newton, J.G., 1984, Sinkholes resulting from ground-water withdrawals in carbonate terranes-an overview: Geological Society of America, Reviews in Engineering Geology, v.6, p.195-202.
- Newton, J.G., 1987, Development of sinkholes resulting from man's activities in the eastern United States: U.S. Geological Survey Circular 968, 54p.
- Newton, J.G., and Tanner, J.M., 1987, Case histories of induced sinkholes in the eastern United States: in Beck, B.F., and Wilson, W.L., eds., Karst Hydrogeology: Engineering and Environmental Applications: Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, A.A. Balkema, Rotterdam, p.15-23.
- Plummer, L.N., Jones, B.F., and Truesdell, A.H., 1976, WATEQF--FORTRAN IV version of WATEQ. A computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations 76-13, 70p.
- Plummer, L.N., Parkhurst, D.L., and Thorstenson, D.C., 1983, Development of reaction models for ground-water systems: Geochemical Cosmochim. Acta 47, p. 665-686.
- Plummer, L.N., Wigley, T.M.L., and Parkhurst, D.L., 1978, The kinetics of calcite dissolution in CO₂-water systems at 5° to 60° C and 0.0 to 1.0 atm CO₂: American Journal of Science 278, 179-216.
- Solley, W.B., Merk, C.F., and Pierce, R.R., 1988, Estimated use of water in the United States in 1985: U.S. Geological Survey Circular 1004, 82p.
- Troester, J.W., and White, W.B., 1984, Seasonal fluctuations in the carbon dioxide partial pressure in a cave atmosphere: Water Resources Research, v.20, p.153-156.
- Troester, J.W., and White, W.B., 1986, Geochemical investigation of three tropical karst drainage basins in Puerto Rico: Ground Water, v.24, no.4, p.475-482.
- Troester, J.W., White, E.L., and White, W.B., 1984, A comparison of sinkhole depth frequency distributions in temperate and tropical karst regions: in Beck, B.F., ed., Sinkholes: their geology, engineering and environmental impact: Proceedings of the First Multidisciplinary Conference on Sinkholes, A.A. Balkema, Rotterdam, p.65-73.
- Troester, J.W., Back, William., and Mora-Castro, S.C., 1987, Karst of the Caribbean, in Graf, W.L., Geomorphic Systems of North America: Geological Society of America, DNAG (Decade of North American Geology) Centennial Special Volume Number 2, p.347-357.
- Truesdell, A.H., and Jones, B.F., 1974, WATEQ, A computer program for calculating chemical equilibria of natural waters: U.S. Geological Survey Journal of Research, v.2, p. 233-248.
- U.S. Geological Survey, 1970, The national atlas of the United States of America: U.S. Geological Survey, Washington, D.C., 417p.

- U.S. Geological Survey, 1985, National water summary 1984--Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467p.
- U.S. Geological Survey, 1986, Hydrologic hazards in karst terrain: U.S. Geological Survey Open-File Report 85-677, 2p.
- Vecchioli, John, 1979, Monitoring of subsurface injection of wastes, Florida: Ground Water, v. 17, no. 3, p. 244-249.
- White, W.B., 1984, Rate processes: Chemical kinetics and karst landform development: in LaFleur, R.G., ed., Groundwater as a geomorphic agent: Allen and Unwin, Boston, p.227-248.
- White, W.B., 1988, Geomorphology and Hydrology of Karst Terrains: Oxford University Press, New York, 464p.
- Yuan, Daoxian, 1987, Environmental and engineering problems of karst geology in China, in Proceedings volume, Karst Hydrogeology: Engineering and Environmental Applications, A.A. Balkema, Rotterdam, and Boston p. 1-11.