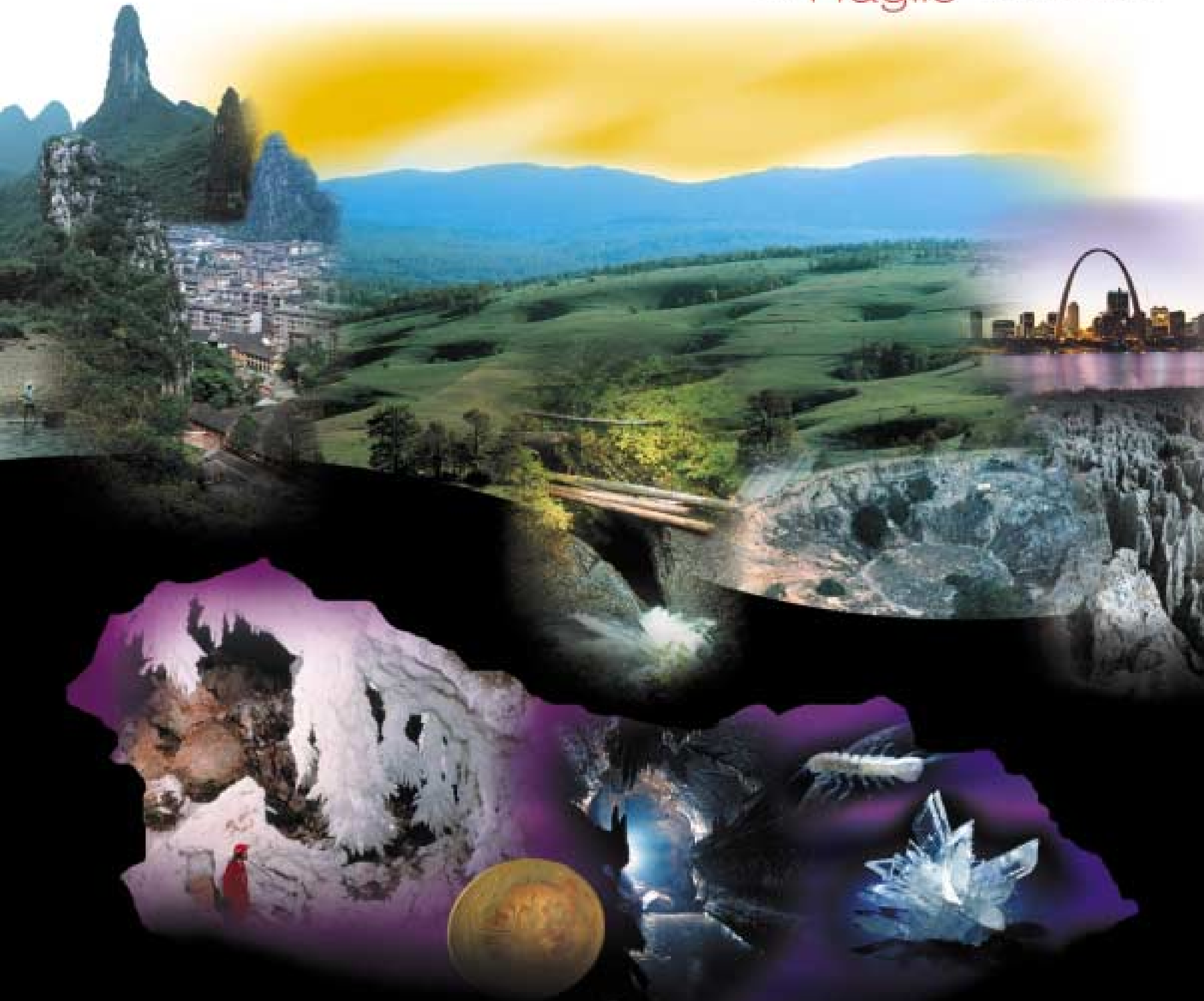
LIVING WITH KARST

A Fragile Foundation



AGI ENVIRONMENTAL AWARENESS SERIES

Publishing Partners

AGI gratefully acknowledges the following organizations' support for the *Living with Karst* booklet and poster. To order, contact AGI at www.agiweb.org or (703) 379-2480.

National Speleological Society
(with support from the National Speleological Foundation and the Richmond Area Speleological Society)

American Cave Conservation Association
(with support from the Charles Stewart Mott Foundation and a Section 319(h) Nonpoint Source Grant from the U.S. Environmental Protection Agency through the Kentucky Division of Water)

Illinois Basin Consortium
(Illinois, Indiana and Kentucky State Geological Surveys)

National Park Service

U.S. Bureau of Land Management

USDA Forest Service

U.S. Fish and Wildlife Service

U.S. Geological Survey

AGI Environmental Awareness Series, 4

LIVING WITH KARST

A Fragile Foundation

George Veni
Harvey DuChene
Nicholas C. Crawford
Christopher G. Groves
George N. Huppert
Ernst H. Kastning
Rick Olson
Betty J. Wheeler

With a Foreword by
Philip E. LaMoreaux

American Geological Institute

in cooperation with

National Speleological Society
and
American Cave Conservation Association, Illinois Basin Consortium
National Park Service, U.S. Bureau of Land Management, USDA Forest Service
U.S. Fish and Wildlife Service, U.S. Geological Survey

ABOUT THE AUTHORS

George Veni is a hydrogeologist and the owner of George Veni and Associates in San Antonio, TX. He has studied karst internationally for 25 years, serves as an adjunct professor at The University of Texas and Western Kentucky University, and chairs the Texas Speleological Survey and the National Speleological Society's Section of Cave Geology and Geography

Harvey R. DuChene, a petroleum geologist residing in Englewood, CO, has been studying caves throughout the world for over 35 years; he is particularly interested in sulfuric acid karst systems such as the Guadalupe Mountains of New Mexico and west Texas.

Nicholas Crawford, a professor in the Department of Geography and Geology and Director of the Center for Cave and Karst Studies at Western Kentucky University, has written over 200 articles and technical reports dealing with groundwater contamination of carbonate aquifers.

Christopher G. Groves is an associate professor and director of the Hoffman Environmental Research Institute at Western Kentucky University. His current work involves development of geochemical models to understand carbon cycling within karst landscape and aquifer systems. The Institute, hoffman.wku.edu, is working on a variety of cooperative karst-related research and educational programs.

Ernst H. Kastning is a professor of geology at Radford University in Radford, VA. As a hydrogeologist and geomorphologist, he has been actively studying karst processes and cavern development for over 30 years in geographically diverse settings with an emphasis on structural control of groundwater flow and landform development.

George Huppert is professor and chair of the Department of Geography and Earth Sciences at the University of Wisconsin at La Crosse. He has been active in researching karst management and conservation problems for over 30 years. He is also a life founding member and Vice President for Conservation of the American Cave Conservation Association.

Rickard A. Olson has served as the ecologist at Mammoth Cave National Park for the past seven years, and has conducted cave-related research on a variety of topics for the past 25 years. Most of his research efforts have been motivated by cave and karst conservation needs.

Betty Wheeler, a hydrogeologist in the Drinking Water Protection Section of the Minnesota Department of Health in St. Paul, has been studying karst groundwater processes for 17 years. She served as the book review editor for the *Journal of Cave and Karst Studies* for more than 10 years, and she is currently conducting susceptibility assessments of noncommunity public-water-supply wells throughout Minnesota.

Design: De Atley Design
Printing: CLB Printing Company

ISBN 0-922152-58-6

CONTENTS

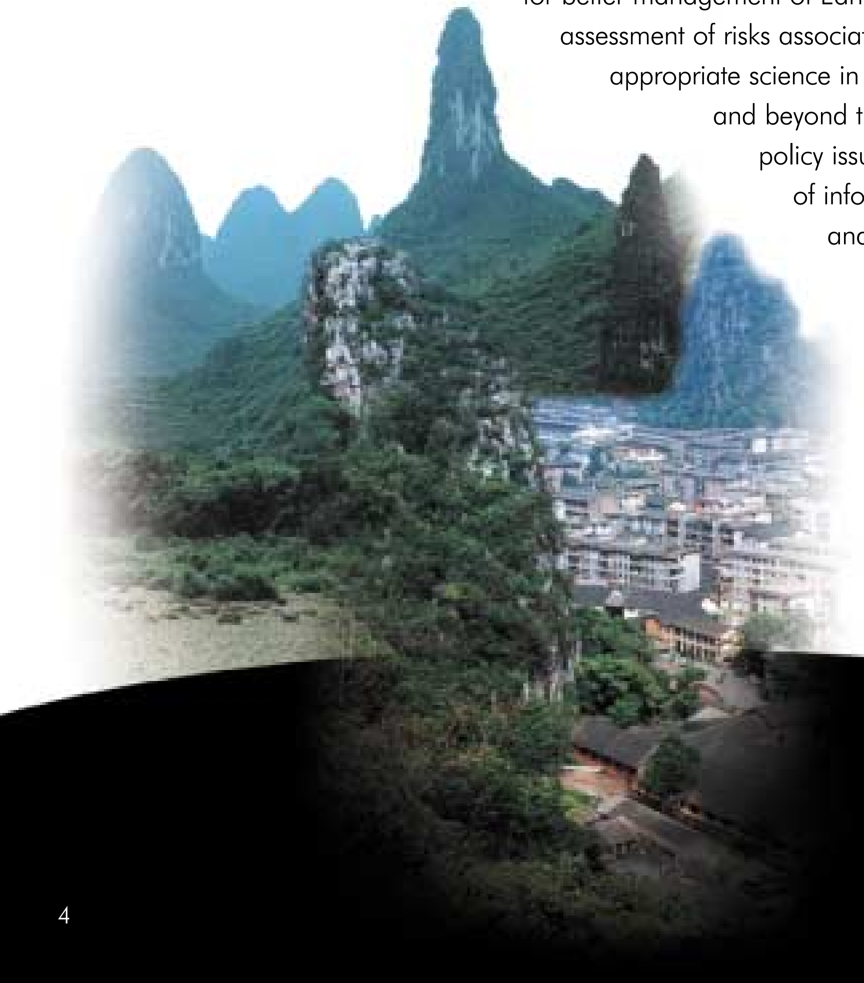
FOREWORD

Karst regions, areas underlain by limestone, dolomite, marble, gypsum, and salt, constitute about 25% of the land surface of the world. They are areas of abundant resources including water supplies, limestone quarries, minerals, oil, and natural gas. Many karst terrains make beautiful housing sites for urban development. Several major cities are underlain in part by karst, for example, St. Louis, MO; Nashville, TN; Birmingham, AL; Austin, TX; and others. However, since people have settled on karst areas, many problems have developed; for example, insufficient and easily contaminated water supplies, poor surface water drainage, and catastrophic collapse and subsidence features. By experience we have learned that each karst area is complex, and that special types of investigation are needed to help us better understand and live in them. In addition, urban development in these areas requires special sets of rules and regulations to minimize potential problems from present and future development.

The American Geological Institute produces the Environmental Awareness Series in cooperation with its Member Societies and others to provide a non-technical framework for a better understanding of environmental geoscience. This booklet was prepared under the sponsorship of the AGI Environmental Geoscience Advisory Committee (EGAC) with the support of the AGI Foundation. Publishing partners that have supported development of this booklet include: The American Cave Conservation Association, the Geological surveys in the states of Kentucky, Indiana, and Illinois (Illinois Basin Consortium), National Park Service, National Speleological Society, U.S. Bureau of Land Management, USDA Forest Service, U.S. Fish and Wildlife Service, and the U. S. Geological Survey.

Since its creation in 1993, the EGAC has assisted AGI by identifying projects and activities that will help the Institute achieve the following goals: increase public awareness and understanding of environmental issues and the controls of Earth systems on the environment; communicate societal needs for better management of Earth resources, protection from natural hazards, and assessment of risks associated with human impacts on the environment; promote appropriate science in public policy through improved communication within and beyond the geoscience community related to environmental policy issues and proposed legislation; increase dissemination of information related to environmental programs, research, and professional activities in the geoscience community.

This booklet describes ways to live safely, comfortably, and productively in karst areas, and illustrates that through use of improved science and technology, environmental concerns associated with karst can be better assessed and significantly resolved.



Philip E. LaMoreaux
Chair, AGI Environmental
Geoscience Advisory Committee,
1993-

PREFACE

Karst areas are among the world's most diverse, fascinating, resource-rich, yet problematic terrains. They contain the largest springs and most productive groundwater supplies on Earth. They provide unique subsurface habitat to rare animals, and their caves preserve fragile prehistoric material for millennia. They are also the landscapes most vulnerable to environmental impacts. Their groundwater is the most easily polluted. Water in their wells and springs can dramatically and rapidly fluctuate in response to surface events. Sinkholes located miles away from rivers can flood homes and businesses. Following storms, droughts, and changes in land use, new sinkholes can form suddenly, collapsing to swallow buildings, roads, and pastures.

The unique attributes of karst areas present challenges. In many cases, understanding the complex hydrologies of karst aquifers still requires specialists for accurate assessments. Unlike other terrains where most processes occur and can be observed at the surface, many critical processes in karst occur underground, requiring monitoring of groundwater flow and exploration and study of caves. Rather than being mere geologic curiosities, caves are now recognized as subsurface extensions of karst landscapes, serving vital roles in the evolution of the landscapes, and in defining the environmental resources and problems that exist in those areas.

This booklet unravels some of the complexities and provides easy to understand, sound practical guidance for living in karst areas. Major topics include

- Describing what karst is and how it "works."
- Identifying the resources and uses of karst areas from prehistoric to modern times.
- Outlining the problems that can occur in karst areas and their causes.
- Providing guidelines and solutions for preventing or helping overcome problems.
- Presenting sources of additional information for further research and assistance.

Karst areas offer important resources, with much of their wealth hidden underground. Careful use can produce many economic and scientific benefits. Sound management of karst areas requires the conscientious participation of citizens including homeowners, planners, government officials, developers, farmers, ranchers, and other land-use decision makers. It's up to you to manage your karst areas wisely. We hope this booklet helps.

We greatly appreciate the assistance we received from individuals and organizations in preparing this booklet. Several reviews helped craft the manuscript and ensure that the information was correct and up-to-date. Numerous photographs, in addition to those provided by the authors, were kindly donated for use. Our special thanks go to the organizations named on the inside cover who supported the publication and to the American Geological Institute for producing it.

George Veni and Harvey DuChene, editors
May, 2001

1

IT HELPS TO KNOW...

Sinkhole plain, typical of many well-developed karst landscapes.

For a landscape that makes up over a fifth of the United States, "karst" is a word that is foreign to most Americans. Major karst areas occur in 20 states and numerous smaller karst regions occur throughout the nation (Fig. 1). Karst describes landscapes characterized by caves, sinkholes, underground streams, and other features formed by the slow dissolving, rather than mechanical eroding, of bedrock. As populations have grown and expanded into karst areas, people have discovered the problems of living on those terrains, such as sinkhole collapse, sinkhole flooding, and easily polluted groundwater that rapidly moves contaminants to wells and springs. With the help of science and technology, residents and communities are developing solutions to the problems of living with karst.

What the Environmental Concerns Are

Karst regions require special care to prevent contamination of vulnerable groundwater supplies and to avoid building in geologically hazardous areas. Living in karst environments may result in

- Urban pollution of groundwater by sewage, runoff containing petrochemicals derived from paved areas, domestic and industrial chemicals, and trash;
- Rural groundwater pollution from sewage, fertilizers, pesticides, herbicides, dead livestock, and trash;
- Destabilization of the delicate equilibrium between surface and underground components of karst resulting in alteration of drainage patterns and increasing incidents of catastrophic sinkhole collapse, particularly in areas of unplanned urban growth;
- Construction problems, particularly the clearing and stabilization of land for buildings and roads;
- Challenges to water-supply development;
- Challenges to mine dewatering and excavation.

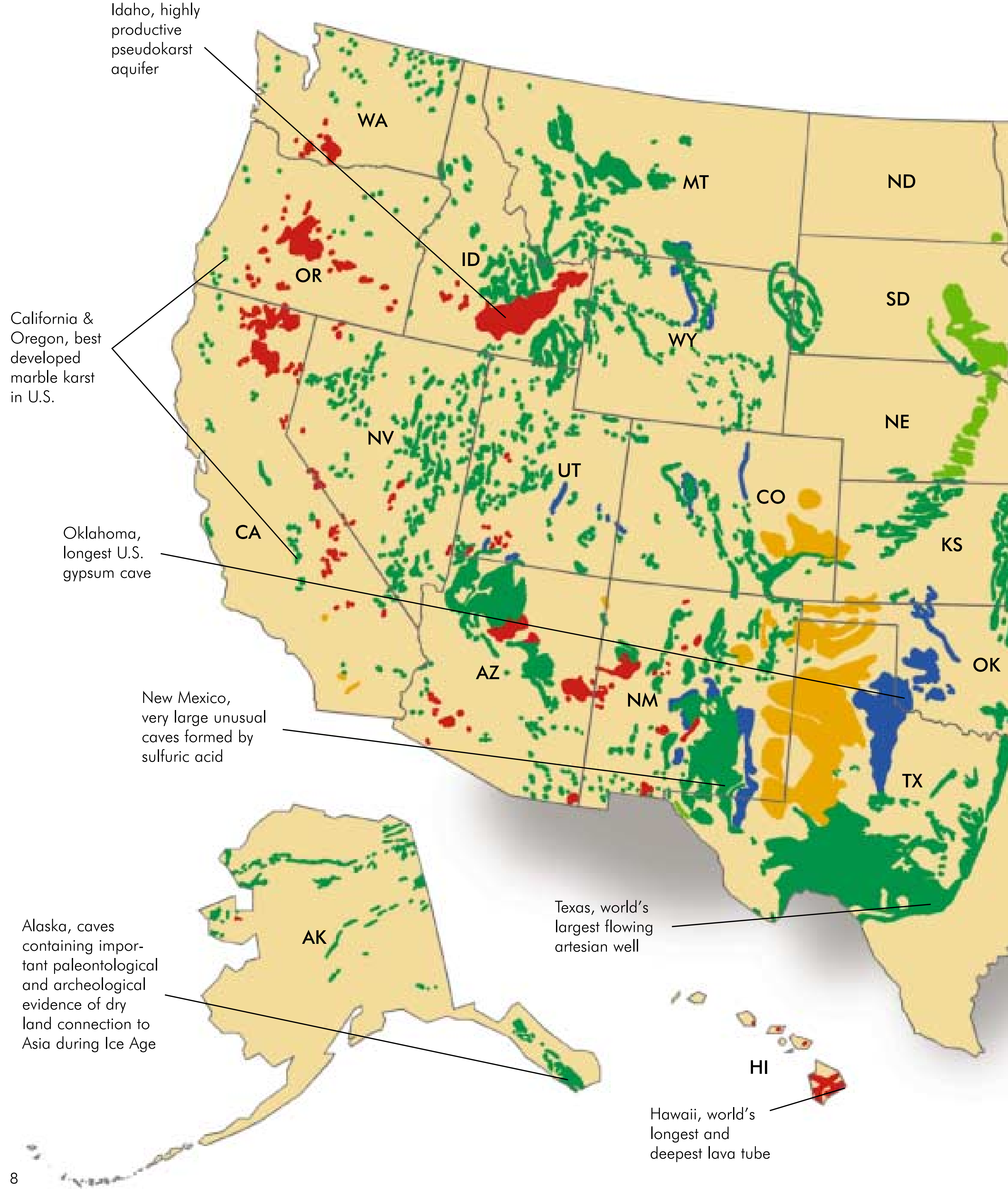
The financial impacts of these problems are substantial. As an example, the repair costs of five large dam sites in karst settings were in excess of $140 million. According to the U.S. National Research Council report, *Mitigating Losses from Land Subsidence in the United States* (1991), six states have individually sustained at least $10 million in damages resulting from sinkholes. As a result, awareness programs for catastrophic subsidence areas have been developed, as well as insurance programs applicable to sinkhole problems.

How Science and Technology Can Help

Complicated geologic processes increase the problems of living in karst regions. As our understanding of karst systems has improved, so has our ability to prevent many land-use problems and to remediate those that do occur. Science and technology can

- Provide information about karst aquifer systems so that residents can better protect groundwater supplies from pollution;
- Supply information on geological hazards such as areas with the potential for collapse due to shallow cave systems, thereby helping planners avoid building in unstable areas;
- Provide the means to map the subsurface hydrology and geology to identify areas where productive water wells may be located and to identify potential karst problems;
- Provide information for planners, developers, land management officials, and the general public about the special problems of living in karst environments; and
- Provide solutions for environmental problems when they do occur.

Karst is landforms and landscapes formed primarily through the dissolving of rock.



Idaho, highly productive pseudokarst aquifer

California & Oregon, best developed marble karst in U.S.

Oklahoma, longest U.S. gypsum cave

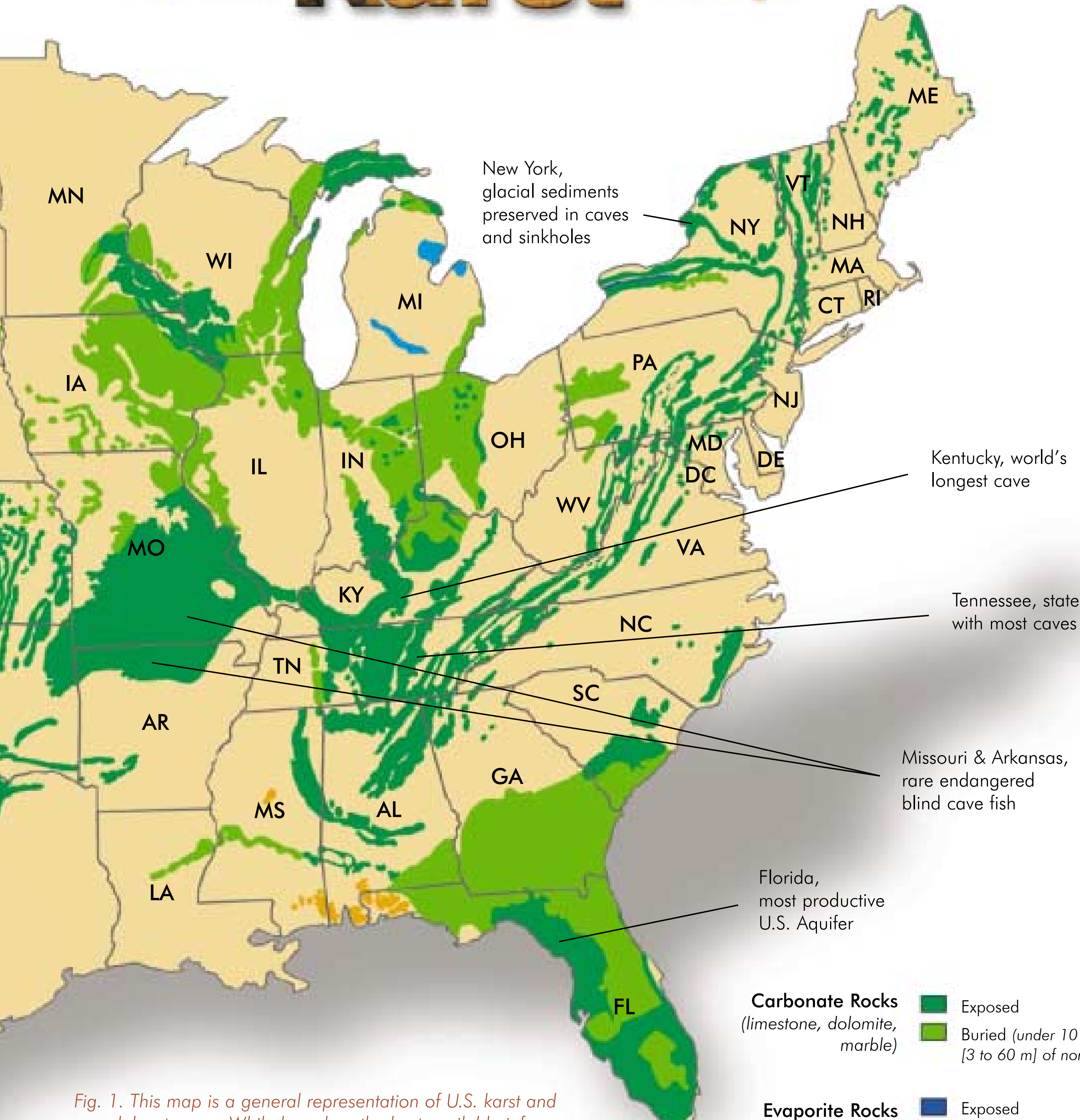
New Mexico, very large unusual caves formed by sulfuric acid

Alaska, caves containing important paleontological and archeological evidence of dry land connection to Asia during Ice Age

Texas, world's largest flowing artesian well

Hawaii, world's longest and deepest lava tube

U.S. Karst Map



New York,
glacial sediments
preserved in caves
and sinkholes

Kentucky, world's
longest cave

Tennessee, state
with most caves

Missouri & Arkansas,
rare endangered
blind cave fish

Florida,
most productive
U.S. Aquifer

Carbonate Rocks *(limestone, dolomite, marble)*
- 🟩 Exposed
- 🟩 Buried *(under 10 to 200 ft. [3 to 60 m] of non-carbonates)*

Evaporite Rocks *(gypsum, halite)*
- 🟦 Exposed
- 🟦 Buried *(under 10 to 200 ft. [3 to 60 m] of non-evaporites)*

Pseudokarst
- 🟥 Volcanic
- 🟨 Unconsolidated material

Fig. 1. This map is a general representation of U.S. karst and pseudokarst areas. While based on the best available information, the scale does not allow detailed and precise representation of the areas. Local geologic maps and field examination should be used where exact information is needed. Karst features and hydrology vary from place to place. Some areas are highly cavernous, and others are not. Although most karst is exposed at the land surface, some is buried under layers of sediment and rock, and still affects surface activities.

2

WHAT IS KARST?

Tourist trails through large karst pinnacles in Lunan Stone Forest, China.

Landforms produced primarily through the dissolving of rock, such as limestone, dolomite, marble, gypsum, and salt, are collectively known as karst. Features of karst landscapes include sinkholes, caves, large springs, dry valleys and sinking streams. These landscapes are characterized by efficient flow of groundwater through conduits that become larger as the bedrock dissolves. In karst areas, water commonly drains rapidly into the subsurface at zones of recharge and then through a network of fractures, partings, and caves, emerges at the surface in zones of discharge at springs, seeps, and wells.

The appearance of karst varies from place to place, with different features having greater or lesser prominence according to local hydrogeologic factors. Even ancient or "paleokarst" that is buried under other rocks and sediments and is not exposed at the surface can have an effect on surface land use. Several false or "pseudokarst" areas also occur, especially in the western United States (Fig.1). These regions contain karst-like features which have developed in poorly soluble rocks. Although formed by different processes, pseudokarst areas are often similar to karst areas in how they are used and affected by human activities.

How Karst Forms

Karst forms as water dissolves soluble bedrock. Although water alone can dissolve salt and gypsum, limestone, dolomite, and marble are less soluble and require acidic water. Carbonic acid is a mild, naturally occurring acid that is very common in groundwater. This acid is created when water falling through the atmosphere takes on a small amount of carbon dioxide. As the slightly acidic rainwater passes through soil, the water absorbs additional carbon dioxide and becomes more acidic. Acidic water readily dissolves calcite, the principal mineral in limestone and marble, and an important mineral in dolomite.

Acidic groundwater moving through fractures and other spaces within the rock gradually alters small openings creating large passages and networks of interconnected conduits. Solution sinkholes form by dissolving the bedrock at the surface downward as surface water is captured and diverted underground (Fig. 2). Most flow and enlargement take place at or just below the water table, the level below which the ground is saturated with water. The circulation of water and bedrock dissolution are greatest there because fractures are connected and most open, whereas underground spaces tend to become progressively narrower and smaller with depth. Where these openings are dissolved large enough to allow human entry, they are called "caves."


Fig. 2. This solution sinkhole holds water above the water table. Although most sinkholes drain rapidly, some like this one, have natural plugs and may hold water for many years.

Fig. 3. (Right) Horizontal cave passages form below the water table, and they usually have a smooth, rounded to elliptical shape. The water table has since dropped below this Mexican cave, and recent floods washed in the boulders.

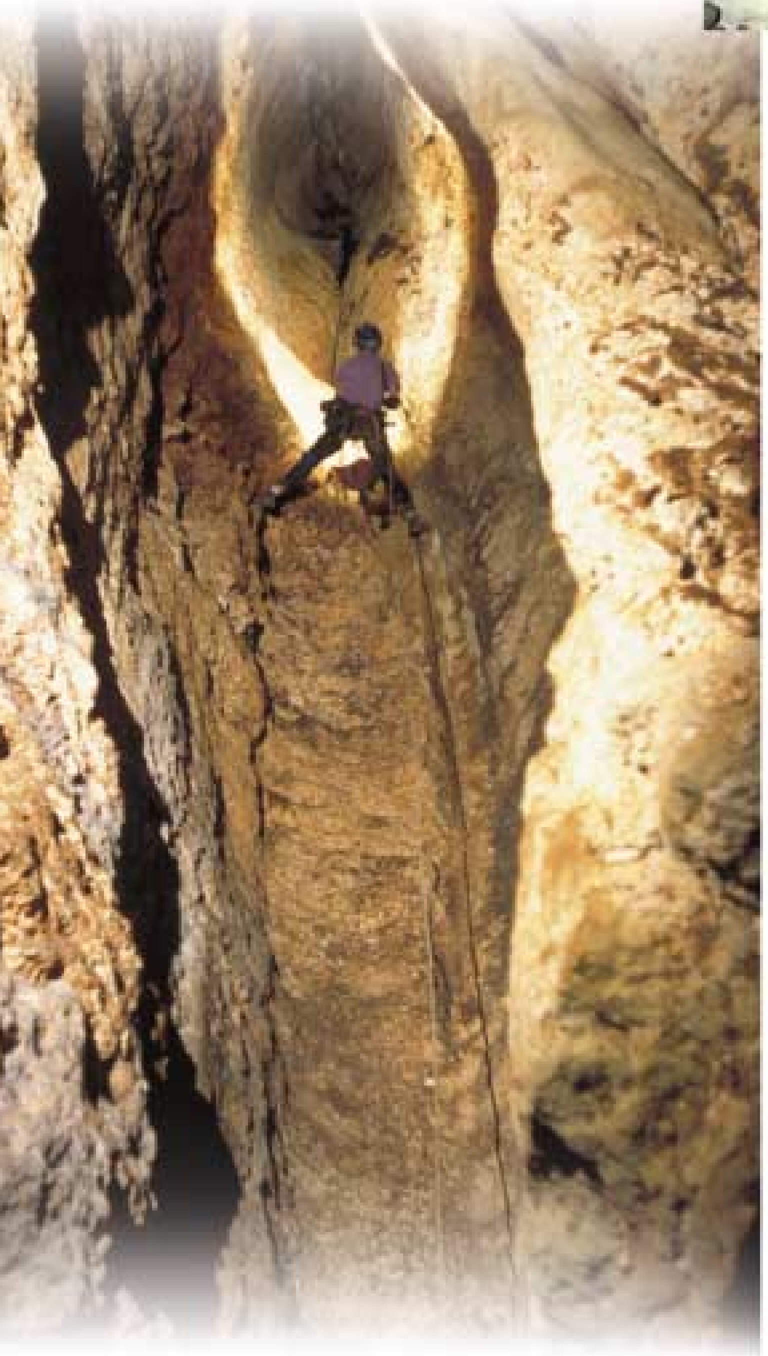


Fig. 4. (Above) Vertical cave passages, like this one, typically form above the water table, usually along fractures, and they efficiently channel water that enters caves down to the aquifers below.

Most caves form at or just below the water table, and consequently cave passages are generally horizontal. In cross section, these cave passages are elliptical tubes usually developed in soluble beds of rock (Fig. 3). In contrast, passages formed above the water table are canyon-like corridors that have been formed by dissolution and physical erosion as water cut down through the rock. Cross sections of cave passages formed above the water table are narrow and tall, and pits are common (Fig. 4).

Caves above the water table are tributaries to caves below the water table. Over time, small channels and conduits merge to form large cave passages in the downstream direction. In a mature cave system, an underground branching, tree-like drainage network develops that resembles surface stream systems (Fig. 5). The flow of water is concentrated in large conduits and typically emerges at a few springs with high rates of discharge. At this stage, the karst groundwater system

Fig. 5. (Below) Flow patterns for underground water in karst commonly have a branching shape. Small branches, which begin by capturing surface water from sinkholes and fractures, gain in size and water volume as they flow downstream, merge, and eventually discharge at springs.

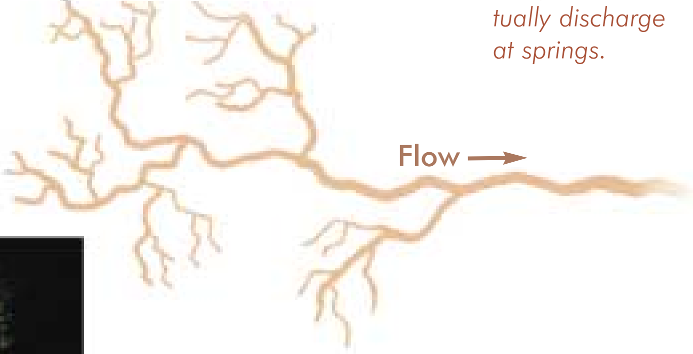
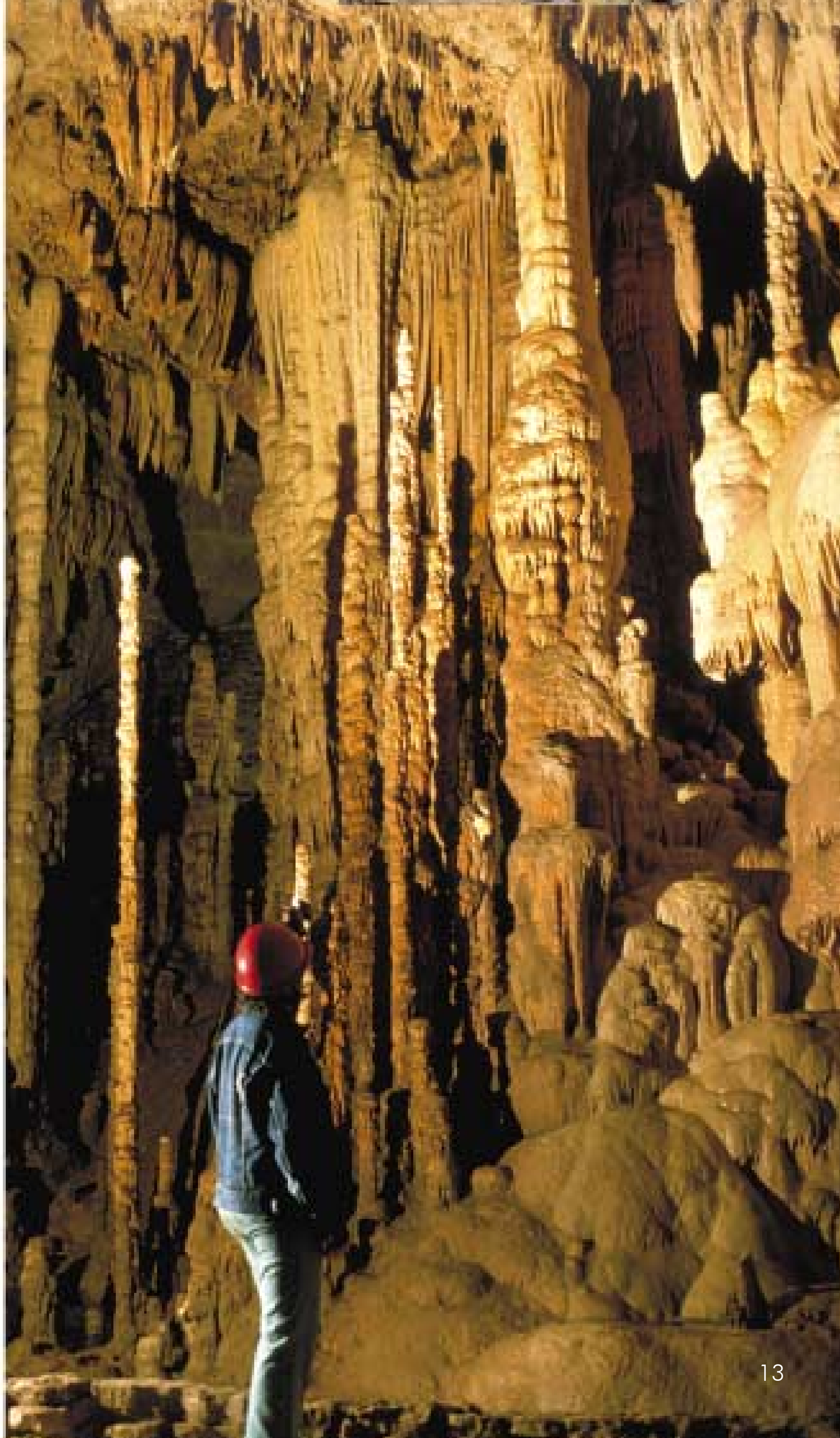


Fig. 6. (Left) This split-level cave in Mexico formed by water first flowing through the dry upper passage, which was abandoned as the water table dropped and groundwater cut a new route through the lower passage to reach the current water table.

Fig. 8. (Right) The sharp edges along the walls and the tell-tale angular rocks on the floor are evidence that this passage formed by the collapse of a deeper passage.

Fig. 9. (Below) On rare occasions, a collapsing cave room or passage may extend high enough that a collapse sinkhole forms in bedrock on the surface.

Fig. 7. (Right) A "speleothem" is a mineral deposit formed in caves by precipitation from mineral-rich water. Common examples are stalactites hanging from the ceiling, stalagmites growing up from the floor, and columns where the two join. Natural Bridge Caverns is a show cave in Texas.



is a coherent part of the hydrologic cycle. Water passes downward from the surface, through this efficient system of natural "pipes" and emerges elsewhere at the surface as seeps and springs.

Because springs usually discharge into valleys that are continually deepened by surface streams, water tables gradually fall and springs migrate to lower elevations. Consequently, newer cave passages form at lower elevations, while previously formed upper-level passages and rooms are drained (Fig. 6). These caves are relatively dry except for dripping water and an occasional stream making its way from the surface to the water table. Water dripping or flowing into passages may deposit calcite speleothems, such as stalactites, stalagmites, and columns (Fig. 7). Ceilings of rooms and passages collapse when passages become too wide to support the bedrock overlying them (Fig. 8). The danger of collapse increases when water is drained from the cave and its buoyant force is not present to help support ceilings. Some collapse sinkholes develop where collapse of the cave roof reaches the surface of the Earth (Fig. 9). More commonly, they develop when soil collapses after deeper soils wash into underlying caves.

Fig. 11. The fractures and pits in this limestone have become larger as the surrounding rock dissolved by solution.

Fig. 10. When it rains, this New York swallet "swallows" all of the water that flows down the creek bed.

Unlike other landscapes, groundwater recharge into karst aquifers carries substantial amounts of dissolved and suspended earth materials underground. First, the water contains ions that are produced naturally as the rock is dissolved. Second, water conveys particles that range in size from submicroscopic clay particles to boulders. Great volumes of sediment are transported underground in karst areas, sometimes resulting in openings becoming clogged. The mechanical and chemical removal of material in karst occurs throughout the zone between the land surface and the bedrock. Unlike other terrains, where weathering forms a soil that may thickly blanket the bedrock and retard erosion, in karst, the continual removal of material into the subsurface allows high, sustained rates of erosion. Many karst areas, especially in the western United States where soil production is slow, are covered with only thin or patchy soils.

Hydrologic Characteristics

Karst features may or may not be easily recognizable on the surface, but areas where the surface bedrock is limestone or gypsum have a high probability of karst development. Karst areas commonly lack surface water and have numerous stream beds that are dry except during periods of high runoff. These regions have internal drainage; streams flow into the closed depressions called sinkholes where there is no surface outlet. A typical sinkhole is bowl shaped, with one or more low spots along its bottom. In some cases a swallow hole, or swallet, may be present at the bottom of the sinkhole where surface water flows underground into fractures or caves (Fig. 10). Water may also enter a karst aquifer along streams that flow over karst areas and disappear from the surface. A stream of this type is known as a sinking stream and in some cases it may lose water along a substantial part of its length. In the subsurface, the storage and flow of groundwater is controlled by the porosity and permeability of the rock.

Porosity and Permeability

All rock contains pore spaces. Porosity is the percentage of the bulk volume of a rock that is occupied by pores (Fig. 11).

For example, a porosity of 20% means that bedrock is 80% solid material (rock) and 20% open spaces (pores or fractures). Voids in the bedrock are the openings where groundwater can be stored. Where voids are connected, they also provide the paths for groundwater flow.

Permeability is a measure of how well groundwater flows or migrates through an aquifer. A rock may be porous, but unless those pores are connected, permeability will be low. Generally speaking, the permeability of rocks in well-developed karst areas is very high when networks of fractures have been enlarged and connected by solution (Fig.12).

In most limestones, the primary porosity and permeability, or hydrologic characteristics created as the rock formed, are generally low. However in karst areas, large cavernous porosities and high permeability are common. These hydrologic characteristics, including fractures and openings enlarged by solution, are almost always secondary or tertiary features that were created or enhanced after the rock was formed.

The Hydrologic Cycle

The source of groundwater for all aquifers is precipitation. When rain falls, plants and soil absorb some of the rain water, some of it drains into streams, some evaporates, and the remainder moves downward into aquifers recharging them (Fig. 13). Groundwater moves through the hydrologic cycle as part of a dynamic flow system from recharge areas to discharge areas that flow into streams, lakes, wetlands, or the oceans. Streams that flow during periods of little rainfall are fed by groundwater.

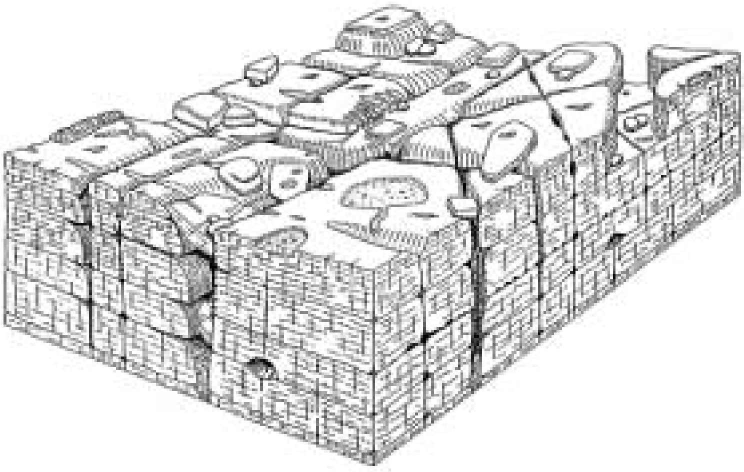


Fig. 12. The bedrock surface in karst terrains is often highly fissured and permeable. In areas lacking soil, this surface can be directly viewed and is called karst pavement (Fig. 52).

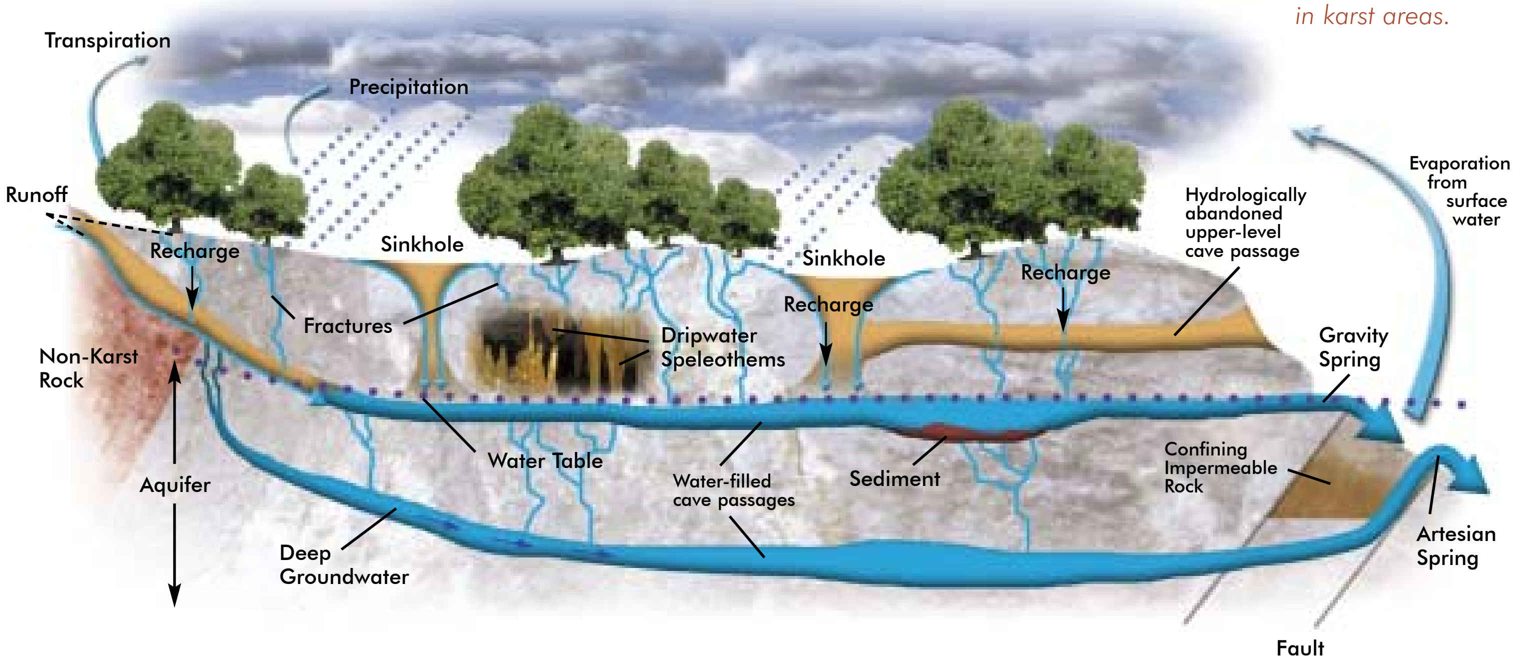


Fig. 13. The hydrologic cycle in karst areas.

The Karst Aquifer

An aquifer is a zone within the ground that serves as a reservoir of water and that can transmit the water to springs or wells. Karst aquifers are unique because the water exists and flows within fractures or other openings that have been enlarged by natural dissolution processes. However, water flow in karst aquifers is commonly localized within conduits, with little or no flow in the adjacent rock. This situation means that successful wells must intersect one or more voids where the water is flowing. In a karst region, drilling for water may be a hit-or-miss endeavor; in contrast to drilling in porous media aquifers where flow conditions are more uniform and the probability of finding adequate water is higher.

Once sufficient permeability is established through the bedrock, water circulates freely from places of recharge to areas of discharge.

Vadose and Phreatic Zones

The area between the surface of the land and the water table, which is called the vadose zone, contains air within the pore spaces or fractures. In the vadose zone, groundwater migrates downward from the surface to the phreatic zone, in which pore spaces are filled with water. The boundary between the vadose and phreatic zones is the water table (Fig. 14). The vertical position of the water table fluctuates in response to storms or seasonal changes in weather, being lower during dry times and higher during wetter periods. In non-karst aquifers, the vadose and phreatic zones are called the unsaturated and saturated zones. The use of those terms in regard to karst aquifers is not recommended, because chemical saturation of the water with dissolved minerals is a critical factor in aquifer flow and development.

Karst aquifers may contain perched water, which is groundwater that is temporarily pooled or flowing in the vadose zone. Although perched water generally occurs in relatively small volumes, it can provide water to wells and springs.

Groundwater Recharge and Discharge

The process of adding water to an aquifer is known as recharge. Where surface water enters an aquifer at specific spots, such as sinkholes and swallets, discrete recharge occurs. When water infiltrates into underlying bedrock through small fractures or granular material over a wide area, the recharge process is referred to as diffuse recharge. Where water comes to the surface at specific springs (Fig. 15) or wells, it is known as discrete discharge, but where water flows out of the ground over a larger area, such as a series of small springs or seeps, the discharge is diffuse. While recharge and discharge vary in magnitude in all aquifers, they vary the most in karst aquifers by allowing the greatest rates of water flow. Large springs tend to be most commonly reported. Thus, those states with the greatest number of recorded springs, including more than 3,000 each in Alabama, Kentucky, Missouri, Tennessee, Texas, Virginia, and West Virginia, also have significantly large karst areas.

Once sufficient permeability is established through the bedrock, water circulates freely from places of recharge to areas of discharge. In karst areas where the water table is near the surface, such as Florida's Suwannee River basin, declines in the water table can change springs into recharge sites, and rises in the water table can convert sinkholes into springs. Features that sometimes discharge water and other times recharge water are known as estavelles.

In areas where groundwater in karst flows through open conduits, the aquifers

Fig. 14. The surface of this cave stream marks the water table of this karst aquifer. The area above the water table is called the "vadose zone" and the area below, where all voids are filled with water, is the "phreatic zone."

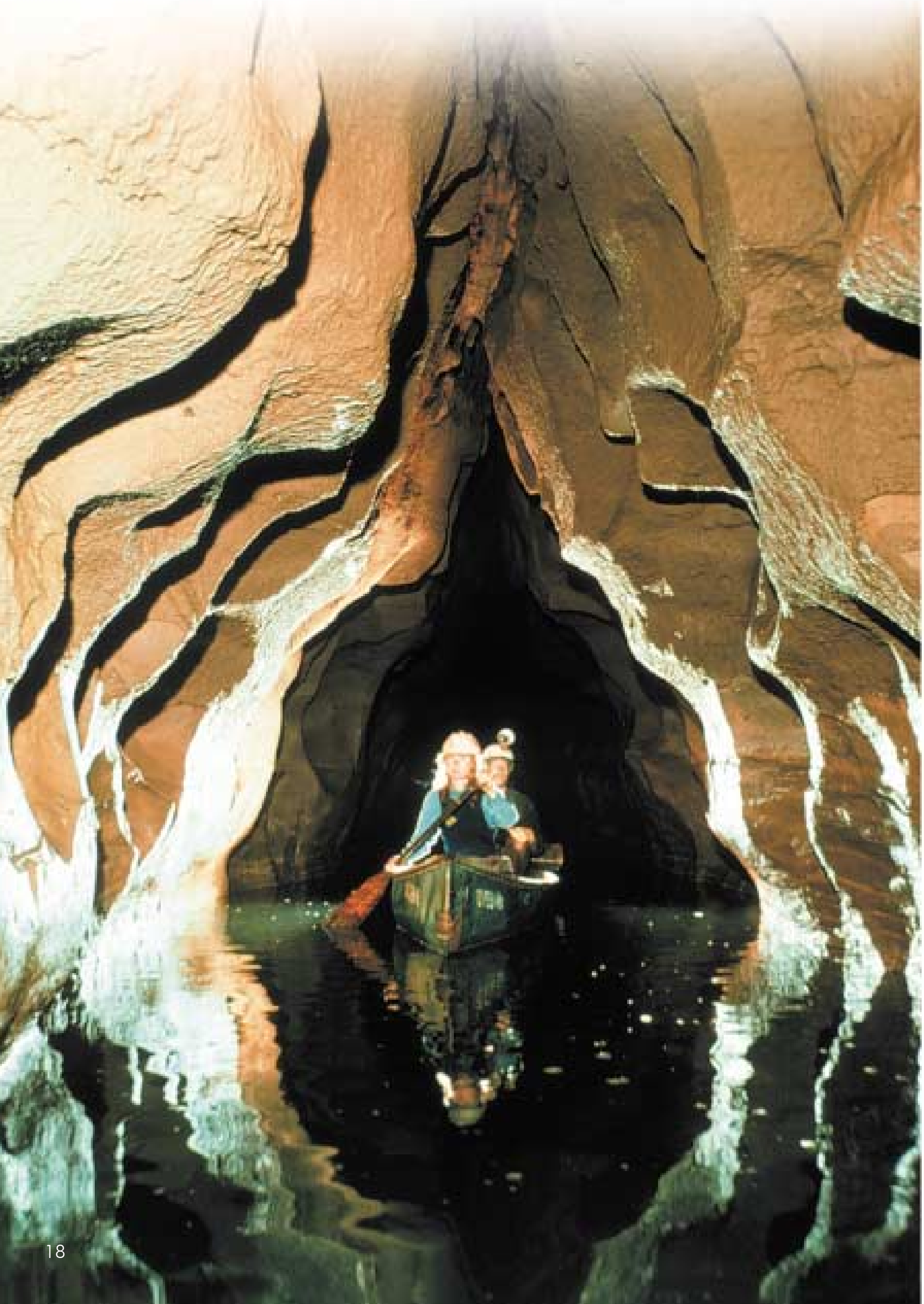
respond very quickly to surface events such as storms and stream flooding. This response is typically many times greater and faster than would occur in non-karst aquifers. Therefore, interactions between surface and groundwater processes are greatly enhanced in karst.

It is important to know that even in the absence of surface streams, a karst region is a zone of drainage into the aquifer; the entire area can be a recharge zone. Surface water over the whole area, not just within sinkholes, carries sediment and pollutants into the subsurface. Removal of vegetation from surrounding areas through farming, forestry, or urbanization may significantly change drainage conditions leading to alteration of the aquifer by clogging of openings, ponding, and flooding, as well as contamination of groundwater resources. As the world's population grows and continues expanding onto karst areas, people are discovering the problems of living on karst. Potential problems and environmental concerns include sinkhole flooding, sinkhole collapse, and easily polluted groundwater supplies, where contaminants move rapidly to wells and springs. The following chapters discuss assets of karst as well as some of the challenging aspects of living in karst areas.

Fig. 15. Some springs rise from streambeds while others pour out of bedrock. Blanchard Springs Caverns, Arkansas.

3

WHY KARST AREAS ARE IMPORTANT



Karst areas are rich in water and mineral resources and they provide unique habitats and spectacular scenery.

Fig. 16. Until recently, many Maya of Mexico and Central America would walk long distances each day to a nearby cave, then climb down inside to retrieve water, as shown in this 1844 drawing by Frederick Catherwood.

Karst areas are among the most varied of Earth's landscapes with a wide array of surface and subsurface terrains and resources. Some of their features are unique to karst, and others tend be most abundant in karst regions. The following sections describe the most frequently used or encountered karst resources.

Water Resources

Without a doubt, water is the most commonly used resource in karst areas. Although the lack of surface water is commonly characteristic of karst areas, they also contain some of the largest water-producing wells and springs in the world. Until the development of well-drilling technologies, communities generally were located along the margins of karst areas, downstream from large springs that provided water for drinking, agriculture, and other uses.

Historical accounts describe the vital role of karst groundwater for communities as far back as pre-Biblical times in Europe and the Middle East. Assyrian King Salmanassar III recognized the importance of karst springs as early as 852 B.C., as recorded in the description of his study of the cave spring at the head of the Tigris River. For centuries throughout the world, water has been channeled from springs toward towns and fields, or collected from caves and sinkholes in vessels (Fig.16) or by hand or wind-powered pumps. These methods are still used in parts of the world where drilling technology is not affordable or practical.

Water-well drilling has allowed more people to move into karst areas. However, water yield from karst aquifers can range from zero to abundant, depending on the number of fractures and voids penetrated by a well bore and the amount of water they carry. The world's largest flowing artesian well intersected a cave passage in Texas' Edwards Aquifer estimated to be 8 ft (2.4 m) high, and tapped water under such pressure that it shot a 3-ft (1 m) diameter, 30 ft (9 m) high fountain into the air and flowed at a rate of 35,000 gallons/minute (2.2 cubic meters/second) (Fig. 17).

Fig. 17. Before it was capped, the record-setting "Catfish Farm Well" shot water 30 ft (9 m) into the air from the Edward Aquifer in Texas.

The cavernous nature of karst aquifers allows considerable volumes of water to be stored underground. This is especially valuable in arid climates where evaporation is high. In some parts of the world, cave streams are large enough to economically merit damming to store water for direct usage, mechanical water-wheel power, hydroelectric power, and to limit downstream flooding. The Floridan Aquifer in Florida yields over 250 million gallons/day (947,500 m^3/day) to wells, and Figeh Spring, in Syria, which is the 3rd largest spring in the world, on average discharges 63,200 gallons/minute (4.0 m^3/sec) and supplies the entire city of Damascus with water.

Fig. 19. Vats used in the 1800s to leach saltpeter for gunpowder. Mammoth Cave, Mammoth Cave National Park, KY.

Fig. 18. (Above) Ice speleothems are present year-round in this Swiss cave.

Fig. 20. (Right) Cinnabar and other hydrothermally deposited minerals in a cave intersected by a mine.

Earth History

Karst plays an important role in increasing our understanding of the history of past climates and environments on Earth. Sediments and speleothem or mineral deposits in caves are among the richest sources of paleoclimate information, providing detailed records of fluctuations in regional temperature, atmospheric gases, rainfall, ice ages, sea-level changes, and plants and animals that once inhabited the areas during the past several hundred thousand years.

Mineral Resources

Prehistoric peoples found shelter and mineral resources in caves. It is well-documented that they mined caves for flint (also known as chert) to make stone tools and for sulfate minerals and clays for medicines and paint pigment. In Europe, a soft speleothem known as moonmilk was used as a poultice, an antacid, to induce mother's milk, and to remedy other medical woes. Prior to refrigeration, cold caves were mined for ice (Fig. 18), and in the early 1800s, the beer brewing industry of St. Louis, Missouri, was based on the availability of caves as places of cold storage.

In the United States during the Revolutionary War, War of 1812, and Civil War, over 250 caves were mined for saltpeter, which was used in the production of gunpowder (Fig. 19). Like saltpeter, phosphate-rich bat guano deposits used to enrich agricultural soils are mined in caves. Bat guano was the most highly rated fertilizer of the 19th and early 20th centuries until it was supplanted by cheaper and more easily obtained chemical fertilizers.

The most common mineral resource extracted from karst areas is the quarried rock itself. Limestone, dolomite, marble, gypsum, travertine, and salt are all mined in large quantities throughout the world. Quarry operators prefer mining non-cavernous rock, but in many areas this is not available and many caves are lost. Unfortunately, sometimes the exotic mineral deposits called speleothems are also mined from caves, despite such collecting being an illegal activity in many states. The removal of speleothems results in the loss of thousands of years of information on Earth's history and the vandalism of beautiful natural landscapes.

Karst areas, including ancient or paleokarst, may contain large reserves of lead, zinc, aluminum, oil, natural gas, and other valuable commodities. Paleokarst is karst terrain that has been buried beneath younger sediments. Significant economic ore deposits accumulate in the large voids in paleokarst rocks, especially where mineral-bearing thermal or sulfide-rich solutions have modified the bedrock. In some areas, lead and zinc deposits are common, forming large economically valuable mineral deposits like those in Arkansas and Missouri (Fig. 20). Many oil and gas fields throughout the world tap highly porous and permeable paleokarst reservoirs where tremendous volumes of petroleum are naturally stored. Abundant deposits of aluminum occur in laterite soils composed of the insoluble residue derived from limestone that has been dissolved in humid climates.

Ecology

Many species of bats, including those that form some of the world's largest colonies, roost in caves (Fig. 21). Nectar feeding bats are important pollinators, and a number of economically and ecologically important plants might not survive without them. Insectivorous bats make up the largest known colonies of mammals in the world. Populations from some of these colonies may eat nearly a million pounds (454,000 kg) of insects per night, including moths, mosquitoes, beetles, and related agricultural pests. Fruit-eating bats eat ripe fruit on the branch, scatter the seeds, and thereby contribute to the propagation of trees. In Pacific islands, the regenreation of at least 40% of tree species are known to depend on bats, and in western Africa, bats carry 90-98% of the seeds that initiate reforestation of cleared lands.

Because caves lack sunlight, they create highly specialized ecosystems that have evolved for survival in low-energy and lightless environments. Troglobites are animals that are adapted to living their entire lives underground. They have no eyes, often lack pigment, and have elongated legs and antennae. Some have specialized organs that detect smell and movement to help them navigate in a totally dark environment and find food. Fish, salamanders, spiders, beetles, crabs, and many other animals have evolved such species (Fig. 22). Since cave habitats are

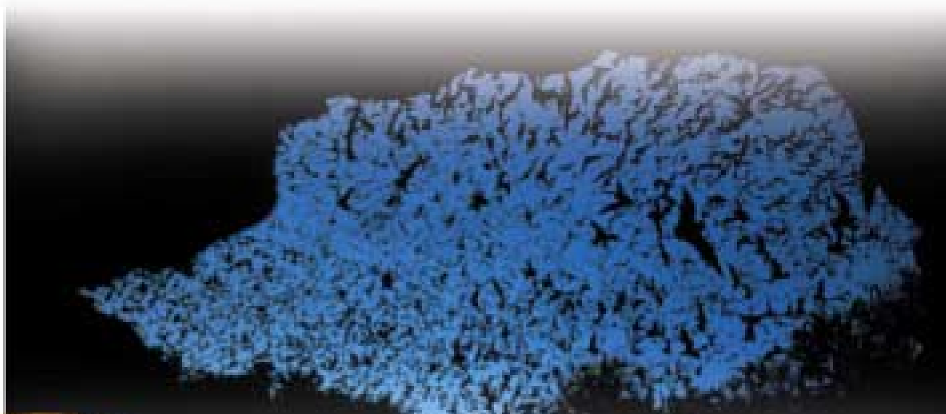


Fig. 21. Mexican free-tailed bats flying out from Bracken Cave, Texas, at night to feed. Each spring, about 20 million pregnant bats migrate to this maternity colony from Mexico. On average, each gives birth to one pup and by the fall the population swells to 40 million — the largest bat population and greatest known concentration of mammals in the world. During a typical night, they will eat roughly 1,000,000 pounds (454,000 kg) of insects, including many agricultural pests.

Fig. 22. (Left) These blind shrimp-like animals, which live in many karst aquifers, are an example of a troglobite species. These animals have adapted to their food-poor, lightless environment by loss of sight and lack of pigmentation.

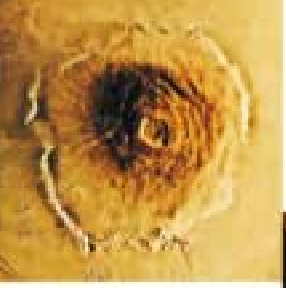


Fig. 23. (Left) The study of microbes in biologically extreme cave environments is teaching scientists how and where to search for life on Mars and other planets.

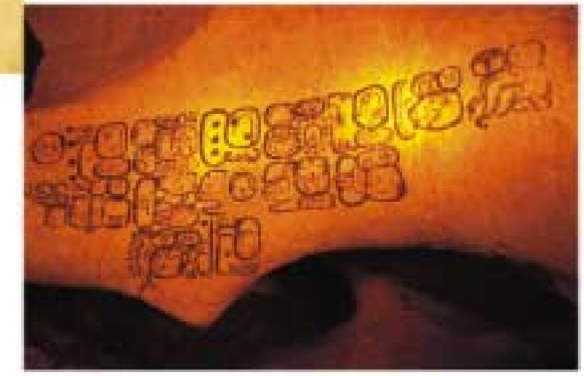


Fig. 24. (Right) Thirteen hundred year old Mayan hieroglyphic paintings preserved in a Guatemalan cave.

Fig. 25. A tourist enjoying the splendors of Bailong Dong (White Dragon Cave), a show cave in China.

far less complex than those on the surface, biologists study these animals for insights into evolution and ecosystem development. An extreme example of an isolated karst ecosystem is in Movile Cave, Romania. Geologic evidence indicates that the cave was blocked-off from the surface for an estimated 5 million years until a hand-dug well accidentally created an entrance in 1986. This cave has a distinct ecosystem based on sulfur bacteria that are the base of a food chain that supports 33 invertebrate species known only from that site.

Microbial organisms in caves have only recently been studied, but they are important contributors to biological and geological processes in karst environments. Microbes accelerate dissolution by increasing the rate of limestone erosion in some circumstances. In other cases, they may contribute to the deposition of speleothems. Changes in the number and types of certain bacteria are indicators that have been used to trace groundwater flow paths and to identify pollution sources. Several cave microbes are promising candidates for cancer medicines, and others may be useful for bioremediation of toxic wastes spilled into the environment. Certain sulfur-based microorganisms are being studied as possible analogs for life in outer space (Fig. 23).

Archaeology and Culture

From early times in human development, caves have served, first as shelters, and later, as resource reservoirs and religious sites. Many of the world's greatest archaeological sites have been found in caves, where fragile materials that would easily be destroyed in other settings have been preserved. Caves were reliable sources of water when other sources went dry, and minerals and clays were mined for both practical and ceremonial use. Generations of habitation resulted in deep accumulations of bones, ash, food scraps, burials, wastes, and other materials. The archaeological importance of caves stems not only from the volume of cultural material, but also from the degree of preservation. Fragile and ephemeral items such as footprints, woven items of clothing and delicate paintings are examples of these rare artifacts (Fig. 24).

Recreation

Karst areas provide three main types of recreational settings: show or commercial caves, wild caves, and scenic areas. For many people, their only exposure to the karst environment occurs when they visit show caves. There, they can view delicate and grand mineral displays, vaulted chambers, hidden rivers, and other underground wonders (Fig. 25). Some of the world's most outstanding caves are open to the public in the United States. Mammoth Cave, Kentucky, is the world's longest cave with over 355 miles (572 km) mapped. Carlsbad Caverns, New Mexico, which like Mammoth Cave, is a U.S. national park, contains some of the world's largest rooms and passages. Caverns of Sonora, a privately owned cave in Texas, is internationally recognized as one of the world's most beautiful show caves.

"Wild" caves remain in their natural state, and they are located throughout the country on public and private land. For most people, a visit to a wild cave is a one-time adventure, but for thousands of "cavers" worldwide, it is a regular pastime. Caving is a sport that contributes to science, because many cavers create detailed maps as they explore and note features that may be of scientific importance.

The above-ground portions of karst areas form some of the most unusual landscapes in the world, epitomized by the impressive Tower Karst region of southeast China (Fig. 26). Other exceptionally scenic karst regions occur in, but are not limited to, Brazil, Croatia, Cuba, France, Malaysia, Slovenia, Thailand, the United States, and Vietnam. Recreational activities in scenic karst areas include car touring, boating, hiking, fishing, camping, swimming, backpacking, nature watching, photography, and, of course, exploring wild and show caves.

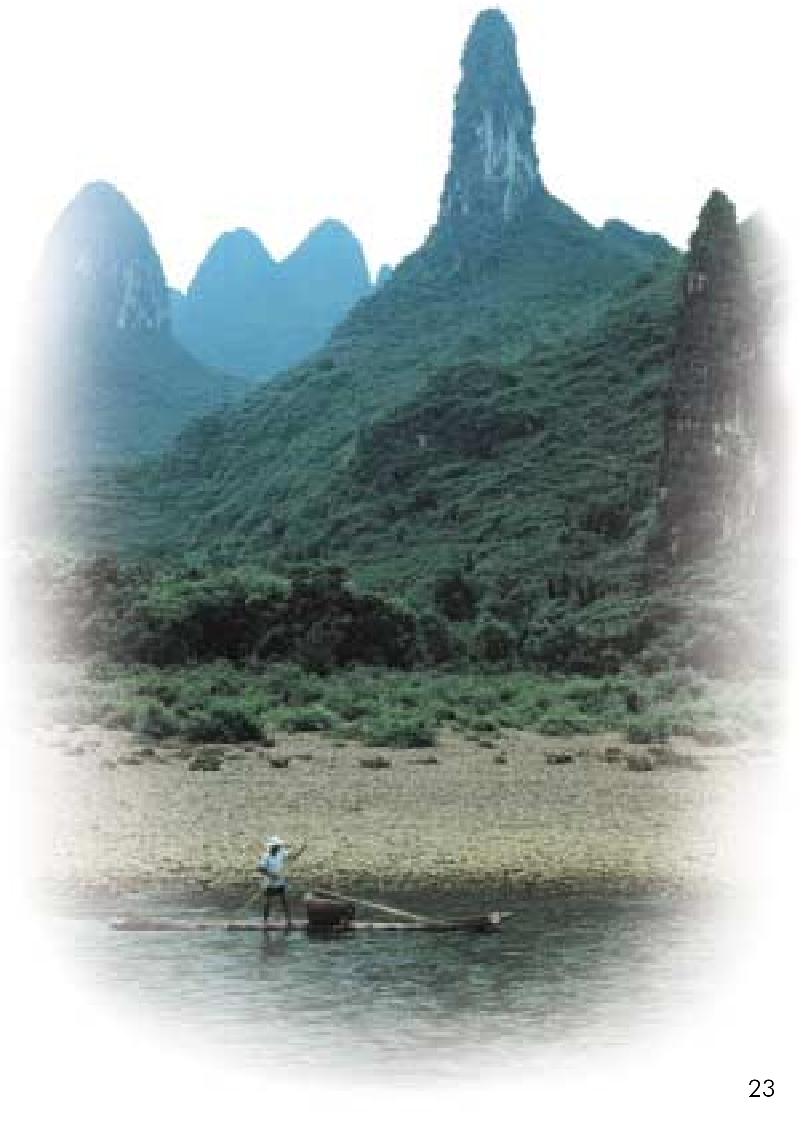


Fig. 26. The spectacular tower karst along the Li River in China.

4

ENVIRONMENTAL & ENGINEERING CONCERNS

Sinkhole collapse in Winter Park, Florida.

When karst landscapes are sites of urban development, their particular structural and hydrological characteristics must be understood. The occurrence of cavities in the rock and the soil requires special engineering considerations to provide stable foundations for the construction of roads and buildings. Because groundwater moves very rapidly in karst regions, pollutants can be spread long distances in a short period of time. Adequate supplies of drinking water may be difficult to locate and are at risk of contamination. Sinkhole collapse, drainage problems, and groundwater contamination are engineering and environmental concerns associated with development on karst terrains.

Sinkhole Collapse

Although collapse of cave passages within solid limestone bedrock is part of the normal process of landscape development in karst areas, it is a very rare event over human time scales. Most observed collapses occur in soils and sediments overlying the bedrock. In some karst areas, such sinkhole collapses reach spectacular proportions and cause considerable damage. For example, many catastrophic sinkhole collapses, such as the one on the opposite page have occurred within the relatively young, soil-covered karst of north-central Florida. This sinkhole developed in Winter Park, Florida, in 1981. Within a few days it had grown to over 330 ft (100 m) long by 300 ft (90 m) wide, swallowing cars, buildings, trees, a road, and part of a swimming pool.

Probably the most catastrophic sinkhole event in recorded history occurred in December 1962, in West Driefontein, South Africa. Twenty-nine lives were lost by the sudden disappearance of a building into a huge collapse that measured over 180 ft (55 m) across. This event, along with an additional 10 fatalities and a great deal of property damage from sinkhole collapse during the 1960s and 1970s, caused the government of South Africa to establish an intensive research program addressing the problems and mechanisms of sinkhole collapse. Collapses in the “dolomite land” areas of the country result from water entering the ground from failed water and sewer systems, poorly designed drainage, and ground vibrations. In one study in suburban Pretoria, it was determined that 96% of nearly 400 sinkholes were induced by human activities. Rapid lowering of the area’s water table by dewatering deep gold mines caused a loss of buoyant support and resulted in especially large collapses.

Sinkhole collapses occur naturally; they also may be induced by human activities (Fig. 27). Natural sinkholes and induced sinkholes can generally be separated on the basis of physical characteristics, frequency and density of occurrence, and environmental setting. Induced sinkholes generally develop much faster than natural sinkholes, although all collapse sinkholes require some dissolution of the underlying bedrock.

Fig. 27. Catastrophic sinkhole collapses have occurred in karst areas around the world and have proven costly in both dollars and lives.

Sinkhole collapse — sequence of events

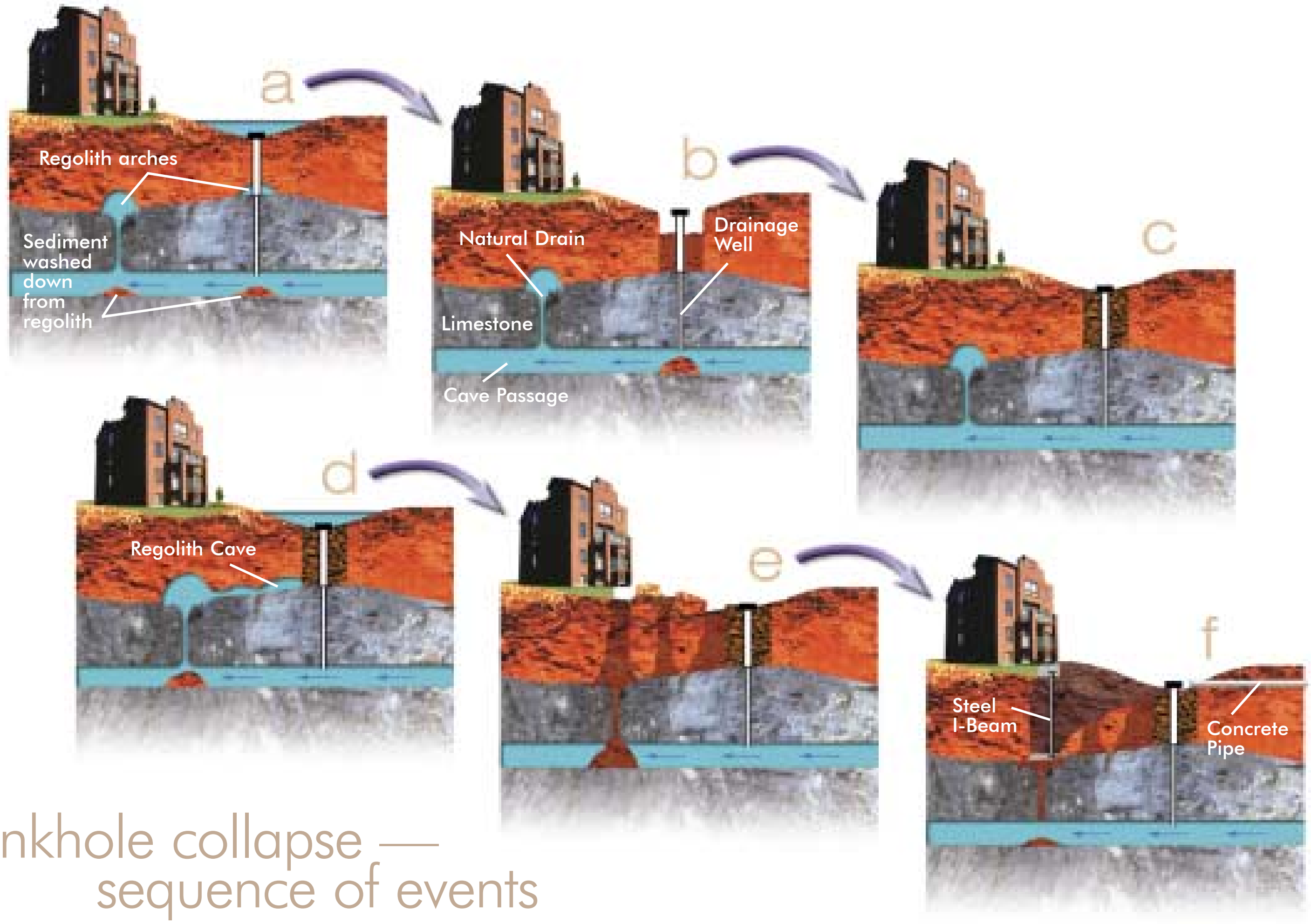


Fig. 28. (Above) ***(a)*** *In the layer of unconsolidated rock material, or regolith, arches form at a drainage well below a retention basin and at a natural drain under a building.* ***(b)*** *During a flood, collapse occurs at the drainage well.* ***(c)*** *The collapse is excavated to bedrock and filled with rocks (large at the bottom and smaller toward the top) to allow drainage into the well yet block sediment flow. In this example, that remediation is not adequate.* ***(d)*** *Water and sediment begin to flow to the natural drain, enlarging that regolith arch and forming a horizontal regolith cave.* ***(e)*** *Surface collapse occurs in three places due to collapse of the regolith arch over the natural drain and collapse of the regolith cave.* ***(f)*** *The collapses are excavated to bedrock under the building and a concrete slab poured over the natural drain in the bedrock. Steel I-beams are installed to support a new steel reinforced building foundation. The excavation is then filled with compacted soil, the retention basin is graded over, and a concrete pipe laid to direct storm-water runoff to a stream, storm sewer, or another retention basin.*

Fig. 30. Sinkhole collapse commonly results where the casings of drainage wells are not properly sealed to the bedrock.

Urbanization increases the risk of induced sinkhole collapse. The risk of collapse may increase because of 1) land-use changes, stream bed diversions, and impoundments that locally increase the downward movement of water into bedrock openings beneath the soil, and 2) greater frequency and magnitude of water-table fluctuations caused by urban groundwater withdrawal and injection.

Induced sinkhole collapses typically form by the collapse of the regolith, a general term for the layer of unconsolidated material near the surface of the land, including soil, sediment, and loose rocks (Fig. 28). Collapses are especially catastrophic when the soils and sediments are at least 20-30 ft (6-9 m) thick. These collapses result from soil washing into an underlying cave system, leaving voids in the unconsolidated material above the bedrock. In some cases, collapses occur as slow subsidence of the land surface over periods of weeks to years, rather than sudden collapses that occur over periods of minutes to days.

In areas where the water table is normally above the soil-bedrock contact, soil collapses occur when the water table drops below the soil zone, either during droughts or due to high pumping rates (Fig. 29). These collapses are caused by loss of buoyant support above the voids, or by upward propagation as saturated soil falls or washes downward. Eventually, the surface subsides gradually or abruptly collapses. Soil collapses also occur in situations where the water table is below the soil-bedrock contact. Construction and land-use changes that concentrate surface runoff in drains and impoundments will locally increase the downward movement of water. The rapidly moving water causes soil to be washed into holes in the bedrock, leaving voids behind. Increasing the load on these voids by construction or by accumulation of impounded water can initiate collapse. Collapses can also be caused by water leaking from drainage wells, pipelines, septic tanks, and drainage ditches (Fig. 30).

Although many sinkholes collapse with little or no advance warning, other collapses can be recognized by features at the land surface that indicate their development. Some of the more common features include

- Circular and linear cracks in soil, asphalt, and concrete paving and floors;
- Depressions in soil or pavement that commonly result in the ponding of water;
- Slumping, sagging, or tilting of trees, roads, rails, fences, pipes, poles, sign boards, and other vertical or horizontal structures;
- Downward movement of small-diameter vertical structures such as poles or posts;
- Fractures in foundations and walls, often accompanied by jammed doors and windows;
- Small conical holes that appear in the ground over a relatively short period of time;
- Sudden muddying of water in a well that has been producing clear water; or
- Sudden draining of a pond or creek.

Fig. 29. Water well drilling near this Florida home triggered a sinkhole collapse beneath both the drill rig and the house.

Drainage Problems

Most of the rain that falls in a karst area drains into the ground rather than flowing to a surface stream. Sinkholes may provide drains where water enters the underground flow system (Fig. 31). Cave entrances may also serve as drains. In many cases, the drains may be buried under the soil. In undisturbed karst areas, the capacity of a sinkhole drain is more or less in balance with the long-term climate and it can drain the water produced by most storms. Water backs up only during large storms when input exceeds outflow (Fig. 32).

Problems occur when the landscape is altered by urban development. Erosion is a common side effect of construction, transporting soil to the lowest part of the sinkhole where it clogs the drain. Thereafter, smaller, more frequent storms are capable of flooding the sinkhole. Impermeable ground covers such as roads, parking lots, and buildings increase the rate at which water collects and flows on the surface, flooding homes and businesses in the sinkhole (Fig. 33). Some flood-prone areas are miles from the nearest surface stream or floodplain, and property owners may not realize that they are at risk until a flood occurs.

Storm-water drainage systems can be constructed to direct runoff away from urban centers. Where sinkholes are common, the shape of the landscape complicates construction of these systems. Storm-water sewers are expensive to build where soils are thin and simple gravity drainage isn't possible without extensive trenching and/or zig-zagging the sewers around sinkholes.

One moderately effective solution is the installation of storm-water drainage wells, sometimes called "drywells." The U.S. Environmental Protection Agency classifies these drainage wells as Class V, group 5 injection wells. They are constructed in sinkhole bottoms, ditches, and storm-water retention structures where water collects after heavy rains. Drainage wells may be constructed by drilling, or by placing a pipe into a hole made by a backhoe. At some locations, the effectiveness of a drainage well can be enhanced by modifications to cave entrances, sinkhole drains, and sinkhole collapses (Fig. 34). A drainage well will function as intended if it intersects at least one unclogged crevice of sufficient size to direct storm-water into the subsurface.

Unfortunately, water directed into drainage wells is similar to water flowing directly into caves and most sinkholes, because it bypasses natural filtration and goes directly into the aquifer (Fig. 35). Runoff water should be sent to drainage wells only after incorporating Best Management Practices (page 37) to reduce the introduction of refuse and contaminants into groundwater (Fig. 36). In some commercial and industrial areas, storm-water runoff may be diverted into

Fig. 31. A sinkhole plain, typical of many well developed karst landscapes.

drainage

Fig. 33. (Left) A shopping center parking lot built in a Kentucky sinkhole floods parked cars.

Fig. 34. (Left) This cave entrance has been modified to accept drainage and prevent clogging from debris to minimize flooding of an urban Kentucky neighborhood.

Fig. 35. (Below) Unfiltered storm-water runoff from an urban area floods into a normally dry cave entrance.

Fig. 32. (Below) A rural roadway covered by sinkhole floodwaters.

Fig. 36. (Below) This sinkhole has been modified to drain storm-water runoff. Two drainage wells have been drilled into the floor of the sinkhole. Rocks and hemispherical metal grates provide some filtration of sediments and organic debris.

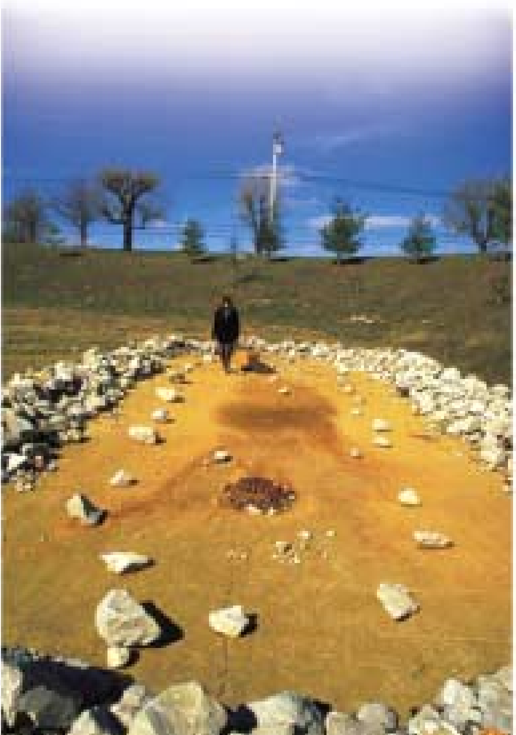


Fig. 37. (Above) A large sinkhole collapse around a poorly installed drainage well.

Fig. 38. (Below) During normal flow in a shallow karst aquifer, ***(a),*** *water is captured from sinkholes and fractures and moves downstream. A collapse in the cave passage restricts the flow, but not significantly. When flooding occurs,* ***(b),*** *the collapse acts like a leaky dam, allowing the normal flow to pass but holding back most water, raising the water table to flood Sinkholes 2 and 3. Sinkhole 1 is above the water table, but holds water due to a constriction that prevents rapid flow down into the cave stream. When a drainage well is placed in Sinkhole 1 to breach the constriction and relieve sinkhole flooding,* ***(c),*** *more water reaches the flooding cave system so the water table and flood levels in Sinkholes 2 and 3 rise even higher. At such times, buildings that would normally be above flood levels might get flooded. The same result occurs when Sinkhole 1 does not have a constriction, but receives more water as impervious material from urbanization covers the surrounding area.*

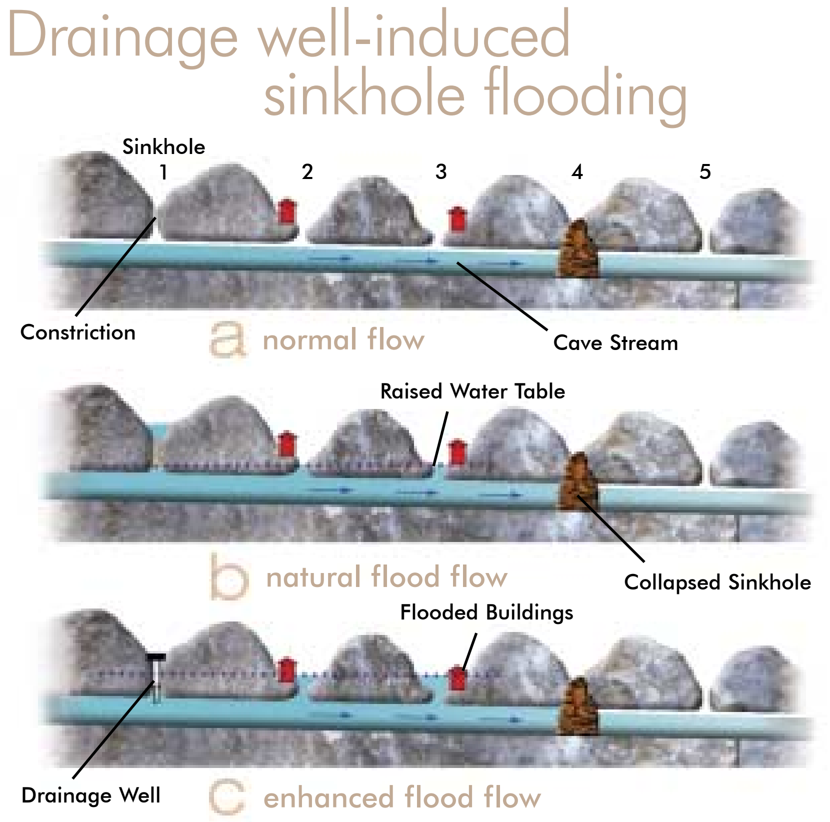


Fig. 39. Sewage, fuels, and other chemicals leave a black stain on the floor of this Kentucky cave stream.

sanitary sewers, or pretreated on site before being disposed into drainage wells. Even if good quality recharge can be maintained, the increased flooding could harm rare or endangered ecosystems within the aquifer.

Induced sinkhole collapse is a potentially severe problem associated with poor drainage well installation (Fig. 37). The casings of many old wells only extend through the soil and rest on uneven bedrock surfaces. This situation allows water to flow out from the gaps between the casings and bedrock to saturate the surrounding soil each time the well fills with water. When the water level drops below the gap, saturated soil flows into the well, leaving a void in the soil that expands upward to the surface. Extending and sealing the casings of wells into the bedrock can alleviate this problem.

Drainage wells, while meant to relieve sinkhole flooding, can cause other sinkholes to flood. Sinkholes can flood from the bottom, as water rises upward through the drain. When the capacity of the underground drainage system is exceeded, it causes any excess water in the ground to flow up into a sinkhole. This type of flooding is sometimes made worse by urban development in the headwaters of a karst drainage system and the injection of storm water into drainage wells (Fig. 38).

Groundwater Contamination

Urban and Industrial

Contamination is common in karst aquifers beneath urban areas with high population densities. Pollutants include septic tank effluent, runoff that contains metals, oil and grease, solid trash and wastes, and accidental or intentional dumping of chemical wastes by industrial facilities and homeowners. Karst aquifers in the United States have been

Fig. 41. Runoff into this sinkhole is polluted by livestock manure.

Fig. 40. A railroad runs through a sinkhole plain. Leaks and spills along transportation and pipeline corridors have introduced significant contaminants into karst aquifers.

contaminated by toxic metals, polychlorinated byphenols (PCBs), radioactive chemicals, organic solvents, and many other pollutants (Fig. 39). Although these contaminants are common in any developed area, it is the ease with which they can enter karst aquifers and the rapid rates at which they can be spread that makes karst groundwater especially vulnerable.

Accidental spills and intentional dumping of waste rapidly contaminate karst aquifers because chemicals travel easily through the soil and limestone bedrock. Spills along roads and railroads, leaking oil and gas wells, pipelines, and especially underground storage tanks have harmed many karst aquifers (Fig. 40). Gasoline has been the cause of some notable contamination problems in Hick's Cave, Kentucky, and Howard's Waterfall Cave in Georgia, where one person lost his life when the flame from a carbide miner's lamp ignited gasoline fumes. In the mid-1980s, the U.S. Environmental Protection Agency declared a "Health Advisory" for Bowling Green, Kentucky, when gasoline fumes from leaking underground storage tanks collected in the Lost River Cave System beneath the town. With time, the fumes rose into homes and schools where they posed serious health and safety problems. Eventually the source of the leak was cut off, and the underground river was able to flush the explosive material from the system.

In karst areas, landfills present special challenges. Throughout the world, landfills leak into karst aquifers and cause severe contamination problems with greater frequency, speed, and severity than in non-karst aquifers, even with modern pollution prevention methods. Part of the problem is the ease with which contaminants move through karst. Another important problem is how soils can wash into underlying voids below landfills, causing collapses that can breach liners meant to hold landfill waste in place.

Rural and Agricultural

In rural and agricultural areas, karst aquifers are subject to environmental degradation from a variety of sources including chemical fertilizers, pesticides, and herbicides, along with their breakdown products. Levels of these contaminants are high following seasonal application periods, and increase during storms. Elevated concentrations of pathogens can also be flushed through soils into aquifers beneath animal pastures and feedlots (Fig. 41). Bacterial concentrations within karst aquifers in these areas can increase thousands of times as a result of such flushing. Well and spring waters in karst are commonly contaminated, yet in rural areas there may not be an alternative water supply. Municipal water treatment and distribution facilities

Fig. 42. Soils eroded from a housing development run unfiltered into a karst aquifer.

are not available in sparsely populated karst landscapes, especially in developing areas of the world.

Another problem in karst regions is the transport of sediment into the aquifer by flowing water, making soil and other sediment washed from rural and urban land use and mining operations a significant contaminant (Fig. 42-43). Sediments can also impact the flow of groundwater by filling in conduits and modifying underground drainage. Programs to minimize soil loss are critically important for many karst areas. The impact of herbicides associated with no-till farming practices on groundwater quality should also be carefully evaluated.

A common practice in many rural landscapes is the dumping of household refuse, construction materials, and dead livestock into sinkholes. Karst aquifers have been found to contain automobile tires, car parts (Fig. 44), and in one underground river in Kentucky, a park bench and refrigerator. The amount of contamination that enters an aquifer is related to the volume and types of materials that are dumped into the sinkholes. Common harmful products include bacteria from dead animals; used motor oil and antifreeze; and "empty" herbicide, solvent, and paint containers (Fig. 45). These substances readily enter the aquifer and rapidly travel to nearby water wells and springs. Few people would throw a dead cow into a sinkhole if they realized that the water flowing over the carcass might be coming out of their kitchen faucet a few days later.

Fig. 43. Mining in and near karst aquifers poses threats of contamination from sediments and toxic metals, and destroys caves and any resources they contain.

Fig. 44. This Texas cave was used was a rural dump and is filled with car parts and other trash.

Sewage Disposal

Ideally, a rigorously maintained sewage treatment system is best for communities located on karst, including suburban and rural subdivisions. This solution is not always financially or practically possible, especially when dealing with isolated rural home or farm sites where individual septic systems are the norm. Properly designed, constructed, and, most importantly, maintained small septic systems can and have been successfully installed on karst. However, this is commonly not the case. Most karst areas have thin, rocky soils that are inadequate to reduce bacteria levels effectively. Older systems may leak from years of use without repair, or be overloaded from initially poor design or later changes to the household. Owners of failing systems often state that they have had minimal or no problems even though they have provided no maintenance! These systems can contribute significant pollutants to the groundwater. The U.S. Environmental Protection Agency has noted that the failure of septic systems is a major source of karst groundwater pollution.

Residential sewage disposal systems generally consist of a septic tank designed and constructed to hold raw sewage, separate solids from liquids, digest organic matter through anaerobic bacterial action, and allow clarified effluent to discharge to a buried soil absorption system. After effluent leaves the septic tank, it flows through a series of buried perforated pipes and is discharged into the soil. Here, pathogens are removed by microbial plant and animal life, filtration, chemical decomposition, and bonding within the soil. Septic tank effluent must be fully purified before it passes to the water table and becomes drinkable water. In non-karst areas, effluent continues to be processed after it leaves the soil as it slowly flows through the small pores and fine cracks of the aquifer. The slow movement of the effluent provides time for pathogenic bacteria and other microbial organisms to die.

Fecal coliform bacteria are organisms that live in the intestines of humans and warm-blooded animals. They have a limited life span after leaving the body so that even one colony of these bacteria indicates that water has recently been in contact with human or animal waste. Bacteria levels in wells, cave streams, and springs in karst areas may increase by thousands of times during storms. These high levels are caused when runoff from fields and septic-tank leach fields rapidly percolates through thin soils and into the bedrock. In areas where soils are too thin to effectively reduce bacteria levels, associated shallow karst aquifers should be considered unsuitable water sources. Shallow aquifers can contaminate deeper aquifers by leakage along natural fractures and conduits and through poorly designed or maintained wells. Municipal water treatment facilities should be developed in urban, residential, business, and industrial areas. Significant advances in sewage and septic system technology have recently been made and should be examined for their potential use.

Fig. 45. Household trash fills the sinkhole leading into a cave in West Virginia.

History-Making Days in the *Pike Spring Basin*

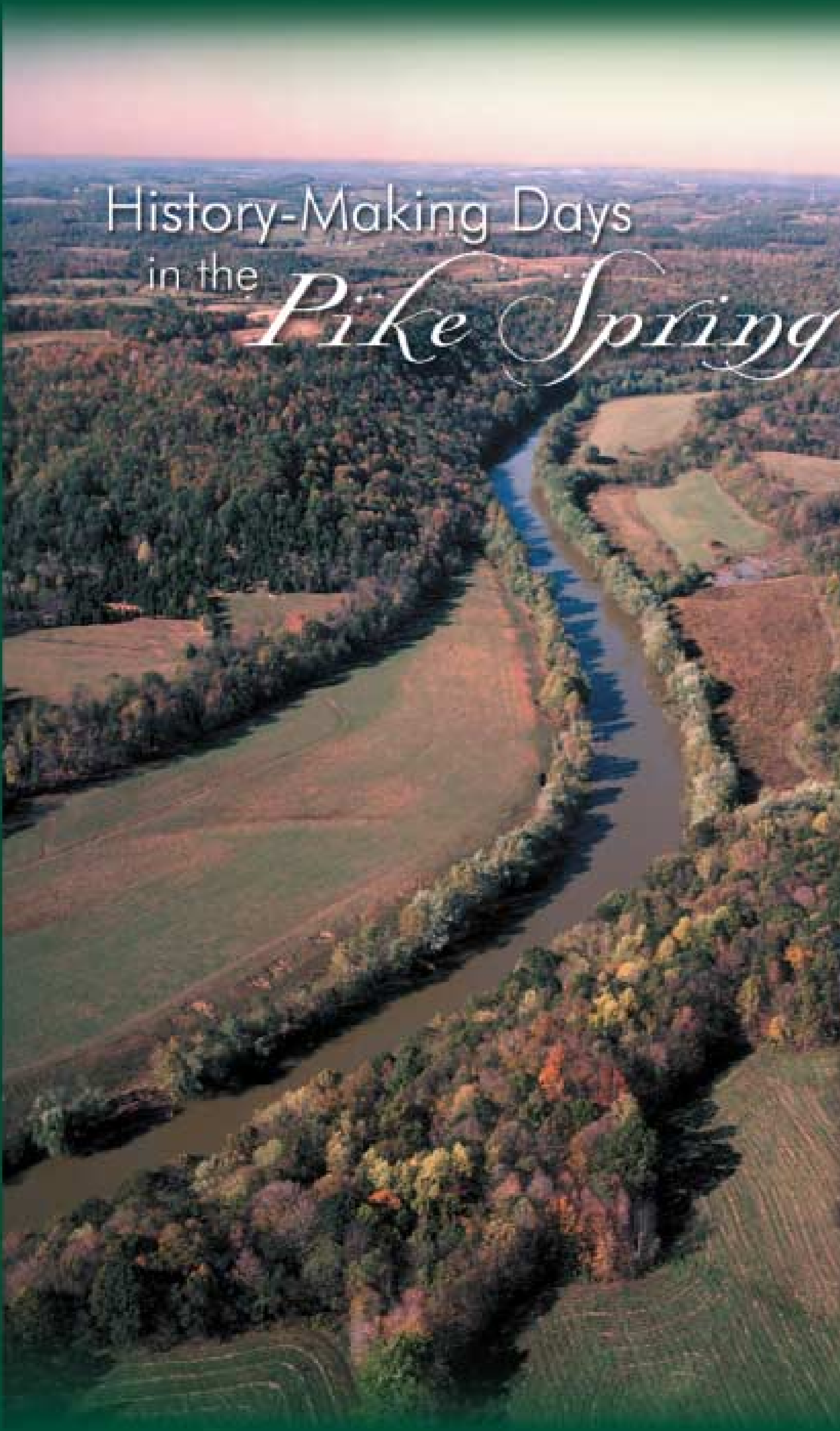


Fig. 46. (Right) Endangered Kentucky Cave Shrimp.

The landscape near Mammoth Cave National Park in central Kentucky is characterized by sinkholes, underground drainage via a karst aquifer, and intimately connected ecosystems above and below ground. A portion of the park lies within the Pike Spring Groundwater Basin, with groundwater and cave passages freely crossing the park boundary. Aquatic cave life in this basin includes blind fish, crayfish, and the largest known population of the Kentucky Cave Shrimp, which is on the federal Endangered Species List (Fig. 46). Mammoth Cave, with more than 355 mi (572 km) of charted passages, supports diverse ecosystems and is connected with and ultimately drained by the Green River (facing page).

Over the past two centuries in this rural area, residents have dumped refuse into sinkholes on their properties. Until recently, trash pickup and sanitary landfills were unavailable, and sinkholes were seen as convenient dump sites. This misplaced waste has washed into the underlying caves over time, and trash has been reported by survey teams near the park under Hamilton Valley in the Salts Cave section of Mammoth Cave.

In an effort to mitigate the environmental hazards of trash-filled sinkholes, a volunteer cooperative project called *Don't Mess With Mammoth Days* was organized in the mid-1990s. The Cave Research Foundation, Mammoth Cave National Park, and Hart County Solid Waste have been the primary organizers, with crucial assistance from the National Speleological Society, and the American Cave Conservation Association.

On the first field day, which was held in March 1996, more than 30 volunteers removed tangles of wire, sheet metal, broken glass, appliances, and automobile parts that had been discarded in sinkholes (Fig. 47). Seven truckloads of rubbish and recyclable metal were removed, and remedial work was performed on gullies to stop erosion. Subsequently, participation in *Don't Mess With Mammoth Days* events has varied from 25 to 45 volunteers, with similar impressive outcomes. To date, approximately 150 tons of rubbish, and 30 tons of recyclable metals have been recovered from dumps within the Pike Spring Basin. Although much of this waste is non-toxic, many agricultural chemical containers with residual product have been recovered as well. Ecologically, sinkholes funnel food into caves, and when they are clogged with trash, the organic matter needed by wildlife such as the Kentucky Cave Shrimp cannot get into the caves.

How long will it take to clean up Pike Spring Basin? Nobody knows. We need to learn how many dumps exist, and how many landowners within the basin would welcome the clean-up effort. Changing the way people dispose of solid waste will take time, because proper disposal of trash also costs money. Dumping trash into sinkholes may not cost money today, but the costs in terms of groundwater pollution, loss of ecosystems, and risks to public health are far greater. Cooperative efforts like *Don't Mess With Mammoth Days* provide a much-needed service, help clean up the environment, and educate by example. In the long term, education is the best tool for cleaning up and maintaining karst environments.

Fig. 47. Volunteers hauling trash out of a large sinkhole that had been used as a garbage dump for many years.

5

GUIDELINES FOR LIVING WITH KARST

Karst watershed protection is of special concern to residents of San Antonio, Texas.

Fig. 48. As San Antonio, Texas, grows, it is purchasing and preserving undeveloped sensitive karst areas to protect its groundwater supply.

The proper management of a groundwater basin is more important on karst than any other terrain. Management planning must consider all of the natural resources found within the basin, as well as interactions with adjacent areas. In this way, the quality of land, water, and subterranean environments and resources will be maintained.

The following guidelines provide a template for avoiding and solving problems encountered by people who live in karst environments.

Best Management Practices

The goal of Best Management Practices (BMPs) is to conserve natural resources, including prevention of soil erosion and minimizing the amount of contaminants that reach the groundwater system. BMPs cover a wide range of topics such as irrigation water recovery, land reclamation, nutrient management, and the sealing of abandoned wells. Many BMPs are mandated by federal, state, county and other regulatory agencies, but not all are specific to karst and thus may not adequately address karst issues. In some karst areas, best management will require exceeding the mandated BMPs with more effective actions.

Urban, Industrial, and Road Development

Industrial and urban developments commonly produce a greater variety and toxicity of contaminants than do rural areas. Communities located along the margins of karst areas should limit development in karst and encourage development in other directions. Some cities near karst regions have gone as far as purchasing aquifer areas for permanent protection. In May 2000, the citizens of San Antonio, Texas, voted for a 1/8 cent sales tax increase to raise $65 million over four years for the purchase of critical portions of the Edwards Aquifer as well as other important watershed and biological areas (Fig. 48). Where communities are located within extensive karst areas and prohibition of development in karst is not feasible, regulations may be needed to satisfactorily protect karst resources, particularly as related to the location of landfills, underground storage tanks, oil and gas wells and pipelines, and facilities that manufacture and/or store hazardous materials.

Protection of stream watersheds is vital to protecting biological and water quality. Studies examining the relationship of stream water quality to impervious cover, such as roads, buildings, and parking lots, show increased degradation when impervious cover exceeds 15% of the watershed area. Since the extent of impervious cover is a measure of urban impact that can be correlated to pollutant-load levels in urban runoff, aquifer water-quality ordinances in Austin and San Antonio, Texas, require that the percentage of impervious cover be kept low in growing urban areas. Other land-management measures that can help protect watersheds include

- Identifying and studying highly vulnerable karst features, such as caves, sinkholes,

Fig. 49. A road being built over and sealing a cave runs the risk of collapse and problems with water quality and quantity.

Fig. 50. Possible contaminants at higher elevations cannot directly reach the well because of the casing, but the well draws water from a cave stream that is exceptionally vulnerable to contamination.

and fractures enlarged by solution, prior to development. Construction may then be planned to avoid the features and preserve natural drainage into them (Fig. 49). These areas could be developed into educational neighborhood parks that increase the value of adjoining land and of the overall developments. It is important to remember that protection of these features alone will not protect karst aquifers.

- Leaving low traffic roads without curbs so that contaminants in the runoff will be diluted over broad areas and filtered through vegetated areas and soils.
- Channeling curbed runoff from major roads into storm-water sedimentation and filtration basins with hazardous materials traps. Vegetated wetland basins are the most effective at removing contaminants from the water. For such basins to be effective, they must be properly maintained and the filter material changed regularly. Runoff that may enter caves or sinkholes should either be diverted or treated through filtration systems. In 1993, the Indiana Department of Transportation established landmark guidelines for the planning, design, construction, and maintenance of roads in karst areas.
- Minimizing the use of pesticides, fertilizers, and de-icing salts on roads and urban landscapes on karst. Plants native to the area and tolerant to local pests, diseases, and climatic conditions can be grown to reduce the need for chemical support and treatment.
- Monitoring the groundwater quality of springs and wells to determine the effectiveness of the groundwater protection measures enacted. Wells are important to a monitoring plan, but not nearly as important as nearby springs that drain the area. Contaminants in karst aquifers can easily

flow past and be missed by monitoring wells, giving a false sense of security. Springs, however, capture essentially all flow (and contaminants) within their drainage basins. Sampling during high flows after storms is a good time to determine if significant levels of contaminants are present in the aquifer.

Water Supplies

Wells

As a general rule, wells should be placed where there is little or no surface drainage toward the well site. They should be located away from, and at a higher elevation than, any nearby source of contamination. Wells should be constructed to prevent contaminated water from the surface or upper level aquifers from leaking into the drinking-water aquifer. Where necessary, casing should be installed through any contaminated zone and into the productive aquifer to protect the drinking water supply from contamination. The spacing between the casing in a well and the wall of the borehole should be cemented to prevent leakage and downward migration of contaminated water (Fig. 50).

Wells should be tested for coliform bacteria and nitrates at least once a year, more often in areas of thin soil cover, and especially following storms when bacteria are most likely to be washed into the aquifer. County extension agents, community and county health agencies, water well contractors or private laboratories can provide information and assistance for well testing.

When a well is no longer used it should be disconnected from existing water systems, kept clean and, if possible, its casing should be removed. The well bore should be sealed with clean rock and a sand-cement grout to produce a continuous plug from the bottom of the well to the surface. When all abandonment procedures are complete, the well should be permanently capped. These actions are designed to prevent surface water from migrating down the well bore and polluting the aquifer.

Water well requirements vary from state to state, so it is necessary to check with the regulatory agency in your area for minimum setback distances for wellhead protection and other regulations. As an example, Minnesota requires that

- Wells must be located at least 75 ft (23 m) from cesspools, leaching pits, and dry wells, and 100 ft (30 m) or more from below-ground manure storage areas (i.e., manure lagoons), and large petroleum tanks which are protected with a containment dike, etc. They must be a minimum 150 ft (46 m) from a chemical preparation or storage area, large unprotected petroleum tanks, wastewater treatment pond or wastewater treatment plant, and they must be at least 50 ft (15 m) from septic tanks, subsurface sewage disposal fields, graves, livestock yards and buildings, and manure storage piles.
- Wells with casings less than 50 ft (15 m) deep and penetrating less than 10 ft (3 m) of clay or shale must be at least 150 ft (46 m) from cesspools, leaching pits, and dry wells, and at least 100 ft (30 m) from a subsurface sewage disposal field or manure storage pile.

Regulators and well owners must understand that although such guidelines are helpful, commonly, they are not written for karst areas. General guidelines cannot assure protection from contamination given how easily pollutants can flow long distances through

Fig. 51. Water flowed abundantly and forcefully from the first wells drilled into Texas' Edwards Aquifer in 1897. Now, with large water withdrawals from the aquifer, water discharge is restricted.

karst aquifers. Where greater assurance against pollution is needed, a detailed, site-specific hydrogeologic study, possibly to include a dye tracing test, pumping test, and test drilling may be necessary.

Groundwater Mining

While water quality issues receive most attention in the management of karst aquifers, water quantity can pose equally significant problems in arid and semi-arid climates. The large and open conduits that make karst aquifers so prone to contamination also allow massive volumes of water to be pumped out by wells (Fig. 51). If average water withdrawal exceeds the average recharge of the aquifer, the groundwater is being mined, meaning it is removed without being fully replenished. Long-term continuation of such practices is not sustainable. Springs will run dry, as will wells. Some wells can be deepened, with increased energy costs of raising water greater distances to the surface. Taken to the extreme, the aquifer would no longer yield useful quantities of water and would be abandoned.

Several methods can be used to prevent groundwater mining

- Develop a groundwater budget for the aquifer to determine its sustainable yield.
- Monitor major spring flows as rough estimates of balanced water use; extended periods or low or no flow may indicate overuse of the aquifer.
- Apply water conservation and water reuse measures.
- Consider enhancing recharge into the aquifer through dams and diversion of uncontaminated surface water into sinkholes; enhanced recharge will tend to quickly flow out of the aquifer and should only be considered for karst aquifers with high storage and relatively low velocities.
- Develop limits for the amount of water that can be withdrawn from the aquifer. Set the limits so that the water used, whether discharged from wells or springs, does not exceed average aquifer recharge. To meet these limits may require limiting community growth within the aquifer's region. Florida has developed legislation and regulations that require strict adherence to defining the impact of groundwater withdrawals on surface water, shallow aquifers, and the Floridan Aquifer. The regulations require the development of a "regional impact statement" and an application for a "consumptive use permit" based upon detailed surface water and groundwater studies.

Septic and Sewage Systems

Standard septic systems should not be placed near sinkholes, caves, springs, fractured bedrock, crevices, bedding planes, or areas of thin soil cover. There should be a minimum of 3 ft (0.9 m) of aerated soil (i.e., soils that show no mottling) below the bottom of drain field trenches. Less than that amount could result in pathogens reaching the groundwater system (Fig. 52). Soils underlying these septic systems should have percolation rates between 1 and 60 minutes/inch (0.4 to 24 minutes/cm). If the minimum parameters cannot be met, a mound system is the next preference. Other possible systems would include a designed active wetland or other experimental system with frequent groundwater monitoring results to check water treatment efficacy.

Continued maintenance is critical to the proper performance of a septic system. Maintenance is probably the most ignored BMP of operating a home septic system. Unfortunately, if the drainage does not back-up into the house it is assumed that the system is operating properly. The holding tank needs to be pumped at regular intervals (depending on the size of the tank and the number of people served) or sewage will clog the system, and untreated waste may discharge into the karst. This can happen without noticeable effects in the house. If the septic tank has not been pumped for several years and the system appears to be operating properly, suspect a leak from the tank into the karst aquifer.

Good septic-system operating practices include

- Having the system inspected regularly and pumped annually if possible, but at least every three years.

(continued on page 44)

Fig. 52. Establishing non-polluting septic systems is difficult in karst due to thin or absent soils, such as this karst pavement in Great Britain, or soils underlain by such highly dissolved limestone that promote soil collapses and rapid movement of contaminants into aquifers.

Hidden River Cave

Back from the Brink

Fig. 53. (Left) Hidden River Cave today, in the town of Horse Cave, Kentucky.

(Above) Historic Water Works at Hidden River Cave — the cave provided the town with drinking water from around 1900-1930. By the 1930s the water had become too contaminated for use.

The largest spring in Kentucky is fed by water flowing through Hidden River Cave, and the best-known entrance to the cave is located in the city of Horse Cave (Fig. 53). Beginning in 1887 the cave served as an important water supply and attraction for the city. Tours and boat rides were offered in the cave for 27 years. However, in 1931 an oil refinery began dumping its wastes into a sinkhole that drained into the cave stream. About the same time, residential sewage began to be disposed directly into the ground. By the early 1930s, the cave was abandoned as a water supply and in 1943 the cave was closed to the public due to the stench that rose from its waters out of the entrance and up to the city streets.

Eventually, water from a spring 20 miles (32 km) away was tapped for the community, and a sewage treatment plant was built in 1964. Unfortunately, the treatment plant increased pollution of the aquifer, by gathering all of the city's wastes, providing only a low level of treatment, and discharging the treated wastes into a sinkhole. Toxic heavy metals escaped treatment at the plant, and increased agricultural and urban runoff bypassed the plant and flowed directly into the cave.

In 1989, a new regional waste-water plant was built that treated the effluent to a higher standard and discharged the treated water into the Green River and away from the karst. As a result, the aquifer is slowly recovering; rare species thought lost have begun to repopulate the cave from refuges in small, unpolluted areas. Hidden River Cave is again open to the public, and it now houses the American Cave and Karst Center and Museum. Hidden River Cave is a model that shows both how severe sewage and general groundwater contamination problems can become in karst terrains, and the methods to solve those problems.

(Below) Karst Exhibit at American Cave Museum.

Historic entrance of Hidden River Cave taken around 1940 before the cave became heavily polluted.

(Left) Trickling Filter at old Horse Cave Sewage Treatment Plant. The poorly treated effluent was discharged into caves and sinkholes upstream from the city of Horse Cave.

- Avoid putting excess water through the system;
- Repairing or replacing malfunctioning systems quickly;
- Never pumping out of an inspection riser. (Report any contractor who pumps from an inspection port to the state licensing or health board);
- Putting only sewage into the system. Do not put hazardous material in the system and never put any chemical down your drain that you would not drink (e.g., paints, thinners, solvents, oils, etc.);
- Protecting the land over the septic tank and leach field. Do not build over it. Do not allow any vehicles, including garden tractors, snowmobiles, all-terrain vehicles, etc., to drive across it. Plant lawn or native grasses and other ground covers to reduce soil erosion;
- Avoiding septic tank additives. Additives can destroy the biomat, which is formed by bacteria that naturally treat and purify the wastewater; and
- Using a reputable, licensed, and bonded septic-system contractor. If your state does not license such contractors, compare the education and apprenticeship credentials among different contractors, and request information from a county extension agent or a community or county health agency, on county- and state-level septic pumping standards. At a minimum, choose a contractor who is bonded.

Sewage systems can be effective at minimizing impacts to karst aquifers if they are properly built and maintained. If not, their large flows of effluent can easily pollute major sections of aquifers. Sewer lines should be inspected regularly. In areas where sinkhole collapse is common, annual inspections and/or closely-spaced flow meters are needed to detect loss of effluent; double-walled pipelines with leak detectors in the outer pipe may be warranted in some cases. Wherever possible, sewage treatment facilities should be located off karst areas. If the treated wastewater cannot be released away from the karst, it should be treated to as near drinking-water quality standards as possible before release, especially if the aquifer is used as a potable water supply.

Sinkhole Flooding and Collapse

An effective way of dealing with sinkhole flooding in the hard-rock karst areas of the mid-continental U.S. is by building storm water retention basins. These are constructed depressions where runoff from streets, parking lots and other impermeable areas is stored until it can slowly drain through the soil. Retention basins alleviate local flooding problems and provide a means of filtering storm water through the soil, thus protecting the karst system from silt, trash, and some pollutants. Basins designed and maintained to filter sediments and pollutants are known as sedimentation and filtration basins.

Fig. 54. Some sinkhole ponds in Bowling Green, Kentucky, are used in innovative ways to capture and treat urban runoff for non-potable uses.

Bowling Green, Kentucky, a city of over 50,000 residents, is built almost entirely on a sinkhole plain (Fig. 54). Building codes there require flood easements below a line 12 inches (30 cm) above the standing water level produced by a 100-year storm of 3 hours duration where there is effectively no drainage through a sinkhole. The area below this line has been defined as a "sinkhole flood plain." Storm-water retention basins are required to accommodate drainage produced by changes in land-use accompanying development. Although the city has been successful in reducing flood losses, the numerous storm water retention basins have taken valuable urban land out of production and are expensive for developers to build and maintain. Land uses that affect the hydrologic system, such as filling of sinkholes with debris, are illegal in some areas.

Sinkhole Collapse

The most important tool in preventing and repairing sinkhole collapse is site-specific knowledge of the karst system, as well as an understanding of how karst processes affect engineered structures through time (Fig. 55). Sinkhole collapse is difficult to predict even in well-studied karst regions. Dangerous areas such as the floors of large karst valleys may be easily recognized, but buried sinkholes and fracture trends are harder to detect. When combined with large withdrawal of groundwater and a dropping water table, these areas have the greatest potential for collapse. The seemingly random nature of collapse events dictates that a special knowledge of karst is needed to guide urban and suburban development in these areas.

A variety of approaches can help avoid sinkhole collapse problems associated with urban development of karst areas.

- Karst areas should be mapped thoroughly to help identify buried sinkholes and fracture trends. Geophysical methods, aerial photography, and digitally enhanced multi-spectral scanning can identify hidden soil drainage patterns, stressed vegetation, and moisture anomalies in soils over sinkholes.
- Sinkhole collapses are commonly "repaired" by dumping any available material into the hole. This technique usually diverts water to other locations and promotes collapse. Mitigate by excavating collapses to the bedrock drain, then refilling the dug hole with material graded upward from coarse rocks to finer sediments to allow natural flow through the bedrock drain without the loss of sediments that cause collapse. If a storm-water drainage well is needed, its casing should extend into and be tightly sealed along the bedrock.
- In large sinkholes, use bridges, pilings, pads of rock, concrete, special textiles, paved ditches, curbs, grouting, flumes, overflow channels, or a combination of methods to provide support for roads and other structures.
- Large buildings should not be built above domes in caves. In areas where caves have collapsed in the past, a test-drilling program is needed prior to construction to avoid building on unstable bedrock.
- In less severe cases and in rural areas, place fences around sinkholes to keep animals out and discourage dumping. Construct berms to divert polluted runoff, and establish natural vegetation buffer zones to help filter pollutants and sediment.

Fig. 55. A small sinkhole collapse has formed around a poorly installed drainage well.

Fig. 56. Animal wastes are stored on a concrete pad until they can be applied onto fields when plants will most readily take up nutrients, breakdown bacteria, and reduce the contaminants washed down into the aquifer. This process also saves farmers money on commercial fertilizers.

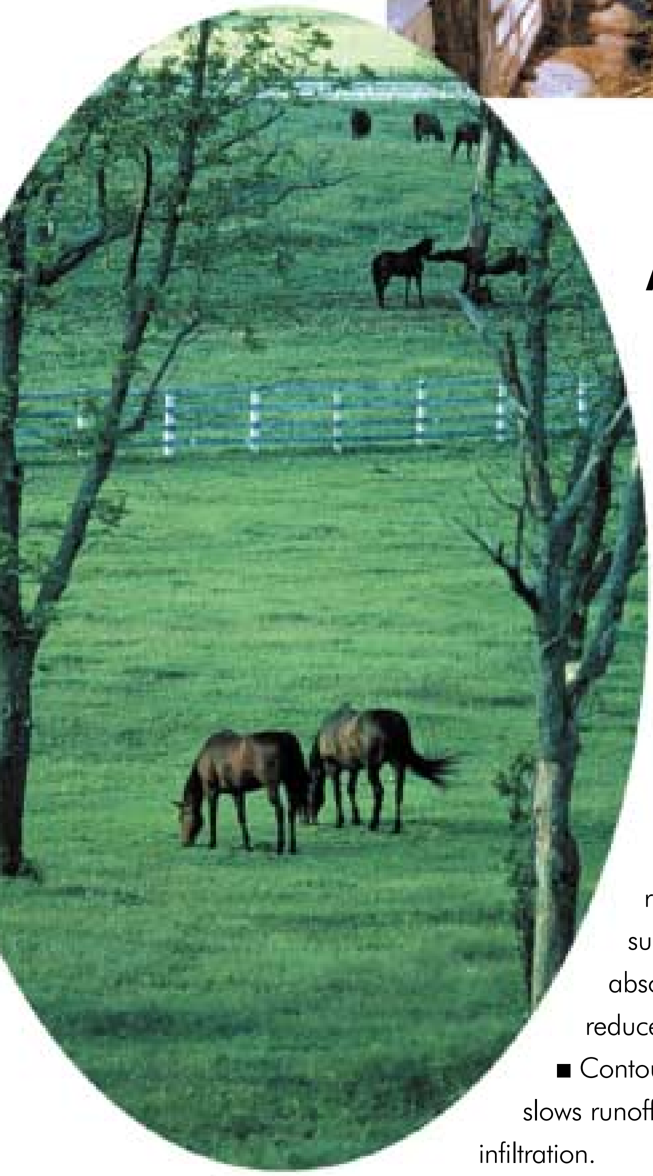


Fig. 57. Livestock can be well-maintained in karst pastures by following best management practices.

Agriculture

An important objective in managing agricultural lands in karst regions is to keep polluted surface water out of the groundwater system.

Some methods to help achieve this goal are

- "No till" cultivation, where plant residue is kept on the surface of the soil to absorb water and reduce erosion.
- Contour tillage, which slows runoff and increases soil infiltration.
- Reseeding cleared areas as quickly as possible to reduce erosion.
- Using fertilizers wisely and only in necessary amounts.
- Minimizing the use of pesticides, and using less toxic and biodegradable types.
- Not dumping waste material into sinkholes.
- Creating a long-term plan for living on karst by conducting a whole-farm and /or household evaluation of all land uses, including application or disposal of nutrients, pesticides, and hazardous materials as well as maintenance of the groundwater system.

Livestock Production

An important part of the Best Management Practices concept is recognition of the social and economic needs of the landowners and farmers whose land use practices directly impact the health of the aquifer. In karst regions, a general goal of livestock management is to keep runoff and livestock away from waterways, sinkholes, springs, crevices, and caves. On demonstration farms in the Midwestern United States, specially constructed cattle feedlots have been built where solid cattle waste is stored on a concrete stack pad (Fig. 56), with liquid waste channeled into a lined lagoon. The solid and liquid wastes are applied to fields during active phases of the growing cycle so that the plant uptake of the nutrients in these substances is maximized.

Some guidelines for keeping effluent from pastures and feedlots out of karst aquifers are

- Maintaining a herd size within the carrying capacity of the soil and water resources.
- Resting heavily grazed fields (Fig. 57).
- Using movable paddock-style pasturing when possible.
- Surrounding waterways, caves, springs, crevices, and sinkholes with strips of vegetation and fences.
- Frequently moving salt licks and watering tanks to reduce soil compaction and mini-

mize the concentration of waste products.

- Constructing sealed manure-holding tanks that are well maintained and regularly inspected.
- Cleaning abandoned manure storage sites and basins, and applying residual manure and stained soils to cropland.
- Using downspouts, gutters, berms, and storm water culverts to divert runoff away from farm buildings, feedlots and manure storage areas.

timber

Timber Harvesting

Some methods of timber harvesting remove much of the vegetation from an area and can cause significant soil erosion unless mitigating steps are taken. In karst areas, soils and plant debris can be washed into sinkholes and caves resulting in pollution of groundwater (Fig. 58). Some suggestions for a timber harvest plan in karst areas are

- Locating roads, skid trails, and work areas away from places where storm water enters the groundwater system.
- Maintaining an unharvested buffer zone around streams, springs, sinkholes, and caves (Fig. 59).
- Using bridges or culverts where roads and skid trails cross streams to minimize erosion and turbidity.
- Stabilizing cut areas quickly to prevent erosion. Slopes should be seeded and protected.
- Leaving some waste wood on the land to help stabilize it further, and to return nutrients to the soil as the waste decays.
- Not dumping waste cuttings into sinkholes or cave entrances because the debris reduces water quality, hinders drainage, and damages the habitat of cave species.
- Using selective harvesting rather than clear-cutting techniques when feasible.

Fig. 58. Timber harvest debris clogs this Canadian sinkhole, resulting in flooding and less water to replenish the aquifer.

Fig. 59. This Canadian sinkhole is in a forested area, but with an appropriate buffer area to allow unrestricted clean water to enter the aquifer.

Laws and Regulations

Because karst areas are extremely vulnerable to environmental impacts, laws and regulations that are effective in other terrains may not be as effective in karst settings. Human development and exploitation of karst aquifers can trigger catastrophic events and result in numerous legal actions that go beyond property boundaries. Few laws provide direct, significant levels of protection for karst and caves, yet substantial indirect protection may exist depending on local rules and jurisdictions. With increased awareness of the ways cave protection also protects groundwater and other resources, many existing statutes are likely to be strengthened. The following section gives examples of laws and regulations that can apply to development and use of karst areas. For a more thorough consideration of laws that may be of some benefit in the protection of karst, the reader should refer to the 1997 article in *Environmental Geology* by LaMoreaux and others (facing page).

Caves and Karst The Federal Cave Resources Protection Act of 1988 directed the secretaries of the interior and agriculture to inventory and list significant caves on federal lands, and provides a basis for protecting caves. Public Law 101-578, enacted in 1990, directed the Secretary of the Interior to work through the National Park Service to establish and administer a cave research program and to prepare a proposal for Congress that examined the feasibility of a centralized national cave research institute. The Lechuguilla Cave Protection Act, passed in 1993, recognized the international significance of the scientific and environmental values of the cave. In 1998, Congress passed the National Cave and Karst Research Institute Act that mandated the National Park Service to establish and operate the institute.

Puerto Rico, the Cherokee Nation, and 22 U.S. states have cave protection statutes in effect. Typically, they focus on protecting speleothems and placing gates on caves. Some include prohibitions against dumping trash or hazardous materials into caves, and protection for cave fauna and archeological and historic materials. A number of states have laws protecting paleontological, archaeological and historic sites, and some of these include specific mention of caves. Even without the mention of caves as such in these laws they are likely protected by being significant sites. In addition, caves may be protected as critical habitat under the provisions of some state endangered species acts. Unfortunately, in many states violation of these laws are considered misdemeanors or low-level felonies and the penalties are often slight. State cave-protection laws commonly apply on state land only, and damage can be done in a privately owned cave if the landowner gives permission. More information on state cave and karst protection laws can be found in Huppert's 1995 article on the topic (facing page).

Aquifers The Safe Drinking Water Act (SDWA), the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) aim to protect non-karst and karst aquifers. SDWA sets drinking water standards that are used to protect groundwater, to include provisions for sole-source aquifers and wellhead protection. RCRA gives the U.S. Environmental Protection Agency authority to set up programs to prevent hazardous wastes from leaching into groundwater from landfills, surface impoundments, and underground tanks. CERCLA is often called the "Superfund" because it set up a fund to support federal and state responses to hazardous waste problems.

Water quality Probably the most influential regulations that protect karst, albeit indirectly in most cases, are the many federal, state, and local laws established to protect surface and groundwater quality. Caves and karst features are seldom addressed in most water rules. However, in order to adequately protect their highly vulnerable karst areas and features, municipalities, counties, and water management agencies can pass local ordinances that provide higher levels of protection than broad-sweeping state and federal regulations. For example, New Castle County, Delaware, has passed subdivision, zoning, and building codes dealing with water-resources protection in that karst area, including amending the building code to require special procedures in "subsidence areas."

Wildlife Some caves and karst springs provide habitat for species that are listed as endangered or threatened by the U.S. Fish and Wildlife Service or equivalent state agencies (Fig. 60). Regulations to protect caves and karst areas in order to preserve their species commonly include measures that protect water quality, and sometimes require standards more stringent than those in some water laws. For example, Texas has no state pumping limits for groundwater. However, sustainable pumping of Texas' Edwards Aquifer is required by federal statute to preserve adequate flows for endangered species living in the springs, which in turn protects local communities from overpumping and depleting their primary water supply.

Fig. 60. Protection of Rhadine beetles and other endangered species living in caves and karst aquifers has provided protection for those resources where laws to provide for human needs have sometimes been inadequate.

Antiquities The Federal Archaeological Resources Protection Act can be of significant use in the conservation of caves on federal land. Most states also have regulations protecting historic and prehistoric materials. Cave specific rules are rare, but caves are included within the usual scope of these laws.

Insurance While insurance policies don't fall under the category of laws and regulations, they can be legally and financially useful or required. In Florida, insurance is available to cover personal and property damages as a result of a catastrophic sinkhole collpase. In the sinkhole plain of central Kentucky, federal flood insurance has been made available to people living in sinkholes that flood from rises in underground streams.

……

References

Huppert, George N. 1995. "Legal Protection for Caves." *Environmental Geology,* Vol. 26, No. 2, pp. 121-123.

LaMoreaux, P. E., W. J. Powell and H. E. LeGrand. 1997. "Environmental and Legal Aspects of Karst Areas." *Environmental Geology,* Vol. 29, No. 1/2, pp. 23-36.

wastes from leaching into groundwater from landfills, surface impoundments, and underground tanks. CERCLA is often called the “Superfund” because it set up a fund to support federal and state responses to hazardous waste problems.

Water quality Probably the most influential regulations that protect karst, albeit indirectly in most cases, are the many federal, state, and local laws established to protect surface and groundwater quality. Caves and karst features are seldom addressed in most water rules. However, in order to adequately protect their highly vulnerable karst areas and features, municipalities, counties, and water management agencies can pass local ordinances that provide higher levels of protection than broad-sweeping state and federal regulations. For example, New Castle County, Delaware, has passed subdivision, zoning, and building codes dealing with water-resources protection in that karst area, including amending the building code to require special procedures in “subsidence areas.”

Wildlife Some caves and karst springs provide habitat for species that are listed as endangered or threatened by the U.S. Fish and Wildlife Service or equivalent state agencies (Fig. 60). Regulations to protect caves and karst areas in order to preserve their species commonly include measures that protect water quality, and sometimes require standards more stringent than those in some water laws. For example, Texas has no state pumping limits for groundwater. However, sustainable pumping of Texas’ Edwards Aquifer is required by federal statute to preserve adequate flows for endangered species living in the springs, which in turn protects local communities from overpumping and depleting their primary water supply.

Fig. 60. Protection of Rhadine beetles and other endangered species living in caves and karst aquifers has provided protection for those resources where laws to provide for human needs have sometimes been inadequate.

Antiquities The Federal Archaeological Resources Protection Act can be of significant use in the conservation of caves on federal land. Most states also have regulations protecting historic and prehistoric materials. Cave specific rules are rare, but caves are included within the usual scope of these laws.

Insurance While insurance policies don’t fall under the category of laws and regulations, they can be legally and financially useful or required. In Florida, insurance is available to cover personal and property damages as a result of a catastrophic sinkhole collpase. In the sinkhole plain of central Kentucky, federal flood insurance has been made available to people living in sinkholes that flood from rises in underground streams.

……………………

References

Huppert, George N. 1995. “Legal Protection for Caves.” *Environmental Geology,* Vol. 26, No. 2, pp. 121-123.

LaMoreaux, P. E., W. J. Powell and H. E. LeGrand. 1997. “Environmental and Legal Aspects of Karst Areas.” *Environmental Geology,* Vol. 29, No. 1/2, pp. 23-36.

6

LOOKING TO THE FUTURE

Karst regions, like this one in Norway, provide water resources, environmental challenges, habitats, and recreation.

This booklet has provided an overview of karst areas, what they are, and how we can benefit from their resources while minimizing our impact on them. Karst terrains are so complex that it has been impossible to cover all of their aspects and issues in a booklet of this size. However, we have aimed to provide you with a good starting point for understanding and appreciating karst, as well as some directions toward sound management. As understanding of karst areas has grown, we are thrilled to see increasing interest in these regions. We hope that this booklet and the enclosed poster will greatly increase the numbers of people who understand the meaning of the word "karst" and how it affects their daily lives.

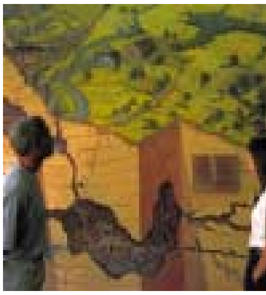
Where to Find Help

This section covers organizations that are likely to have useful information about karst and karst hydrogeology. In addition, some university departments of geology, geography, civil engineering, biology, and agricultural science offer courses related to karst issues, and may have karst experts. Local soil conservation agents are another possible source of information and assistance in some karst areas. Karst hydrogeology is a highly specialized field. Unless you are dealing with a karst-specific organization, remember that karst experts, while growing in number, are still relatively few across the country.

Land-use planners in karst areas commonly find themselves without skilled individuals for carrying out the fieldwork needed to resolve a problem or situation. The following organizations may be able to provide information and assistance about caves and karst. Nearly every state in the United States has a cave or speleological association and several state and regional cave conservancies also exist, including in Indiana, Texas, Virginia, and the southeastern United States.

American Cave Conservation Association

www.cavern.org

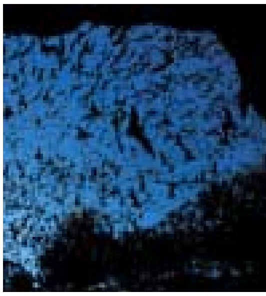


The American Cave Conservation Association (ACCA) is a national organization dedicated to the conservation and management of caves and karst resources. ACCA operates the American Cave and Karst Center and Museum in Horse Cave, Kentucky. It sponsors cave management workshops and symposia, provides curricula and training programs for teachers and students, operates public-education programs, designs and constructs cave gates, and provides technical assistance and public information on cave management issues.

American Cave Conservation Association
American Cave and Karst Center
P.O. Box 409
Horse Cave, Kentucky 42749
Tel: (270) 786-1466
e-mail: acca@caveland.net

Bat Conservation International

www.batcon.org



If a development plan involves bats, Bat Conservation International should be contacted for information. It is headquartered in Austin, Texas, and works closely with the public and local to international levels of government to promote understanding, research, and conservation of bats.

Bat Conservation International
P.O. Box 162603
Austin, Texas 78716
Tel: (512) 327-9721

Bureau of Land Management

www.blm.gov/nhp/

The Bureau of Land Management (BLM), an agency within the U.S. Department of the Interior, administers 264 million acres of America's public lands — about one-eighth of the land in the United States — and about 300 million additional acres of subsurface mineral resources. Most of the lands the BLM manages are located in the western United States, including Alaska, and are dominated by extensive grasslands, forests, high mountains, arctic tundra, and deserts. The BLM manages a wide variety of resources and uses, including energy and minerals; timber; forage; wild horse and burro populations; fish and wildlife habitat; wilderness areas; archaeological, paleontological, and historical sites; and other natural heritage values.

Bureau of Land Management
Office of Public Affairs
1849 C Street, N.W., Room 406-LS
Washington, D.C. 20240
Tel: (202) 452-5125

Center for Cave and Karst Studies

caveandkarst.wku.edu/

The Center for Cave and Karst Studies is located on the campus of Western Kentucky University in Bowling Green, which sits virtually in the center of a large karst landscape that extends from southern Indiana, through central Kentucky and Tennessee, and into northern Alabama. The Center, founded by Dr. Nicholas Crawford, is the only university program in the United States dedicated to karst studies. Its focus is on karst environmental management issues and it offers research assistantships for students, consultations and research for the public, and summer courses at Mammoth Cave National Park on topics such as, karst geology, hydrogeology, geomorphology, ecology, and archaeology.

Center for Cave and Karst Studies
Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky 42101-3576
Tel: (502) 745-4555

IAH Karst Commission

www.iah.org/

The IAH Karst Commission activities are in full agreement with the principal aims of the International Association of Hydrogeologists to advance hydrogeological science by international cooperation between hydrogeologists and specialists in other disciplines with an interest in this field. Thus, the Karst Commission tries by focusing on karst groundwater to initiate, encourage and promote relevant studies; to cooperate with other relevant organizations; to promote or organize meetings or joint meetings with other appropriate organizations; to publish the proceedings of its special studies and scientific meetings; and to promote a better understanding of karst hydrogeological principles.

Heinz Hötzl, Chairman
Department of Applied Geology
University of Karlsruhe
76128 Karlsruhe, Germany
Tel: +49 721 608 8096
e-mail: Heinz.hoetzl@bio-geo.uni-karlsruhe.de

David Drew, Vice-chairman
Department of Geography
Trinity College Dublin
Dublin 2, Ireland
Tel: 353 1 608 1888
e-mail: ddrew@mail.tcd.ie

Karst Waters Institute

www.uakron.edu/geology/karstwaters

The Karst Waters Institute is a group of leading researchers in the fields of karst geology, biology, and engineering. Although headquartered in West Virginia, its members are distributed throughout the United States. The Institute hosts international symposia on karst and has published several reports.

Karst Waters Institute
P.O. Box 490
Charles Town, West Virginia 25414
Tel: (304) 725-1211/ (202) 885-2180
e-mail: karst@american.edu

National Park Service

www.aqd.nps.gov/

Caves and karst features occur in about 77 units of the National Park System (NPS). The number of caves ranges from as few as 10 to 15 caves per unit — as in the Chesapeake & Ohio Canal National Historic Park — to more than 400 caves per unit — as in the Grand Canyon National Park. At this time, there are over 3600 known caves in the National Park System.

National Park System units may solicit the assistance of the Geologic Resources Division with the management and preservation of caves and karst. Recent management included the placement of gates on caves in Mammoth Cave National Park, Kentucky; assessments of cave resources at Petroglyphs National Monument, New Mexico; inventories of the culturally sensitive and important caves of Hawaii Volcanoes National Park; the generation of recommendations for the protection, development, and interpretation of Cathedral Caverns State Park, Alabama; and the development of cave management and protection in China, Mexico, and the Ukraine, including the Crimean peninsula.

Ron Kerbo, Cave Specialist
NPS Geologic Resources
Division
P. O. Box 25287
Denver, CO 80225-0287
e-mail: ron_kerbo@nps.gov

National Speleological Society

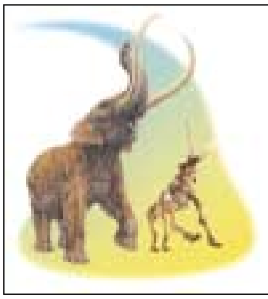
www.caves.org

The National Speleological Society (NSS), a member organization of the American Geological Institute, is an 11,000-member group dedicated to exploration, research, and conservation of caves and karst. The NSS has a history of helping to resolve problems uniquely associated with karst. An extensive library and bookstore are available at the NSS headquarters in Huntsville, Alabama. About 180 NSS chapters, called "grottos" are located throughout the country. Some of the Society's internal and affiliated organizations are specifically geared toward assisting with the management of caves and karst areas, and NSS has published some major books on cave and karst science.

National Speleological Society
2813 Cave Avenue
Huntsville, Alabama 35810-4431
Tel: (256) 852-1300
e-mail: nss@caves.org

USDA Forest Service

www.fs.fed.us/

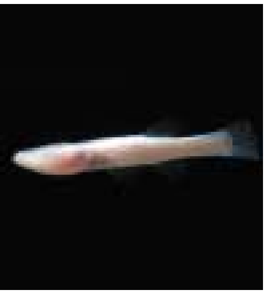


The Forest Service recreation, geology, and watershed programs have key roles in cave and karst management, helping the agency administer 192 million acres to effectively achieve its mission of "Caring for the Land and Serving People." The Forest Service recognizes that caves are a sensitive resource and must be protected. Caves can be locations of sensitive wildlife or cultural resources. In order to protect this valuable resource, the Forest Service does not release information about the locations of specific caves under Forest Service management. In 1996, the oldest human skeletal remains (9,300 years old) in Alaska and Canada were discovered in a Prince of Wales Island (POW) cave, in the Tongass National Forest. This cave, which is one of 500 inventoried caves on POW and its outlying westerly islands, is the focus of a significant international multidisciplinary effort to study the Ice Age and post-Ice Age environment and earliest occupation of northern Prince of Wales Island. In addition to the human skeleton discovery at the cave, black bear bones dating back to over 41,000 years were excavated at the cave.

USDA Forest Service (Headquarters)
P.O. Box 96090 (RHWR)
201 14th Street, S.W.
Washington, D.C. 20090-6090

U.S. Fish and Wildlife Service

www.fws.gov

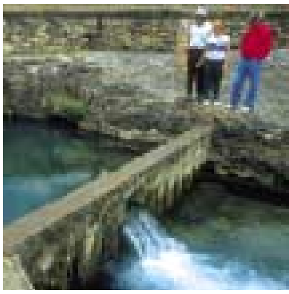


The U.S. Fish and Wildlife Service's major responsibilities are for migratory birds, endangered species, certain marine fish and mammals, and freshwater fish. The Service helps citizens learn about fish, wildlife, plants, and their habitats. Its National Conservation Training Center in West Virginia is the Nation's premier site for fish and wildlife conservation education, where people from government, industry, and non-profit groups all come for the latest in professional conservation training. The Service provides an array of electronic Web sites, where their most popular publications and hundreds of wildlife photographic images are posted and may be downloaded. The U.S. Fish and Wildlife Service has offices in every state and many territories. You can find contact information for each office and, in some cases, find office numbers and individuals listed in online phone directories. For the Refuges Visitor Guide, please call (800) 344-9453.

U.S. Fish and Wildlife Service (Headquarters)
1849 C Street N.W.
Washington, D.C. 20240

U.S. Geological Survey

www.usgs.gov



The U.S. Geological Survey (USGS) collects and disseminates information about the Earth and its resources. USGS groundwater programs encompass regional studies of groundwater systems, multidisciplinary studies of critical groundwater issues, access to groundwater data, and research and methods development.

The Learning Web, on the USGS web site, is dedicated to K-12 education, exploration, and life-long learning. Information and activities there help visitors learn how biology, geology, hydrology, and geography can help them understand our changing world. A USGS publication of particular interest to students and teachers is Open-file Report 97-536-A, *Karst Topography,* Paper model by Tau Rho Alpha, John P. Galloway, and John C. Tinsley III.

U.S. Geological Survey (Headquarters)
12201 Sunrise Valley Drive
Reston, Virginia 20192
Tel: 1 (888) ASK-USGS
e-mail: ask@usgs.gov

American Geological Institute

www.agiweb.org

The American Geological Institute is a nonprofit federation of 37 geoscientific and professional associations that represent more than 120,000 geologists, geophysicists, and other earth scientists. Founded in 1948, AGI provides information services to geoscientists, serves as a voice of shared interests in our profession, plays a major role in strengthening geoscience education, and strives to increase public awareness of the vital role the geosciences play in mankind's use of resources and interaction with the environment.

State Geological Surveys

Karst occurs in almost every U.S. state. Alabama, Florida, Kentucky, Illinois, Indiana, Missouri, Tennessee, Texas, Virginia, and West Virginia are just a few of the states containing large karst areas. In states having lesser amounts, karst may still be a significant resource. South Dakota, for example, has little karst, but its karst resources include Wind Cave National Park and Jewel Cave National Monument. Some state geological surveys, including the members of the Illinois Basin Consortium (Kentucky, Indiania, and Illinois), have karst specialists on staff. To learn more about the natural resources — including karst — and natural history of your state, contact its geological survey.

Geological Survey of Alabama
Tuscaloosa, AL
(205) 349-2852
www.gsa.state.al.us

Alaska State Geological Survey
Fairbanks, AK
(907) 451-5001
www.dggs.dnr.state.ak.us/

Arizona Geological Survey
Tucson, AZ
(520) 770-3500
www.azgs.state.az.us

Arkansas Geological Commission
Little Rock, AR
(501) 296-1877
www.state.ar.us/agc/agc.htm

Division of Mines & Geology
Sacramento, CA
(916) 323-5336
www.consrv.ca.gov./dmg

Colorado Geological Survey
Denver, CO
(303) 866-2611
www.dnr.state.co.us/geosurvey

Geological and Natural History Survey of Connecticut
Hartford, CT
(860) 424-3540
dep.state.ct.us/cgnhs/index.htm

Delaware Geological Survey
Newark, DE
(302) 831-2833
www.udel.edu/dgs/dgs.html

Florida Geological Survey
Tallahassee, FL
(904) 488-4191
www.dep.state.fl.us/geo/

Georgia Geologic Survey
Atlanta, GA
(404) 656-3214
www.dnr.state.ga.us/dnr/environ/aboutepd_files/branches_files/gsb.htm

Hawaii Geological Survey
Honolulu, HI
(808) 587-0230
kumu.icsd.hawaii.gov/dlnr/Welcome.html

Idaho Geological Survey
Moscow, ID
(208) 885-7991
www.idahogeology.org/

Illinois State Geological Survey
Champaign, IL
(217) 333-5111
www.inhs.uiuc.edu/isgsroot/isgshome/isgshome.html

Indiana Geological Survey
Bloomington, IN
(812) 855-5067
www.indiana.edu/~igs

State Geological Surveys

Iowa Department of Natural Resources
Iowa City, IA
(319) 335-1575
www.state.ia.us/government/dnr/index.html

Kansas Geological Survey
Lawrence, KS
(785) 864-3965
www.kgs.ukans.edu

Kentucky Geological Survey
Lexington, KY
(859) 257-5500
www.uky.edu/KGS

Louisiana Geological Survey
Baton Rouge, LA
(225) 388-5320
www.lgs.lsu.edu

Maine Geological Survey
Augusta, ME
(207) 287-2801
www.state.me.us/doc/nrimc/mgs/mgs.htm

Maryland Geological Survey
Baltimore, MD
(410) 554-5500
www.mgs.md.gov/

Massachusetts Executive Office of Environmental Affairs
Boston, MA
(617) 727-5830 (Ext. 305)
www.state.ma.us/envir/eoea.htm

Michigan Department of Environmental Quality
Lansing, MI
(517) 334-6923
www.deq.state.mi.us/gsd/

Minnesota Geological Survey
St. Paul, MN
(612) 627-4780
www.geo.umn.edu/mgs/index.html

Mississippi Office of Geology
Jackson, MS
(601) 961-5500
www.deq.state.ms.us/newweb/homepages.nsf

Missouri Department of Natural Resources
Rolla, MO
(573) 368-2160
www.dnr.state.mo.us/dgls/homedgls.htm

Montana Bureau of Mines & Geology
Butte, MT
(406) 496-4180
mbmgsun.mtech.edu

Nebraska Geological Survey
Lincoln, NE
(402) 472-3471
csd.unl.edu/csd.html

Nevada Bureau of Mines and Geology
Reno, NV
(775) 784-6691
www.nbmg.unr.edu/

New Hampshire Department of Environmental Services
Concord, NH
(603) 271-3503
www.des.state.nh.us

New Jersey Geological Survey
Trenton, NJ
(609) 292-1185
www.state.nj.us/dep/njgs

New Mexico Bureau of Mines & Mineral Resources
Socorro, NM
(505) 835-5420
www.geoinfo.nmt.edu/

New York State Geological Survey
Albany, NY
(518) 474-5816
www.nysm.nysed.gov/geology.html

State Geological Surveys

North Carolina Geological Survey
Raleigh, NC
(919) 733-2423
www.geology.enr.state.nc.us

North Dakota Geological Survey
Bismarck, ND
(701) 328-8000
www.state.nd.us/ndgs

Ohio Department of Natural Resources
Columbus, OH
(614) 265-6988
www.dnr.state.oh.us/odnr/geo _ survey/

Oklahoma Geological Survey
Norman, OK
(405) 325-3031
www.ou.edu/special/ogs-pttc

Oregon Department of Geology & Mineral Industries
Portland, OR
(503) 731-4100
sarvis.dogami.state.or.us

Pennsylvania Bureau of Topographic & Geologic Survey
Harrisburg, PA
(717) 787-2169
www.dcnr.state.pa.us/topogeo/indexbig.htm

Geological Survey of Puerto Rico
San Juan, PR
(809) 724-8774
www.kgs.ukans.edu/AASG/puertorico.html

Geological Survey of Rhode Island
Kingston, RI
(401) 874-2265

South Carolina Geological Survey
Columbia, SC
(803) 896-7700
water.dnr.state.sc.us/geology/geohome.htm

South Dakota Geological Survey
Vermillion, SD
(605) 677-5227
www.sdgs.usd.edu/

Tennessee Division of Geology
Nashville, TN
(615) 532-1500
www.state.tn.us/environment/tdg/index.html

Bureau of Economic Geology
Austin, TX
(512) 471-1534
www.beg.utexas.edu

Utah Geological Survey
Salt Lake City, UT
(801) 537-3300
www.ugs.state.ut.us

Vermont Geological Survey
Waterbury, VT
(802) 241-3608
www.anr.state.vt.us/geology/vgshmpg.htm

Virginia Division of Mineral Resources
Charlottesville, VA
(804) 293-5121
www.mme.state.va.us/Dmr/home.dmr.html

Washington Division of Geology and Earth Resources
Olympia, WA
(360) 902-1450
www.wa.gov/dnr/htdocs/ger/index.html

West Virginia Geological Survey
Morgantown, WV
(304) 594-2331
www.wvgs.wvnet.edu/

Wisconsin Geological & Natural History Survey
Madison, WI
(608) 262-1705
www.uwex.edu/wgnhs/

Wyoming State Geological Survey
Laramie, WY
(307) 766-2286
wsgsweb.uwyo.edu/

GLOSSARY

anaerobic bacteria Bacteria that can live in the absence of free oxygen.

aquifer A body of rocks or sediments, such as cavernous limestone and unconsolidated sand, which stores, conducts, and yields water in significant quantities.

berm A relatively narrow, horizontal shelf, ledge, or bench designed and constructed to deflect water.

best management practices (BMPs) State and/or Federal land-use regulations designed to conserve natural resources and minimize the amount of contaminants that reach the groundwater system

bioremediation The use of biological agents to clean up chemical pollutants.

calcite Calcium carbonate, $CaCO_3$, the principal mineral in limestone.

carbonic acid A mild, naturally occurring acid, H_2CO_3, that dissolves limestone, dolomite, and marble to form karst landscapes.

casing Pipe inserted and cemented into a borehole to prevent collapse and to prevent contaminated water from leaking into or out of a well.

cave A natural underground open space, generally with a connection to the surface and large enough for a person to enter. Caves in karst areas are dissolved out of soluable rock, such as limestone, dolomite, marble, gypsum, or halite.

chert A hard mineral composed mainly of microscopic silica crystals. It commonly occurs in limestone and is also called flint.

dendritic drainage A drainage pattern in which the streams branch in a tree-like pattern.

dissolution In karst, the process of dissolving rock to make landforms.

dolomite A carbonate sedimentary rock composed chiefly of the mineral dolomite, $CaMg(CO_3)_2$.

drainage well A type of well used to drain excess surface water, where the aquifer is permeable enough and the water table far enough below the land surface, to remove water at a satisfactory rate.

dry well A storm-water drainage well.

ecosystem A community of organisms and the environment in which they live including the non-living factors that exist in and affect the community.

effluent A liquid discharged as waste, such as contaminated water from a sewage works or a factory; water discharged from a storm sewer or from land after irrigation.

fecal coliform bacteria Organisms that live in the intestines of humans and other warm-blooded animals.

graded fill Material used to fill and stabilize a collapsed sinkhole. The material grades from coarse at the bottom to fine at the top of the stabilized area.

groundwater (a) That part of the subsurface water that is in the phreatic (saturated) zone, including underground streams. (b) Loosely, all subsurface water including water in both the vadose (unsaturated) and phreatic zones.

grout A cement or bentonite slurry of high water content, fluid enough to be poured or injected into spaces and thereby fill or seal them.

guano Accumulations of dung in caves, generally from bats.

gypsum A widely distributed mineral composed of calcium sulfate and water, $Ca(SO_4)\cdot 2H_2O$.

hydrologic cycle The circulation of water from the atmosphere as precipitation onto the land, where it flows over and through the land to the sea, and its eventual return to the atmosphere by way of evaporation from the sea and land surfaces and by transpiration from plants.

karst A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by dissolution. Karst landscapes are characterized by sinkholes, caves, and underground drainage.

karst aquifer A body of rock in a karst area that contains sufficient saturated permeable material to conduct groundwater and to yield significant quantities of water to springs and wells.

limestone A sedimentary rock consisting chiefly of calcium carbonate, $CaCO_3$, primarily in the form of the mineral calcite.

marble A metamorphic rock consisting predominantly of recrystalized calcite or dolomite.

mitigation The process minimizing or eliminating the effects of a problem.

paleoclimate The climate of a given period of time in the geologic past.

paleokarst Ancient karst features that have subsequently been buried under sediments.

pathogen Any microorganism or virus that can cause disease.

permeability The property or capacity of a rock, sediment, or soil to transmit fluid.

phreatic zone The subsurface zone below the water table in which all spaces are filled with water. Also known as the saturated zone.

pit A vertical cavity extending down into the bedrock; usually a site for recharge, but sometimes associated with collapse.

porosity The percentage of a rock that is occupied by pores, whether isolated or connected.

potable water Water that is safe and palatable for human use.

pseudokarst A landscape that has features similar to those found in karst landscapes, but which are formed in relatively non-soluble rocks by non-karst processes.

regolith A general term for the layer of unconsolidated fragmented rock and soil that nearly everywhere forms the surface of the land and overlies the bedrock.

retention basin Constructed depressions where runoff from streets, parking lots, and other impermeable areas is stored until it can slowly drain through soil into the bedrock.

saltpeter Naturally occurring sodium nitrate or potassium nitrate. Found in floor sediments of some caves, and formerly used in the manufacture of gunpowder.

sinkhole A funnel-shaped depression in a karst area, commonly with a circular or oval pattern. Sinkhole drainage is subterranean and sinkhole size is usually measured in meters or tens of meters. Common sinkhole types include those formed by dissolution, where the land is dissolved downward into the funnel shape, and by collapse where the land falls into an underlying cave.

sinkhole plain A plain on which most of the local relief is due to sinkholes and nearly all drainage is subterranean.

sinking stream A surface stream that loses water to the underground in a karst region.

speleothem Any secondary mineral deposit that is formed in a cave. Common forms include narrow cone-shaped stalactites that hang from ceilings, usually broader cone-shaped stalagmites that build up from the floors, and columns where stalactites and stalagmites have joined.

swallet The opening through which a sinking stream loses its water to the subsurface.

swallow hole A closed depression or cave into which all or part of a stream disappears underground.

terrain A tract or region of the earth's surface considered as a physical feature.

troglobite An organism that must live its entire life underground.

vadose zone The subsurface zone between the surface of the land and the water table. Also known as the unsaturated zone

water table The subsurface boundary between the vadose (unsaturated) and phreatic (saturated) zones.

CREDITS

Front Cover — *(Above ground, left to right)* Karst towers, Li River and Guilin, China (G. Veni); Sinkhole plain, Bosnia (© J. Wykoff); Clean water flowing into an aquifer (G. Huppert); Sinkhole collapse, Winter Park, Florida (Files of the Florida Sinkhole Research Institute courtesy of B. Beck, original photographer unknown); Limestone pinnacles, Black Stone Forest, China (G. Veni); St. Louis, Missouri (Corbis Images).

(Below ground, left to right) Chandelier Ballroom in Lechuguilla Cave, New Mexico (© D. Bunnell); Prehistoric bowl in Chiquibul Cave, Belize (G. Veni); Stream passage in Nutt Cave, West Virginia (© C. Clark); Blind cave isopod, Mammoth Cave (© C. Clark); Gypsum crystal (© C. Clark).

Inside Front Cover/ Title Page — Canadian sinkhole in forested area (G. Huppert); Karst towers, Guilin, China (G. Veni); Cave stream, Texas (K. Menking)

Page 3 — Pinnacle and cutter topography, Black Stone Forest, China (G. Veni)

Page 4 — Karst towers, Li River and Guilin, China (G. Veni)

Page 6 — Sinkhole plain (R. Ewers)

Page 7 — Karst pavement, Great Britain (© E. Kastning)

Pages 8-9 — Figure 1, U.S. Karst Map (G. Veni/ De Atley Design, Adapted from various sources)

Page 10 — Large karst pinnacles, Lunan Stone Forest, China (G. Veni)

Page 11 — Figure 2, Solution sinkhole, Barren County, Kentucky (© J. Currens)

Page 12 — Figure 3, Cave passages, Mexico (© E. Kastning); Figure 4, Pit in Texas cave (G. Veni); Figure 5, Conduit groundwater flow pattern (De Atley Design); Figure 6, Split-level cave, Mexico (© E. Kastning)

Page 13 — Figure 7, Natural Bridge Caverns, Texas (© E. Kastning); Figure 8, Collapsed passage (© E. Kastning); Figure 9, Collapse sinkhole in bedrock (© E. Kastning)

Page 14 — Figure 10, Swallet, New York (© E. Kastning); Figure 11, Fractures and pits in limestone (G. Veni)

Page 15 — Figure 12, Karst pavement (© E. Kastning); Figure 13, Hydrologic Cycle (G. Veni/ De Atley Design)

Page 17 — Figure 14, Cave stream, Texas (K. Menking); Figure 15, Blanchard Springs Caverns, Arkansas (G. Veni)

Page 18 — Canoeing in a cave stream in Indiana (A. Palmer)

Page 19 — Figure 16, Mayan drawing, 1844 (F. Catherwood); Figure 17, Catfish Farm Well, Texas (Edwards Aquifer Authority)

Page 20 — Figure 18, Ice speleothems in Swiss cave (G. Veni); Figure 19, Saltpeter vats in Mammoth Cave, Kentucky (Mammoth Cave National Park); Figure 20, Cinnabar mineral deposits in a cave, Mexico (G. Veni)

Page 21 — Figure 21, Bats in Bracken Cave, Texas (Bat Conservation International); Figure 22, Blind amphipod (J. Cokendolpher)

Page 22 — Figure 23, Olympus Mons, Mars (NASA); Figure 24, Mayan hieroglyphic painting, Guatemala (G. Veni); Figure 25, Bailong Dong (White Dragon Cave), China (G. Veni)

Page 23 — Figure 26, Karst towers along the Li River, China (G. Veni)

Page 24 — Sinkhole collapse in Winter Park, Florida (Files of the Florida Sinkhole Research Institute courtesy of B. Beck, original photographer unknown)

Page 25 — Figure 27, Sinkhole collapse (Files of the Florida Sinkhole Research Institute courtesy of B. Beck, original photographer unknown)

Page 26 — Figure 28, Sinkhole collapse sequence of events (De Atley Design, Adapted from N. Crawford and C. Groves, 1984. Storm water drainage wells in the karst areas of Kentucky and Tennessee. U.S. Environmental Protection Agency, Region 4, 52p.); Figure 30, Drainage well collapse (Center for Cave and Karst Studies)

Page 27 — Figure 29, Florida sinkhole collapse beneath house (B. Beck)

Page 28 — Figure 31, Sinkhole plain (D. Foster)

Page 29 — Figure 32, Flooded roadway (C. Groves); Figure 33, Flooded parking lot, Kentucky (A. Glennon); Figure 34, Cave entrance modified to drain urban storm water runoff, Kentucky (C. Groves); Figure 35, Urban storm water runoff flowing into a Kentucky cave (C. Groves); Figure 36, Modified sinkhole to drain storm water runoff (C. Groves)

Page 30 — Figure 37, Sinkhole collapse around a drainage well (G. Veni); Figure 38, Drainage well-induced sinkhole flooding (De Atley Design, Adapted from N. Crawford, 1986. *Karst hydrologic problems associated with urban development: groundwater contamination hazardous fumes, sinkhole flooding, and sinkhole collapse in the Bowling Green area,* Kentucky. Field trip B guidebook, National Water Well Association, 86 p.); Figure 39, Polluted Kentucky cave stream (G. Veni)

Page 31 — Figure 40, Railroad running through sinkhole plain (C. Groves); Figure 41, Sinkhole polluted by livestock manure (C. Groves)

Page 32 — Figure 42, Soil erosion into a Texas cave (G. Veni); Figure 43, Limestone quarry (R. Ewers)

Page 33 — Figure 44, Trash-filled Texas sinkhole (G. Veni); Figure 45, Household trash leading into a cave in West Virginia, (G. Schindel)

Pages 34-35 — Green River aerial view, Mammoth Cave National Park, Kentucky (© C. Clark); Figure 46, Endangered Kentucky cave shrimp (© C. Clark); Figure 47, Volunteers hauling trash, "Don't Mess with Mammoth Cave Days" (R. Olson)

Page 36 — San Antonio, Texas, night skyline (Digital Stock); San Antonio, Texas, daytime skyline (G. Veni)

Page 37 — Figure 48, Government Canyon State Natural Area, Bexar County, Texas (G. Veni)

Page 38 — Figure 49, Road building (G. Veni); Figure 50, View of well from underground (G. Veni)

Page 40 — Figure 51, Edwards Aquifer wells, Texas, 1897 (R. Hill and T. Vaughn, 1897. Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Texas, with reference to the occurrence of underground waters. 18th Annual Report of the U.S. Geological Survey, p. 193-322)

Page 41 — Figure 52, Karst pavement, Great Britain (© E. Kastning)

Pages 42-43 — Figure 53, Hidden River Cave, Kentucky (American Cave Conservation Association/ M. Ray); *(Left to right)* Historic Water Works, Hidden River Cave (ACCA); Historic entrance to Hidden River Cave, 1940 (The Thomas Family); Horse Cave Sewage Treatment Plant (R. Ewers); Exhibit at American Cave Museum (ACCA)

Page 44 — Figure 54, Sinkhole in Bowling Green, Kentucky (G. Veni)

Page 45 — Figure 55, Sinkhole around drainage well (G. Veni)

Page 46 — Figure 56, Stored animal wastes (C. Groves); Figure 57, Grazing horses (Kentucky Horse Park)

Page 47 — Figure 58, Debris clogging Canadian sinkhole (G. Huppert); Figure 59, Canadian sinkhole in forested area (G. Huppert)

Page 49 — Figure 60, Endangered blind Texas cave beetle (J. Cokendolpher)

Page 50 — Karst area in Norway (J. Mylroie)

Page 51 — Exhibit at American Cave Museum (American Cave Conservation Association); Bats in Bracken Cave, Texas (Bat Conservation International)

Page 52 — Sinkhole in Bowling Green, Kentucky (G. Veni)

Page 53 — Grand Canyon, Arizona (Digital Vision); Soda straw stalactites (G. Veni); Mammoth, Manti-LaSal National Forest, "Fabulous Fossils" poster, USDA Forest Service (College of Eastern Utah Prehistoric Museum)

Page 54 — Blind cave fish, Mammoth Cave, Kentucky (© C. Clark); Artesian San Pedro Park Spring, Texas (G. Veni)

Page 64 — Photo montage (De Atley Design)

Inside Back Cover — Old, dry cave stream, Texas (G. Veni); Waterfall originating from fractures in the ceiling of a cave (G. Veni)

Back Cover — Clouds forming in large room of the Chiquibul Cave System, Belize (G. Veni); Cave painting, Lascaux, France; Karst spring, Val Verde County, Texas (G. Veni); Cone karst in Guatemala (G. Veni)

ADDITIONAL READING

Aley, T.J., J.H. Williams, and J.W. Massello. 1972. *Groundwater Contamination and Sinkhole Collapse Induced by Leaky Impoundments in Soluble Rock Terrain* (Engineering Geology Series No. 5). Missouri Department of Natural Resources, Rolla, Missouri, 30 p.

Chapman, P., 1993. *Caves and Cave Life*. HarperCollins, London, 224 p.

Courbon, P., C. Chabert, P. Bosted, and K. Lindsley (eds.), 1989. *Atlas of the Great Caves of the World*. Cave Books, St. Louis, Missouri, 369 p.

Drew, D., and H. Hötzl, 1999. *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications*. International Association of Hydrogeologists, A.A. Balkema, Rotterdam, 322 p.

Eckenfelder, Inc., 1996. *Guidelines for Wellhead and Springhead Protection Area Delineation in Carbonate Rocks*. Report 904-B-97-003, Ground-water Protection Branch, Region 4, U.S. Environmental Protection Agency.

Ford, D.C., and P.W. Williams, 1989. *Karst Geomorphology and Hydrology*. Unwin Hyman, London, 601 p.

Gibert, J., D.L. Danielpol, and J.A. Stanford (eds.), 1994. *Ground-water Ecology*. Academic Press, San Diego, California, 571 p.

Gillieson, D., 1996. *Caves: Processes, Development, Management*. Blackwell, Oxford, United Kingdom. 324 p.

Hill, C.A., and P. Forti (eds.), 1997. *Cave Minerals of the World*, 2nd ed. National Speleological Society, Huntsville, Alabama, 463 p.

Hughes, T.H., B.A. Memon, and P.E. LaMoreaux, 1994. *Landfills in Karst Terrains*. Bulletin of the Association of Engineering Geologists, v. 31, no. 2, pp. 203-208.

James, N.P., and P.W. Choquette (eds.). 1987. *Paleokarst*. Springer-Verlag, New York, New York, 416 p.

Jennings, J.N., 1985. *Karst Geomorphology*. Basil Blackwell, Oxford, United Kingdom, 293 p.

Klimchouk, A.B., D.C. Ford, A.N. Palmer, and W. Dreybrodt (eds.), 1999. *Speleogenesis: Evolution of Karst Aquifers*. National Speleological Society, Huntsville, Alabama, 527 p.

LaMoreaux, P.E., 1994. "History of Karst Studies." In: Special Report; *Hydrogeology, Part II*. The Professional Geologist, v. 39, no. 9, pp. 9-11. American Institute of Professional Geologists, Littleton, Colorado.

Milanovic, P.T., 1981. *Karst Hydrogeology*. Water Resources Publications, Littleton, Colorado, 434 p.

Milanovic, P.T., 2000. *Geological Engineering in Karst*. Zebra Publishing Ltd, Belgrade, Yugoslavia, 347 p.

Moore, G.W., and Sullivan, N., 1997. *Speleology: Caves and the Cave Environment*, 3rd ed. Cave Books, St. Louis, Missouri, 176 p.

Newton, J.G., 1976. *Early Detection and Correction of Sinkhole Problems in Alabama, with a Preliminary Evaluation of Remote Sensing Applications*. Alabama Highway Research HPR Report No. 76, 83 p.

Veni, G, 1999. *A Geomorphological Strategy for Conducting Environmental Impact Assessments in Karst Areas*. Geomorphology, v. 31, pp. 151-180.

White, W.B., 1988. *Geomorphology and Hydrology of Karst Terrains*. Oxford University Press, New York, 464 p.

Zokaites, C., 1997. *Living on Karst: A Reference Guide for Landowners in Limestone Regions*. Cave Conservancy of the Virginias, Richmond, Virginia, 26 p.

INDEX

Supporting

GEOSCIENCES

for the Future

AGI FOUNDATION

The AGI Foundation was established more than a decade ago to assist the Institute in seeking funding and partnerships with foundations, corporations, other organizations, and individuals that share our commitment to create innovative Earth-science programs of benefit to all citizens. AGI's programs — focusing on education, worldwide information systems, government affairs, environmental awareness and other issues — offer new opportunities for geoscientists, enhance research capabilities of professional Earth scientists, and develop innovative education tools to expand the Earth-science knowledge base of all Americans, not just those who will choose geoscience as a career.

AGI's "popular" Environmental Awareness publications provide a balanced review and discussion of key environmental geoscience concerns. The colorful booklets and posters present accurate environmental geoscience information in an easy-to-digest format. AGI produces the Series with Foundation support — and in cooperation with its member societies and others — to raise public understanding of society's complex interaction with the Earth. In addition to groundwater, soils, metal mining, and karst, the Series will cover environmental geoscience concerns related to water, minerals, petroleum, global change, mapping, and other important topics.

The American Geological Institute gratefully acknowledges the generous contributions the following companies have made to the AGI Foundation in support of AGI's environmental and Earth science education programs.

Anadarko Petroleum Corporation
Atlantic Richfield Company
Baker Hughes Foundation
Barrett Resources Corporation
BP Amoco PLC
Conoco Inc.
Consolidated Natural Gas Company Foundation
Diamond Offshore Company
EEX Corporation
Exxon Education Foundation
Global Marine, Inc.
Halliburton Foundation, Inc.
Kerr-McGee Foundation Corporation
Mobil Oil Foundation
Occidental Oil & Gas Charitable Foundation
Parker Drilling Company
Phillips Petroleum Company
Santa Fe Snyder Corporation
Schlumberger Foundation, Inc.
Shell Oil Company Foundation
Southwestern Energy Production Company
Texaco Foundation
Texas Crude Energy, Inc.
Unocal Corporation
Vulcan Materials Company

AGI Environmental Geoscience Advisory Committee

Philip E. LaMoreaux, Chair
LaMoreaux and Associates

Stephen H. Stow, Co-Chair
Oak Ridge National Laboratory

Kirk W. Brown
Texas A&M University
(Soil Science Society of America)

Harvey R. DuChene
Englewood, CO
(National Speleological Society)

Charles H. Gardner
North Carolina Geological Survey
(Association of American State Geologists)

Lee C. Gerhard
Kansas Geological Survey
(American Association of Petroleum Geologists)

Dennis Goldman
Geological Society of America
(Geological Society of America)

Julian W. Green
Univ. of South Carolina at Spartanburg
(Geoscience Information Society)

Beth A. Gross
GeoSyntec Consultants
(Geo-Institute of American Society of Civil Engineers)

Frederick B. Henderson III
Hendco Services
(Society for Mining, Metallurgy, and Exploration)

Julia A. Jackson
American Geological Institute
(Association of Earth Science Editors)

John C. Jens
Manassas, VA
(American Institute of Professional Geologists)

Anne MacDonald
Exponent Environmental Group
(Association of Engineering Geologists)

John E. Moore
Denver, CO
(International Association of Hydrologists)

Geoffrey S. Plumlee
U.S. Geological Survey
(Society of Economic Geologists)

Karl A. Riggs Jr.
Geologic Services
(SEPM, Society for Sedimentary Geology)

Nelson R. Shaffer
Indiana Geological Survey
(Friends of Mineralogy)

William Siok
American Institute of Professional Geologists
(American Institute of Professional Geologists)

Donald W. Steeples
University of Kansas
(Society of Exploration Geophysicists)

Jill M. Whitman
Pacific Lutheran University
(National Association of Geoscience Teachers)

Scott L. Wing
National Museum of Natural History
(Paleontological Society)

Liaisons

Ron Hoffer
U.S. Environmental Protection Agency

John R. Keith
U.S. Geological Survey

John M. Stafford
Holme, Roberts and Owen

James Twyman
American Petroleum Institute

Sandra L. Waisley
U.S. Department of Energy

American Geological Institute

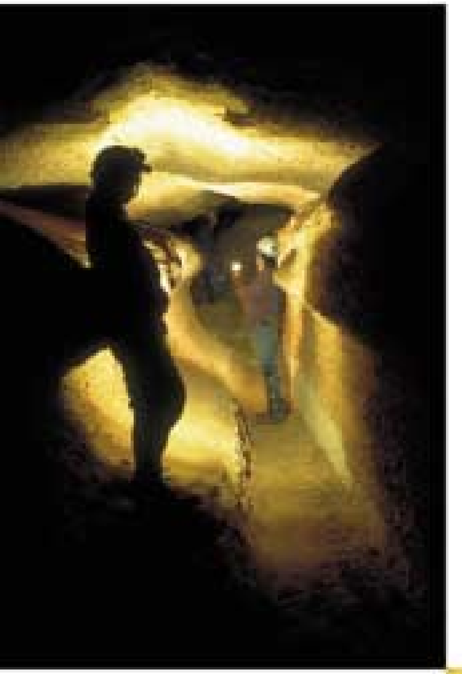
Marcus E. Milling
Executive Director

Travis L. Hudson
Director of Environmental Affairs

AGI Foundation

Bruce S. Appelbaum
Chairman

J. F. (Jan) van Sant
Executive Director



LIVING WITH KARST

A Fragile Foundation

George Veni
Harvey DuChene
Nicholas C. Crawford
Christopher G. Groves
George N. Huppert
Ernst H. Kastning
Rick Olson
Betty J. Wheeler

Nearly 25% of the world's population lives in karst areas — landscapes that are characterized by sinkholes, caves, and underground drainage. *Living With Karst*, the 4th booklet in the AGI Environmental Awareness Series, vividly illustrates what karst is and why these resource-rich areas are important. The booklet also discusses karst-related environmental and engineering concerns, guidelines for living with karst, and sources of additional information.

Produced by the American Geological Institute in cooperation with the National Speleological Society, American Cave Conversation Association, Illinois Basin consortium, National Park Service, U.S. Bureau of Land Management, USDA Forest Service, U.S. Fish and Wildlife Service, and the U.S. Geological Survey.

ISBN 0-922152-58-6

♻ Recycled Paper

American Geological Institute
4220 King Street
Alexandria, VA 22302
(703) 379-2480
www.agiweb.org

National Speleological Society
2813 Cave Avenue
Huntsville, AL 35810
(256) 852-1300
www.caves.org

AGI ENVIRONMENTAL AWARENESS SERIES