

January 2002

Proceedings of the 2002 U.S. Geological Survey Karst Interest Group, Shepherdstown, West Virginia August 20-22, 2002 USGS Karst Interest Group USGS Water-Resources Investigations Report 02-4174

Eve L. Kuniansky

U.S. Geological Survey Karst Interest Group

Follow this and additional works at: https://digitalcommons.usf.edu/kip_talks

Recommended Citation

Kuniansky, Eve L. and U.S. Geological Survey Karst Interest Group, "Proceedings of the 2002 U.S. Geological Survey Karst Interest Group, Shepherdstown, West Virginia August 20-22, 2002 USGS Karst Interest Group USGS Water-Resources Investigations Report 02-4174" (2002). *KIP Talks and Conferences*. 102.

https://digitalcommons.usf.edu/kip_talks/102

This Conference Proceeding is brought to you for free and open access by the Karst Information Portal at Digital Commons @ University of South Florida. It has been accepted for inclusion in KIP Talks and Conferences by an authorized administrator of Digital Commons @ University of South Florida. For more information, please contact digitalcommons@usf.edu.



U.S. Geological Survey Karst Interest Group Proceedings, Shepherdstown, West Virginia August 20-22, 2002

Water-Resources Investigations Report 02-4174



**U.S. Department of the Interior
U.S. Geological Survey**

**U.S. Geological Survey Karst Interest Group
Proceedings, Shepherdstown, West Virginia,
August 20-22, 2002**

Eve L. Kuniarsky, *editor*

**U.S. Geological Survey
Water-Resources Investigations Report 02-4174**

**Atlanta, Georgia
2002**

U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY

CHARLES G. GROAT, Director

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Government.

For additional information, please write to:

Regional Hydrologist
Eastern Region, South
3850 Holcomb Bridge Road
Suite 160
Norcross, GA 30092

Copies of this report can be obtained online from:

Office of Ground Water
U.S. Geological Survey
<http://water.usgs.gov/ogw/karst/index.htm>

Contents

Introduction and Acknowledgments	1
Agenda, U.S. Geological Survey Karst Interest Group Workshop	3
Integrating Science	7
Overview of background resources on karst research emphasizing obscure and “grey area” documents, by Barry F. Beck	7
National Cave and Karst Research Institute—Progress in the first two years, by Zelda Chapman Bailey	8
Considerations for managing karst in the National Park Service, by Ronal C. Kerbo	11
Tracers	13
Demystifying ground-water flow and contaminant movement in karst systems using chemical and isotopic tracers, by Brian G. Katz.	13
Development of a counterterrorism preparedness tool for evaluating risks to karstic spring water, by Malcolm S. Field	20
Comparison of methods to source track bacteria in ground water in karst areas of Berkeley County, West Virginia, by Melvin Mathes, Don Stoeckel, and Ken Hyer	30
Karst aquifers as atmospheric carbon sinks: An evolving global network of research sites by Chris Groves, Joe Meiman, Joel Despain, Liu Zaihua, and Yuan Daoxian	32
State and National Programs	40
Synopsis of karst investigations conducted in Jefferson and Berkeley Counties, West Virginia, by the U.S. Geological Survey West Virginia District, by Mark D. Kozar	40
National Karst Map Project, an update, by Jack B. Epstein, David J. Weary, Randall C. Orndorff, Zelda C. Bailey, and Ronal C. Kerbo	43
Structure and Genesis	45
Karstification along an active fault zone in Cyprus, by Richard W. Harrison, Wayne L. Newell, and Mehmet Necdet	45
Structural and lithologic control of karst features in northwestern New Jersey, by Donald H. Monteverde and Richard F. Dalton	49
Three-dimensional geologic framework modeling for a karst region in the Buffalo National River, Arkansas, by Kyle E. Murray and Mark R. Hudson	51
Stratigraphy-karst relationships in the Frederick Valley of Maryland, by David K. Brezinski and James P. Reger	59

Poster Session Abstracts	66
Evaluating travel times and transient mixing in a karst aquifer using time-series analysis of stable isotope data, by Andrew J. Long and Larry D. Putnam	66
Changes in nitrate concentrations in spring waters due to mixing of surface and ground water in the Woodville Karst Plain, Northern Florida, by B. G. Katz, A. R. Chelette, and T.R. Pratt	74
Use of dye tracing to determine conduit flow paths within source-protection areas of a karst spring and wells in the Bear River Range, northern Utah, by Lawrence E. Spangler	75
Field Trip Guide	81
Hydrogeologic framework of the northern Shenandoah Valley carbonate aquifer system, by Randall C. Orndorff and George E. Harlow, Jr.	81

INTRODUCTION AND ACKNOWLEDGMENTS

Karst aquifer systems occur throughout the United States and its territories. The complex depositional environments that form carbonate rocks combined with post-depositional tectonic events and the varied climate in which these rocks are found, result in unique systems. The dissolution of calcium carbonate and the subsequent development of distinct and beautiful landscapes, caverns, and springs have resulted in some karst areas of the United States being designated as national or state parks and commercial caverns. Karst aquifers and landscapes that form in tropical areas, such as the north coast of Puerto Rico differ greatly from karst areas in more arid climates, such as central Texas or South Dakota. Many of these public and private lands contain unique flora and fauna associated with the water. Thus, multiple Federal, state, and local agencies have an interest in the study of karst areas.

Carbonate sediments and rocks are composed of greater than 50 percent carbonate, CO_3 , and the predominant carbonate mineral is calcium carbonate or limestone, CaCO_3 . Unlike terrigenous clastic sedimentation, the depositional processes that produce carbonate rocks are complex, involving both biological and physical processes. These depositional processes impact greatly the development of permeability of the sediments. Carbonate minerals readily dissolve and precipitate depending on the chemistry of the water flowing through the rock, thus the study of both marine and meteoric diagenesis of carbonate sediments is multidisciplinary. Once the depositional environment and the subsequent diagenesis is understood, the dual porosity nature of karst aquifers presents challenges to scientists attempting to study ground-water flow and contaminant transport.

Many of the major springs and aquifers in the United States occur in carbonate rocks and karst areas. These aquifers and springs serve as major water supply sources and as unique biological habitats. Commonly, there is competition for the water resources of karst aquifers, and urban development in karst areas can impact the ecosystem and water quality of these aquifers.

The idea for developing a Karst Interest Group evolved during the November 1999, National Ground-Water Meeting of the U.S. Geological Survey, Water Resources Division. As a result, the Karst Interest Group was formed in 2000. The Karst Interest Group is a loose-knit organization of U.S. Geological Survey employees devoted to fostering better communication among scientists working on, or interested in, karst hydrology studies.

The mission of the Karst Interest Group is to encourage and support interdisciplinary collaboration and technology transfer among U.S. Geological Survey scientists working in karst areas. Additionally, the Karst Interest Group encourages cooperative studies between the different disciplines of the U.S. Geological Survey and other Department of Interior agencies, and university researchers.

The first Karst Interest Group Workshop was held in St. Petersburg, Florida, February, 13-16, 2001. That meeting was sponsored by Bonnie A. McGregor, Eastern Regional Director of the U.S. Geological Survey and co-hosted by Wanda C. Meeks, Regional Hydrologist, Eastern Region South and Lisa L. Robbins, Director of the Center for Coastal Geology, both of the U.S. Geological Survey. The U.S. Geological Survey, Office of Ground Water, provides support for the Karst Interest Group website. The first proceeding, Water-Resources Investigations Report 01-4011 is available online at: <http://water.usgs.gov/ogw/karst/index.htm>

As agreed by participants at the first Karst Interest Group Workshop in St. Petersburg, Florida, a second workshop was planned in a different geographic location, with a similar workshop format. The Shepherdstown, West Virginia, location is in close proximity to the carbonate aquifers of the northern Shenandoah Valley. Randall Orndorff and George Harlow, U.S. Geological Survey, agreed to develop the workshop field trip and field trip guide. The field trip is designed to help members of the Karst Interest Group understand the hydrogeologic framework of the carbonate aquifers of the northern Shenandoah Valley.

The second workshop and proceedings are sponsored by Zelda C. Bailey, National Park Service Interim Director of the Cave and Karst Research Institute and Norman Grannemann, U.S. Geological Survey, Ground-Water Resources Program Coordinator. This proceedings, Water-Resources Investigations Report 02-4174, will be made available online through the website listed above shortly after the workshop.

This second proceedings results from the efforts of the planning committee to bring together U.S. Geological Survey scientists with other Department of Interior scientists and land managers and University researchers interested in karst hydrology. Additionally, members of the private sector and State agencies involved in karst studies or land management are participating. The presentations cover: integrating science, the use of tracers in karst studies, state and national karst programs, the structure and genesis of karst areas, borehole flow measurements in limestone, and a field trip.

The planning committee for this second workshop included: Zelda C. Bailey, National Park Service; and Alan W. Burns, Norman Grannemann, Eve L. Kuniansky, Randall C. Orndorff, and Albert T. Rutledge, U.S. Geological Survey. We sincerely hope that this workshop promotes future collaboration among scientists of varied educational backgrounds and improves of our understanding of karst systems in the United States and it's territories.

The extended abstracts of U.S. Geological Survey authors were reviewed and approved for publication by the U.S. Geological Survey. Articles submitted by university researchers and other Department of Interior agencies did not go through the U.S. Geological Survey review processes, and therefore may not adhere to our editorial standards or stratigraphic nomenclature. However, all articles were edited for consistency in appearance in the published proceedings. The use of trade names in any article does not constitute endorsement by the U.S. Geological Survey.

The cover illustration was designed by Ann Tihansky, U.S. Geological Survey, Tampa, Florida, Office for the first Karst Interest Group Workshop.

Eve L. Kuniansky
Karst Interest Group Coordinator

AGENDA, U.S. GEOLOGICAL SURVEY KARST INTEREST GROUP WORKSHOP

August 20 – 22, 2002
Shepherdstown, WV
USFWS Training Facility Auditorium

Tuesday, August 20

Time	Title
------	-------

Integrating Science

8:30 – 9:00	Opening Remarks-Eve Kuniansky, U.S. Geological Survey Integrated Science in the U. S. Geological Survey –Tom Armstrong
9:00 – 10:00	Invited Lecture-Overview of Research and Engineering in Karst by P.E. LaMoreaux and Associates –Barry Beck, P.E. LaMoreaux and Associates
10:00 – 10:30	BREAK
10:30—11:00	National Cave and Karst Research Institute–Progress in the First Two Years – Zelda Chapman Bailey. National Park Service
11:00--11:30	Considerations for Managing Karst in the National Park Service --Ronald C. Kerbo. National Park Service
11:30 – 1:00	LUNCH

Tracer session

1:00 – 1:30	Demystification of ground-water flow and contaminant movement in karst systems using chemical and isotopic tracers –Brian G. Katz. U.S. Geological Survey
1:30 –2:00	Age Dating studies in Karst Systems of the Shenandoah Valley –Neil Plummer. U.S. Geological Survey
2:00 – 2:30	Development of Counterterrorism Preparedness Tool for Evaluating Risks to Karstic Spring Water –Malcolm S. Field. U.S. Environmental Protection Agency
2:30 – 3:00	BREAK
3:00 – 3:30	Comparison of methods to source track bacteria in ground water in karst areas of Berkeley County, West Virginia –Melvin Mathes, Don Stoeckel, and Ken Hyer. U.S. Geological Survey
3:30 – 4:00	Karst Aquifers as Atmospheric Carbon Sinks: An Evolving Global Network of Research Sites –Chris Groves, Western Kentucky University and Joe Meiman. National Park Service
4:00 – 5:00	Panel discussion: Natural and Anthropogenic Tracers –Neil Plummer, Malcolm Field, and Brian Katz

Wednesday, August 21

Time	Title
------	-------

State and National Program session

8:00 – 8:30	Managing a hidden landscape. Stakeholders perceptions and concerns –Patricia E. Seiser. West Virginia University
8:30 – 9:00	Synopsis of ground-water investigations by the U.S. Geological Survey in karst areas of Jefferson and Berkeley Counties, West Virginia –Mark D. Kozar. U.S. Geological Survey
9:00 – 9:30	Recent Activities and Accomplishments of the Virginia Department of Conservation and Recreation, Division of Natural Heritage Karst Program –Joey Fagan and Will Orndorff. Virginia Department of Conservation and Recreation
9:30 – 10:00	National Karst Map Project, an Update –Jack Epstein, David Weary, and Randy Orndorff. U.S. Geological Survey, and Zelda Chapman Bailey. National Park Service
10:00 – 10:30	BREAK
10:30 – 11:00	Karst Initiative in the USGS Ground-Water Resources Program –Norman Granneman and Charles Taylor. U.S. Geological Survey
11:00 – 11:30	Panel Discussion: GWRP Karst Initiative –Norman Granneman and Charles Taylor. U.S. Geological Survey
11:30 – 1:00	LUNCH

Structure and genesis session

1:00 – 1:30	Karstification along an active fault in eastern Cyprus –Richard W. Harrison, Wayne L. Newell, and Mehmet Necdet. U.S. Geological Survey
1:30 – 2:00	Structural and lithologic control of karst features in northwestern New Jersey – Donald Monteverde and Richard Dalton. New Jersey Geological Survey
2:00 – 2:30	Three-Dimensional Geologic Framework Modeling for a Karst Region in the Buffalo National River, Arkansas – Kyle E. Murray and Mark R. Hudson. U.S. Geological Survey
2:30 – 3:00	BREAK
3:00 – 3:30	Preliminary findings of a karst-stratigraphy study of the Frederick Valley, Maryland –David Brezinski. and James Reger. Maryland Geological Survey
3:30 – 4:00	Geohydrologic framework of the Northern Shenandoah Valley carbonate aquifer System (Field Trip Overview and Logistics) –Randall Orndorff and George Harlow. U.S. Geological Survey
4:00 – 5:00	Poster session

POSTERS

Evaluating travel times and transient mixing in karst aquifers using seasonal and climatic changes in stable isotopes. –Larry Putnam and Andy Long. U.S. Geological Survey

Use of dye tracing to verify delineation of source-protection zones around selected springs and wells, Bear River Range, Utah –Lawrence Spangler. U.S. Geological Survey

Changes in nitrate concentrations in spring waters due to mixing of surface and ground water in the Woodville Karst Plain, northern Florida –Brian G. Katz, U.S. Geological Survey

An evaluation of borehole flowmeters used to measure horizontal ground-water flow in limestones of Indiana, Kentucky, and Tennessee – John T. Wilson¹, Wayne A. Mandell², Frederick L. Paillet¹, E. Randall Bayless¹, Randall T. Hanson¹, Peter M. Kearl³, William B. Kerfoot⁴, Mark Newhouse¹, and William Pedler⁵. ¹U.S. Geological Survey; ²U.S. Army Environmental Center, Aberdeen Proving Grounds, Maryland; ³Aqua Vision Environmental LLC; ⁴K-V Associates, Inc., Mashpee, Massachusetts; ⁵RAS INC., Golden, Colorado

Karst ground-water basin delineation--Underlying concepts, needed data, and natural variation of evolving flow systems -- Van Brahana¹, R.K. Davis¹, P.D. Hays², Terri L. Phelan³, Tim Kresse⁴, T.J. Sauer⁵, John Murdoch¹. ¹University of Arkansas, Fayetteville; ²U.S. Geological Survey; ³U.S. Department of Agriculture; ⁴Consultant, Fayetteville, Arkansas; ⁵Arkansas Division of Environmental Quality

An hypothesis of endangered cavefish and cave crayfish occurrence and distribution in the mantled karst aquifers of the southern Ozarks -- Van Brahana¹, G.O. Graening², A.V. Brown¹, and Mike Slay¹.
¹ University of Arkansas, Fayetteville; ² Nature Conservancy, Fayetteville, Arkansas

Recurring, multicomponent ground-water tracing experiments at a well-characterized basin in mantled karst--lessons from the Savoy Experimental Watershed --Van Brahana¹, R.K. Davis¹, Tiong Ee Ting¹, Said Al-Rashidy², Kelly Whitsett¹, Sherri Hamilton¹, and Mohammed Al-Qinna¹. ¹ University of Arkansas, Fayetteville; ²Ministry of Water Supply, Sultanate of Oman, Sallalah, Oman

Thursday, August 22

8:00 – 5:00 Field Trip Geohydrologic Framework of the Northern Shenandoah Valley Carbonate Aquifer System

The carbonate aquifer system of the northern Shenandoah Valley of Virginia and West Virginia provides an important water supply to local communities and industry. This is an area with an expanding economy and a growing population, and this aquifer is likely to be further developed to meet future water needs. An improved understanding of this complex aquifer system is required to effectively develop and manage it as a sustainable water supply. Hydrogeologic information provided by a detailed aquifer appraisal will provide useful information to better address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on ground-water levels and instream flows, (3) the relation between karst features and the hydrology and geochemistry of the surface- and ground-water flow systems, and (4) the quality of the ground-water supply and its vulnerability to current and potential future sources of contamination. To answer these questions, a geohydrologic framework is necessary to look at the relationship of water resources to the geology.

Field trip stops will show karst hazards (stop 1), stratigraphic sections of karstic rock (stop 2), sinkholes related to high hydraulic gradient (stop 3), relationship of structural geology to conduit development (stop 3), real-time stream gauging (stop 4), and a karst spring (stop 5).

INTEGRATING SCIENCE

Overview of Background Resources on Karst Research Emphasizing Obscure and “Gray Area” Documents

By Barry F. Beck

P.E. LaMoreaux & Associates, Inc., 106 Administration Road, Suite 4, Oak Ridge, TN 37830

The in-depth understanding of karst is a narrow subspecialty of geology falling within the areas of hydrogeology and/or geomorphology. Inasmuch as it is normally covered only briefly in these undergraduate courses, many geologists have very little specialized understanding of karst principles. However, karst has extremely important practical applications in the fields of environmental and engineering geology.

Moreover, the past and current literature on karst is widely disseminated geographically and technically, and much of it has appeared in obscure or *gray area* publications. This often results in young geologists redoing research that was originally performed decades ago. Some of these publications are simply difficult to find. A good example is the new proceedings volume *Le Voragini Catastrofiche—un nuovo problema per la Toscana*. This is the proceedings of a technical conference on sinkholes held in 2000 in Grosetto, Italy, and sponsored by the Region of Tuscany. This is not *gray*; it is foreign, non-main stream, and in Italian, but it will easily escape notice. However, many of the articles have summaries in English, and there is valuable new information here about the role of upwelling geothermal waters in generating very large sinkholes.

Gray area publications are often the numerous caving and karst newsletters, or consulting reports on karst areas. These publications do not meet the standards of major, refereed professional journals for referencing. Consulting reports are often not published, simply because writing for publication is not a paying job for a consultant. However, this does not mean that this information is any less valuable. Proceedings volumes from professional conferences may also be in this gray zone, depending on the conference, the sponsoring organization, and whether the papers are refereed. The publications of the Florida Sinkhole Research Institute at the University of Central Florida in Orlando are in this gray zone. The Institute was closed for fiscal reasons in 1992 and copies of the Institute's reports are difficult to obtain from the University.

I can offer a good example of the value of thoroughly searching the background information from my own experience. In 1980 I published an abstract at the national GSA meeting on the Big Slough, a karstic drainage channel on the Dougherty Plain in Southwest Georgia; the same material was also in a regional GSA fieldtrip guide and a Southeastern Geological Society fieldtrip guide. Although the Big Slough is shown on state maps as a major, continuous tributary to the Flint River, it is actually a linear array of disjointed karstic drainage developed parallel to the base of the Pelham Escarpment and actually draining in opposite directions in different areas. During later flooding, the Flint River was predicted to crest at serious flood levels in Southwest Georgia, but the floods never materialized. I was surprised to hear a TV newscaster say “experts tell us that the error in the predicted flood level has to do with something called the Big Slough.” If they had done their homework thoroughly, they might have been aware of this in advance, thus increasing the accuracy of their flood prediction.

Background information on karst areas and karst hydrogeology or geomorphology is often difficult to locate and obtain. In many cases personal contacts may be the best way to learn about obscure publications. Fortunately, in this age of electronic communication such personal contacts can be made rapidly, and most karst researchers are quite pleased to know that someone else is interested in their work. The fact that this information is difficult to find does not in any way diminish its usefulness, nor absolve current researchers from acknowledging that someone else thought of the idea first. A thorough background search is the first step in any research. Its just a little bit harder when dealing with karst.

National Cave and Karst Research Institute—Progress in the First Two Years

By Zelda Chapman Bailey

Interim Director, National Cave and Karst Research Institute, National Park Service, PO Box 25287, Denver CO 80225

Abstract

Congress mandated the establishment of the National Cave and Karst Research Institute in October 1998 to further the science of speleology by facilitating research, to enhance public education, and to promote environmentally sound cave and karst management. Considerable progress has been made during the tenure of the Interim Director (2000-2002) toward making the Institute operational. The scope of operation has been defined, and the organizational structure has been designed and approved. Numerous informal partnerships have been formed and formal cooperative agreements are being negotiated and signed. Federal and state matching funds for operating the Institute have been appropriated and staff recruitment is beginning. Initial funding for a building has been appropriated and the design is being discussed. Several research, inventory, and informational projects have been initiated.

BACKGROUND

Congress mandated the establishment of the National Cave and Karst Research Institute in October 1998 (Public Law 105-325) under the direction of the National Park Service. The Act stipulated that the Institute will be located in the vicinity of Carlsbad Caverns National Park in New Mexico (but not inside Park boundaries), and that the Institute cannot spend Federal funds without a match of non-Federal funds.

The mission of the Institute is to further the science of speleology by facilitating research, to enhance public education, and to promote environmentally sound cave and karst management. The goals of the Institute are to:

- Further the science of speleology through coordination and facilitation of research.
- Provide a point-of-contact for dealing with cave and karst issues by providing analysis and synthesis of speleological information and serving as a repository of information.
- Foster partnerships and cooperation in cave and karst research, education, and management programs.
- Promote and conduct cave and karst educational programs.
- Promote national and international cooperation in protecting the environment for the benefit of caves and karst landforms and systems.

- Develop and promote environmentally sound and sustainable cave and karst management practices, and provide information for applying these practices.

PROGRESS IN ORGANIZING AND FUNDING

Key activities during the interim period (2000-2002) were defining the scope of operation, designing an organizational structure, forming partnerships, finding funding sources and a physical facility, and defining research needs. Considerable progress has been made in all these areas toward making the Institute operational.

The Institute will require about 12 employees to fully accomplish the goals. Those include the lead positions of Director, Science Coordinator, Education Coordinator, and Information Coordinator, and support staff under their direction. Voluntary advisory boards made up of representatives from a range of disciplines and organizations will play an important role in guiding the scientific and educational undertakings of the Institute.

The Institute staff will not conduct research but will guide, focus, and encourage research through grants and partnerships. A primary function of the Institute will be to accumulate and organize data and information to make it accessible to investigators and for the Institute staff to use for synthesis of information on

regional and national scales. The Institute will encourage focused research and studies in caves and karst systems so that a more coherent and unified body of knowledge can emerge. The Institute will work toward accumulating funding that can be distributed to researchers through a grant program that focuses on national priorities in cave and karst research.

Partnerships with cave and karst interest groups, agencies, and organizations are critical to the success of the Institute, and to create a national and international focus on research, education, and information dissemination for better understanding and management of cave and karst resources. The Interim Director made numerous presentations at professional and special meetings to encourage dialog on formation of the Institute, as well as meeting individually with many representatives of interest groups, organizations, and agencies. More than a dozen articles or abstracts were published in venues such as *Environmental Geology*, *GSA Today*, and symposia proceedings to publicize the formation of the institute to a wide audience. A web site (www2.nature.nps.gov/nckri) was launched to provide another avenue of communication to and from a wide range of potential partners.

The Institute received its first Federal appropriation for fiscal year 2002 to match the State funding appropriated to the New Mexico Institute of Mining and Technology (NMT) in support of the Institute. The Institute, the City of Carlsbad, and NMT are establishing a memorandum of understanding to define their partnership roles in establishing and managing the Institute. NMT is using their appropriation to create two new positions in cave and karst science: a hydrogeologist in the Bureau of Geology and Mineral Resources stationed in Carlsbad working in close association with the Institute, and a faculty position in cave and karst studies in the Department of Earth & Environmental Science in Socorro, serving as a liaison with the Institute.

The Institute, the City of Carlsbad, and NMT will constitute the founding members of the Institute's Management Advisory Board; additional members will be added after the Board is officially chartered as a governmental advisory board. Additionally, a Science and

Education Advisory Board will be chartered to review and oversee the Institute grant process. A Federal Advisory Board will continue as an extension of the Federal Working Group that has been assisting the Interim Director in the interim period of the Institute.

Temporary office space and clerical support will be provided for the Institute during initial staffing through a partnership agreement between the Institute and New Mexico State University in Carlsbad. The New Mexico State legislature has appropriated initial funds to construct a building in Carlsbad for the Institute to occupy. The Institute, the City, and NMT are jointly working on funding and designing a building for the Institute.

A 5-year cooperative agreement has been negotiated with Western Kentucky University (WKU) so that collaborative projects can be easily initiated with any of their several departments related to cave and karst studies.

PROJECTS

The Institute currently is sponsoring and participating in some initial projects that will provide useful products and will help publicize the Institute.

- The Institute and the Karst Waters Institute (KWI) are collaborating to produce a booklet entitled *A Cave and Karst Management Handbook for America's Protected Lands*. Associates of KWI and staff of the National Park Service (NPS), Bureau of Land Management (BLM), U.S. Fish and Wildlife Service (FWS), and U.S. Forest Service (USFS) are contributing written sections. The Institute and FWS provided funding for KWI to edit, publish, and distribute the booklet. The booklet, anticipated to be completed in late 2002, can be used as a handbook for resource managers to comply with the requirements of the Cave Resources Protection Act, as a source of information for interpreters, and as a training resource.
- The Institute, NPS, and U.S. Geological Survey (USGS) are collaborating to produce a USGS Circular (a magazine-style publication) on the topic of cave and karst science, resource management and research needs in the Federal agencies. In addition to

the Institute and USGS, sections of the report are being written by BLM, FWS, USFS, and the Environmental Protection Agency. Authors are contributing their writing time, the Interim Director is editing and compiling the publication, and USGS is funding the cost of preparation, printing, and distribution in late 2002.

- The Institute and USGS are working closely to organize a program to produce an improved national karst map and an associated web-based network of karst information. Federal and State agencies, the speleological community, and academia have repeatedly expressed the need for an accurate and detailed national karst map to better understand the distribution of soluble rocks in the United States. Maps at a variety of scales are needed to educate the public and legislators about karst issues, to provide a basis for cave and karst research, and to aid Federal, State, and local land-use managers in managing karst resources. The Institute is in a position to coordinate the united efforts of a number of groups in a program of truly national scope. USGS will compile karst maps of each state into a national map by working with the states to establish standards and consistent digital products, and will facilitate the digital compilation and production of the national karst map. The Institute will establish a web-based network of karst information that was used to build the national map.
- The Institute provided partial funding to publish a book compiled by the Denver Museum of Nature and Science, titled "Vertebrate Paleontology of Pleistocene Cave Deposits in North America."
- The Institute provided partial funding to publish a book compiled by the National Speleological Society, titled "Cave Conservation and Restoration."
- Under the cooperative agreement with WKU, a nationwide exploratory survey of DNA extracted from cave sediments will be conducted through the WKU Biotechnology

Center. Caves in different climatic, geologic, and geographic settings may have diverse and variable bacterial communities; however, the natural microbial makeup of caves is unknown and uninventoried on a broad scale. DNA fragment profiles of bacteria in cave sediments will be determined for a general view of community diversity. Initially, 12 caves across the country on federal, state, and private land are being identified for sampling 4 times over a 1-year period. The number of caves sampled will be increased as additional funds become available. The information will be made available on the Internet to any interested research scientists.

- WKU has, over the last several years, developed a graduate program tailored to the needs and schedules of NPS cave and karst resource management staff who wish to further their educational background. Under the cooperative agreement with WKU, the Institute is supporting this program to allow more students access to the benefit of advanced education.

PLANS FOR FISCAL YEAR 2003

A nationwide announcement will be issued in summer 2002 to recruit the permanent Director for the Institute. The Director should report to Carlsbad early in fiscal year 2003. If additional operating funds are appropriated for 2003, additional positions will be recruited, probably including the Science Coordinator and administrative staff.

When the Management Advisory Board and the Science and Education Advisory Board charters are approved, a process to solicit members will be announced in the Federal Register. Members will be appointed by the Secretary of the Interior.

If additional operating funds are appropriated for 2003, a formal grant process can be initiated.

Conservation and Protection of Caves and Karst in the National Parks

By Ronal C. Kerbo

National Cave Management Coordinator, U. S. National Park Service, PO Box 25287, Denver CO 80225

Abstract

Caves and karst features occur in 120 (81 contain caves and an additional 39 contain karst) parks in all regions of the National Park System. Over 3,900 caves are currently known throughout the system.¹ Eleven parks provide some type regular guided tours of caves. The number of caves per park unit ranges from 10 caves—as in the Chesapeake & Ohio Canal National Historic Park, to more than 400 caves—as in the Grand Canyon National Park. The National Park Service's national cave/karst program is coordinated by one person in a central office in Denver Colorado. Servicewide, as of 2002, even though 81 parks have significant cave or karst resources 21 people stationed in 14 park units are devoted to cave and karst management.

A National Park Service cave management plan for an individual park should provide for the following: (1) The protection of natural processes in cave ecosystems, within karst landscapes. (2) Scientific studies and researches in or about cave and karst resources and systems to increase the park's scientific knowledge and broaden the understanding of its cave resources. (3) Detailed cartographic survey of caves and cave systems, and a detailed inventory of resources within cave systems. (4) Educational opportunities for a broad spectrum of park visitors to safely visit, study, and enjoy caves at a variety of levels of interest and abilities. (5) The establishment of regulations, guidelines, and/or permit stipulations that will ensure maximum conservation of cave resources. (6) Direction for cave restoration activities that remove unnatural materials or restore otherwise impacted areas. (7) The establishment of standard operating procedures in the maintenance and upkeep of developed cave passages and monitoring of natural environmental conditions and visitor use impacts. (8) The protection of related cultural resources, and (9) Ensuring the sustainable use of cave resources.

MANAGEMENT OF CAVES AND KARST SYSTEMS

In 1988, the U. S. Congress created a major impetus for the involvement of the United States in cave and karst protection and management by passing the landmark **Federal Cave Resources Protection Act of 1988** (Public Law 100-691; November 18, 1988). The act directs the secretaries of the Department of the Interior and the Department of Agriculture to inventory and list significant caves on federal lands and to provide management and dissemination of information about caves. A current, nationwide assessment of significant federally owned caves is cataloging the known caves on federal land and further increasing the impetus for cave management and research.

In 1990, the Congress also directed the Secretary of the Department of the Interior, acting through the National Park Service, to establish and administer a program on cave research and to examine the feasibility of a centralized national cave and karst research institute. The feasibility study was prepared in cooperation with other federal agencies that manage caves, organizations that are involved in cave-related topics, cave experts, and interested individuals and was forwarded to the Congress. Based on the results of the study, a bill (S. 231) was introduced in the 105th Congress to establish the National Cave and Karst Research Institute in New Mexico.

NPS management policies relating to cave and karst management are as follows.

4.8.1.2 Karst

The Service will manage karst terrain to maintain the inherent integrity of its water quality, spring flow, drainage patterns, and caves. Karst processes (the processes by which water dissolves soluble rock such as limestone) create areas typified by sinkholes, underground streams, caves, and springs.

Local and regional hydrological systems resulting from karst processes can be directly influenced by surface land use practices. If existing or proposed developments do or will significantly alter or adversely impact karst processes, these impacts will be mitigated. Where practicable, these developments will be placed where they will not have an effect on the karst system.

4.8.2.2 Caves

As used here, the term "caves" includes karst (such as limestone and gypsum caves) and non-karst caves (such as lava tubes, littoral caves, and talus caves). The Service will manage caves in accordance with approved cave management plans to perpetuate the natural systems associated with the caves, such as karst and other drainage patterns, air flows, mineral deposition, and plant and animal communities. Wilderness, and cultural resources and values will also be protected.

No developments or uses, including those that allow for general public entry, such as pathways, lighting, and elevator shafts, will be allowed in, above, or adjacent to caves until it can be demonstrated that they will not unacceptably impact natural cave conditions, including sub-surface water movements. Developments already in place above caves will be removed if they are impairing or threatening to impair natural conditions or resources.

Parks will strive to close caves or portions of caves to public use, or to control such use, when such actions are required for the protection of cave resources or for human safety. Some caves or portions of caves may be managed exclusively for research, with access limited to

permitted research personnel. All recreational use of undeveloped caves will be governed by a permit system. "Significant" caves will be identified using the criteria established in the 43 CFR Part 37 regulations for the Federal Cave Resources Protection Act of 1988 (FCRPA). As further established by the FCRPA, specific locations of significant cave entrances may be kept confidential and exempted from FOIA requests.

6.3.11.2 Caves [in wilderness]

All cave passages located totally within the surface wilderness boundary will be managed as wilderness. Caves that have entrances within wilderness but contain passages that may extend outside the surface wilderness boundary will be managed as wilderness. Caves that may have multiple entrances located both within and exterior to the surface wilderness boundary will be managed consistent with the surface boundary; those portions of the cave within the wilderness boundary will be managed as wilderness.

TRACERS

Demystifying Ground-water Flow and Contaminant Movement in Karst Systems Using Chemical and Isotopic Tracers

By Brian G. Katz

U.S. Geological Survey, 227 N. Bronough St., Suite 3015, Tallahassee, FL 32301

INTRODUCTION

In many karst systems throughout the world, ground water and surface water typically constitute a single dynamic system as a result of numerous solution features that facilitate the exchange of water between the surface and subsurface. The combined use of various geochemical and hydrologic tools has considerably enhanced our understanding of complex ground-water flow patterns and the mixing of ground water and surface water in diverse mantled karst systems. Naturally occurring isotopic and other chemical tracers (such as ^{18}O and ^2H , ^{222}Rn , $^{87}\text{Sr}/^{86}\text{Sr}$, ^{13}C , ^{15}N , and major dissolved species) along with geochemical modeling were very effective in quantifying interactions between surface water and ground water in several diverse karst systems in northern Florida. This paper briefly describes results from selected studies of hydrochemical interactions between water from the Upper Floridan aquifer and surface water, including leakage from a sinkhole lake, and a recharge pulse from a sinking stream. Also presented are geochemical techniques that were used to determine sources of nitrate contamination and average residence times of ground water discharging from 24 large springs in the Suwannee River Basin. More detailed information regarding these studies is provided in the references listed at the end of this paper.

INTERACTIONS BETWEEN A SINKHOLE LAKE AND GROUND WATER

In northern Florida, downward leakage of water from sinkhole lakes can be an important source of recharge to the upper Floridan aquifer in areas where the aquifer is poorly confined. Environmental isotopes (oxygen-18, deuterium, $^{87}\text{Sr}/^{86}\text{Sr}$, and tritium), chlorofluorocarbons (CFCs: CFC-11, CCl_3F ; CFC-12, CCl_2F_2 ; and CFC-113, $\text{C}_2\text{Cl}_3\text{F}_3$), and solute tracers (methane,

major ions, silica) were used to investigate ground-water flow patterns near Lake Barco, a seepage lake in a mantled karst setting in north-central Florida (fig. 1) (Katz and others, 1995a,b; Katz and Bullen, 1996). Stable isotope data indicated that the ground water down-gradient from the lake contained 11 to 67 percent lake water leakage, with a lower limit of detection of lake water in ground water of 4.3 percent. The mixing fractions of lake water leakage, which passed through organic-rich sediments in the lake bottom, were directly proportional to observed methane concentrations and increased with depth in the ground-water flow system. In aerobic ground water upgradient from Lake Barco, CFC-modeled ages ranged from 5 years near the water table to the 17 years for water collected at a depth of 30 m below the water table. CFC-modeled recharge ages (based on CFC-12) for anaerobic ground water downgradient from the lake ranged from 17 to 34 years and were consistent with tritium data. CFC-modeled recharge dates based on CFC-11 indicated preferential microbial degradation in anoxic waters. Vertical hydraulic conductivities, calculated using CFC-12 modeled recharge dates and Darcy's law were 0.17, 0.033, and 0.019 m/d for the surficial aquifer, intermediate confining unit, and lake sediments, respectively. These conductivities agreed closely with those used in the calibration of a three-dimensional ground-water flow model for transient and steady-state flow conditions (Lee, 1996).

Chemical patterns along evolutionary ground-water flow paths in silicate and carbonate units were interpreted using solute tracers, carbon and sulfur isotopes, and mass-balance reaction modeling for the complex hydrologic system involving ground-water inflow to and outflow from Lake Barco.

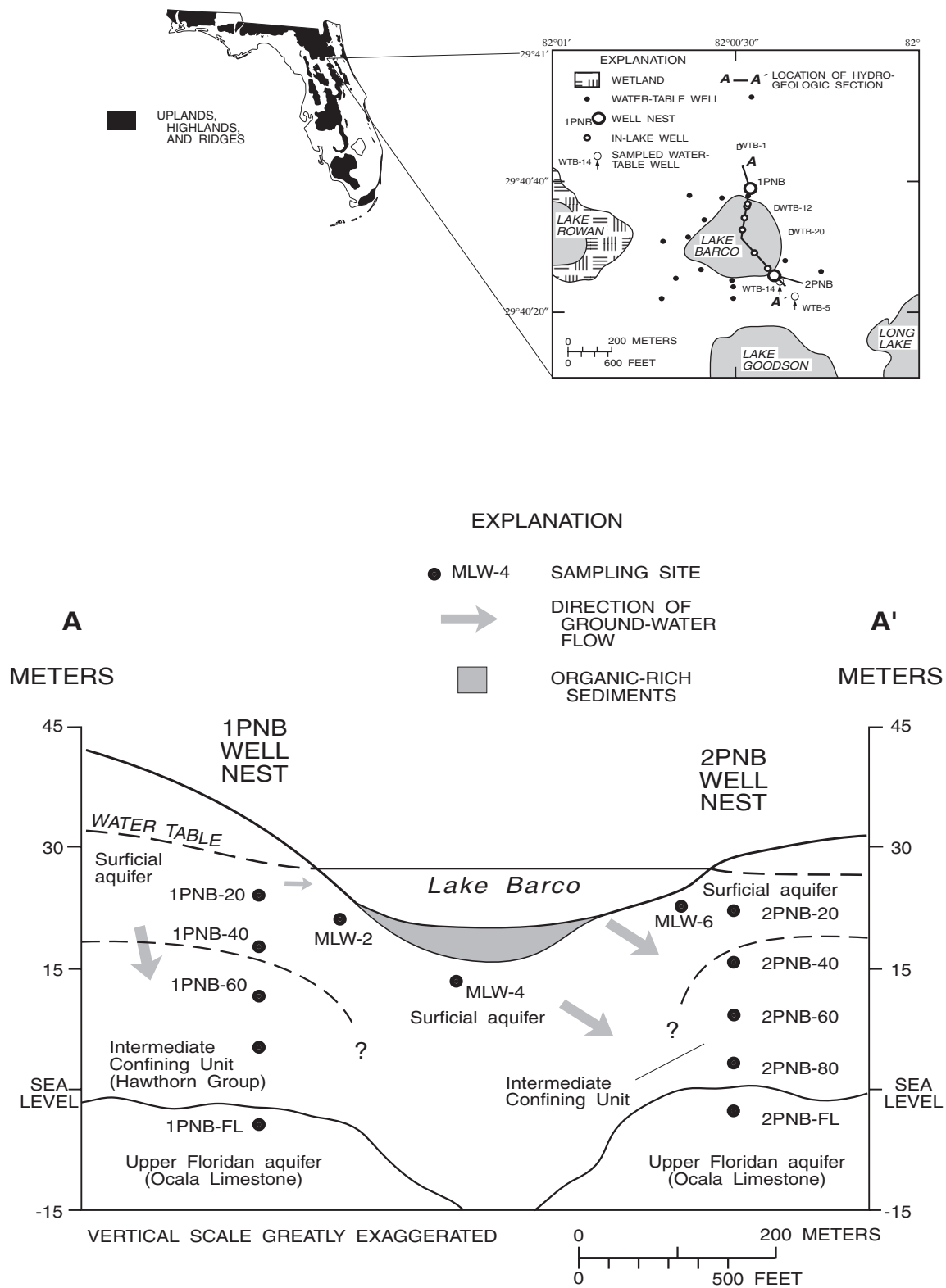


Figure 1. Location map of Lake Barco study area and cross section showing hydrogeologic framework and location of sampling sites.

Rates of dominant reactions along defined flow paths were estimated from modeled mass-transfer and ages obtained from CFC-modeled recharge dates. Ground water upgradient from Lake Barco remains oxic as it moves downward, reacting with silicate minerals in a system open to carbon dioxide (CO₂), producing only small increases in dissolved species. Beneath and downgradient of Lake Barco, the oxic ground water mixes with lakewater leakage in a highly reducing (methanogenic, low-sulfide), silicate-carbonate mineral environment. A mixing model, developed for anoxic ground water downgradient from the lake, accounted for the observed chemical and isotopic composition by combining different proportions of lake water leakage and infiltrating meteoric water. The evolution of major-ion chemistry and the ¹³C isotopic composition of dissolved carbon species in ground water downgradient from the lake can be explained by the aerobic oxidation of organic matter in the lake, anaerobic microbial oxidation of organic carbon, and incongruent dissolution of smectite minerals to kaolinite. The dominant process for the generation of methane was by the CO₂-reduction pathway based on the isotopic composition of hydrogen ($\delta^2\text{H}(\text{CH}_4) = -186$ to -234 per mil) and carbon ($\delta^{13}\text{C}(\text{CH}_4) = -65.7$ to -72.3 per mil). Rates of microbial metabolism of organic matter, estimated from the mass-transfer reaction models, ranged from 0.0047 to 0.039 millimoles per liter per year for ground water downgradient from the lake.

Results from this study provide a framework for a better understanding of the hydrochemical interaction between ground water and lake water in a karst setting, and were used to develop similar studies in other parts of Florida (Katz and others, 1997). The patterns and rates of chemical evolution of ground water near Lake Barco have important hydrochemical implications. First, the potential for mobilization of trace metals in anoxic ground water is high given its low sulfide content. Additional research on the hydrochemical interaction between lake water leakage and ground water is needed, particularly on a regional scale, because of the possibility for degradation of the quality of water in the Upper Floridan aquifer. Second,

higher amounts of CO₂ from microbially mediated reactions downgradient from lakes could result in greater amounts of calcite dissolution, thereby enhancing the development of secondary porosity and solution features.

RECHARGE PULSE FROM A SINKING STREAM

The Little River, an ephemeral stream that drains a watershed of approximately 88 km² in northern Florida (fig. 2), disappears into a series of sinkholes along the Cody Scarp and flows directly into and locally recharges the karstic Upper Floridan aquifer, the source of water supply in northern Florida. Changes in groundwater geochemistry caused by a major recharge pulse from the sinking stream were investigated using geochemical tracers and mass-balance modeling techniques (Katz and others, 1998). Nine monitoring wells, open to the uppermost part of the aquifer, were installed in areas near the sinks where numerous subterranean karst solution features had been identified using ground penetrating radar. During high-flow conditions in the Little River, the chemistry of water in some of the monitoring wells changed, reflecting the mixing of ground water with river water. Rapid recharge of river water into some parts of the aquifer during high-flow conditions was indicated by (1) enriched values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (-1.67 to -3.17 per mil and -9.2 to -15.6 per mil, respectively), (2) elevated concentrations of tannic acid, higher (more radiogenic) ⁸⁷Sr/⁸⁶Sr ratios, and (3) lower concentrations of ²²²Rn, silica, and alkalinity compared to low-flow conditions. Tannic acid concentrations, measured in the field using a portable spectrophotometer, provided real-time quantitative information about mixing of surface water with ground water. This technique also was used in a study of interactions between Suwannee River water and the Upper Floridan aquifer (Crandall and others, 1999). Based on mass-balance modeling, the dominant processes controlling carbon cycling in ground water are the dissolution of calcite and dolomite in aquifer material, and aerobic degradation of organic matter.

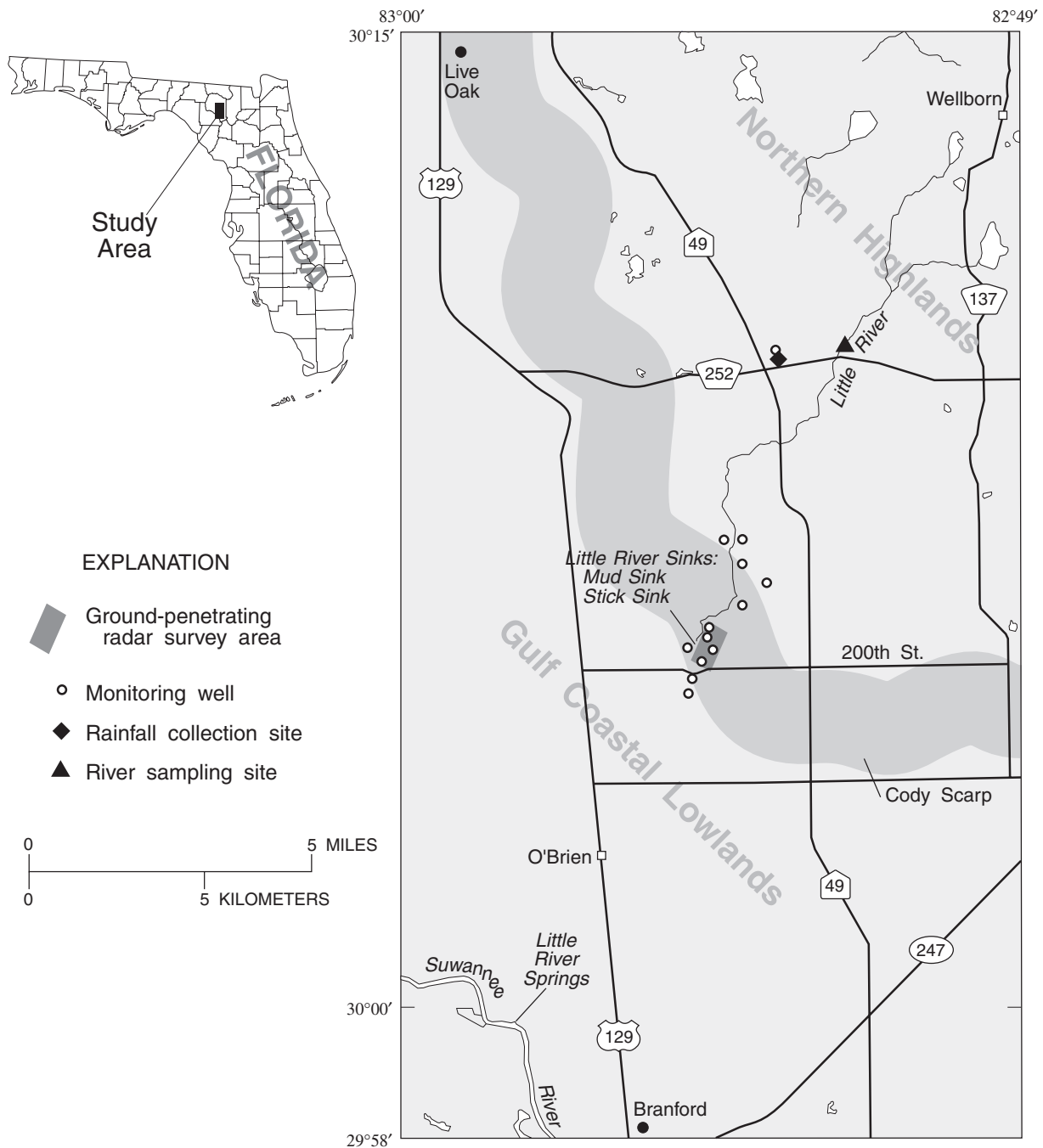


Figure 2. Location map of Little River study area showing sampling sites for ground water, river water, and rainfall.

The proportion of river water that mixed with ground water ranged from 0.13 to 0.84, based on binary mixing models using the tracers $\delta^{18}\text{O}$, $\delta^2\text{H}$, tannic acid, silica, tritium, ^{222}Rn , and $^{87}\text{Sr}/^{86}\text{Sr}$ (Katz and others, 1998). The effectiveness of these

tracers in quantifying the mixing between river water and ground water is related to the difference in the chemical and isotopic composition of the end members and to reactions with aquifer minerals that may occur after mixing.

The corrosiveness of the river water (low saturation index with respect to calcite, <-5.0) leads to rapid dissolution and subsequent enlargement of solution openings, resulting in an increase in the permeability of the aquifer near the Little River sinkholes. During high-flow conditions, the saturation index of ground water with respect to calcite decreased at all sites sampled, with the exception of one site, which did not show any evidence of river water mixing with ground water.

The increase in water levels in wells near the sinkholes, following the recharge pulse from the Little River, indicates the rapid response of the aquifer and can be used to evaluate the susceptibility of the unconfined aquifer to contamination. The hydrochemical response of the aquifer to this recharge pulse from the river is dependent on several factors, such as the degree of interconnectivity of the conduit system and the distance from the recharge input to the zones in the aquifer where the water is withdrawn. Chemical fluctuations often operate on several time scales that can range from days to weeks in response to individual rainfall or recharge events to seasonal cycles related to wet and dry periods. To gain a more complete understanding of the complex interactions among hydrochemical reactions, mixing phenomena, and rates of flow in the aquifer system, more detailed monitoring of stream and ground-water chemistry, ground-water levels, and analysis of stream hydrographs during storms is needed to determine the degree of connectivity between various zones in the aquifer and the location where the Little River disappears underground. This information, coupled with introduced tracers, such as fluorescent dyes, would provide critical data on ground-water flow rates and interconnectivity between various zones of the aquifer.

Although more chemical and hydrologic data are necessary to determine other locations in the aquifer where river water and ground water mix during high-flow conditions, this study demonstrated the effectiveness of combining geophysical techniques (such as ground-penetrating radar for placement of wells) with hydrochemical information (such as

naturally occurring chemical and isotopic tracers in river water and ground water). The investigation also showed that the unconfined Upper Floridan aquifer is highly susceptible to contamination from activities at the land surface in areas where karst features are prevalent. Where direct connections exist between sinkholes and zones in the UFA, recharge of tannic-rich surface waters mix with ground water resulting in elevated organic carbon concentrations. Reactions between these naturally occurring organic compounds and chlorine during disinfection of ground water for public consumption could result in the formation of harmful byproducts such as trihalomethanes (Rostad and others, 2000).

SPRINGS

A multitracer approach consisting of naturally occurring chemical and isotopic indicators, was used to assess sources and timescales of nitrate contamination in spring waters discharging to the Suwannee and Santa Fe Rivers in northern Florida (fig. 3). During 1997-2000, water samples were collected from



Figure 3. Location of springs sampled in the Suwannee River Basin.

24 springs and analyzed for major ions, nutrients, dissolved organic carbon (DOC), and selected environmental isotopes [$^{18}\text{O}/^{16}\text{O}$, D/H, $^{13}\text{C}/^{12}\text{C}$, $^{15}\text{N}/^{14}\text{N}$] (Katz and others, 1999, 2001). Additional water samples were analyzed for chlorofluorocarbons (CFCs; CCl_3F , CCl_2F_2 , and $\text{C}_2\text{Cl}_3\text{F}_3$) and tritium (^3H) to assess the residence times and apparent ages of spring waters and water from shallow zones in the Upper Floridan aquifer. In addition to information obtained from the use of isotopic and other chemical tracers, information on changes in land-use activities in the Suwannee River basin during 1954-97 were used to estimate N inputs from non-point sources for five counties in the basin. Changes in nitrate concentrations in spring waters with time were compared with estimated N inputs for Lafayette and Suwannee Counties.

Agricultural activities including cropland farming, animal farming operations (beef and dairy cows, poultry, and swine), as well as atmospheric deposition have contributed large quantities of nitrogen to ground water in the Suwannee River basin. Changes in agricultural activities during the past 40 years in Alachua, Columbia, Gilchrist, Lafayette, and Suwannee Counties have resulted in variable inputs of nitrogen to the ground-water system. During 1955-97, total estimated N from all nonpoint sources (fertilizers, animal wastes, atmospheric deposition, and septic tanks) increased continuously in Gilchrist and Lafayette Counties. In Suwannee, Alachua, and Columbia Counties, estimated N inputs from all nonpoint sources peaked in the late 1970s corresponding to the peak in fertilizer use during this time. Fertilizer use in Columbia, Gilchrist, Lafayette, and Suwannee Counties has increased substantially during 1993-97.

This heavy usage of fertilizers in the basin is corroborated by nitrogen isotope data, with $\delta^{15}\text{N}$ values of NO_3 in spring waters that range from 2.7 per mil (SUW725791) to 10.6 per mil (Poe Spring), and a median of 5.4 per mil. The range of values indicates that nitrate in the sampled spring waters most likely originates from a mixture of inorganic (fertilizers) and organic (animal wastes) sources, although higher $\delta^{15}\text{N}$ values for Poe and Lafayette Blue Springs

indicate that an organic source of nitrogen probably is contributing nitrate to these spring waters. Dissolved gas data (nitrogen, argon, and oxygen) indicate that denitrification has not removed large amounts of nitrate from the ground-water system. Thus, variations in $\delta^{15}\text{N}-\text{NO}_3$ values of spring waters can be attributed to variations in $\delta^{15}\text{N}-\text{NO}_3$ values of ground-water recharge, and can be used to obtain information about source(s) of nitrate.

Extending the use of age-dating techniques (CFCs and ^3H) to spring waters in complex karst systems required the use of several different approaches for estimating age and residence time of ground water discharging to springs (Katz and others, 1999). These approaches included the use of piston-flow, exponential, and binary-mixing models. When age data (CFC-11, CFC-113, and ^3H) are combined for all springs, models that incorporate exponential mixtures seem to provide reliable estimates of average residence times of ground water discharging to springs. However, data for some individual springs are consistent with a binary mixing model with more than 50 percent young water (recharged within the past 5 years) for all three tracers, whereas data from other individual springs fit a piston-flow model with an age of about 25 years. The young ages of several spring waters (such as SUW718971, SUW725971, and Ginnie Spring) indicate their high vulnerability to contamination. One important conclusion for most springs is that the CFCs indicate that spring waters have large fractions of water that is most likely more than 20 years old. Apparent ages of spring waters is significantly related to the springwater discharge rate, that is springs with lower flows tend to have young ages (shallow ground-water flow systems), whereas springs with higher flows tend to have increased ages (flow from deep systems is dominant). The chemical composition of spring waters can be used as a qualitative indicator of age and ground-water residence time. Nitrate-N concentrations and dissolved oxygen in spring waters are inversely related to apparent ages of spring waters and ground-water residence time in the basin.

Long-term trends in nitrate concentrations in selected spring waters were compared with

estimated inputs of nitrogen from various sources in Suwannee and Lafayette Counties. In both counties, trends in nitrate concentrations in spring waters tracked the estimated contribution of nitrogen from fertilizers to ground water, that is nitrate concentrations decreased with time in four springs from Suwannee County as fertilizer use decreased, and increased with time in three springs from Lafayette County as fertilizer use increased.

The relation between the concentration of nitrate in ground water and the amount of nitrogen that is added to a ground-water contributing area for a spring is controlled by a complex interaction among hydrogeologic, land-use, climatic, and several other land-management factors. Spring waters represent mixtures of converging flow paths that contain ground water with a range of ages. Even if nitrogen inputs were reduced substantially, it may take decades for nitrate concentrations in the ground-water system to return to near background levels.

Results from these studies in northern Florida have demonstrated that the analysis of naturally occurring tracers in ground water along with geochemical modeling lead to a better understanding of hydrochemical interactions between surface water and ground water, and of the processes controlling the chemical composition of water in the Upper Floridan aquifer. This information can assist regulators in making more informed environmental decisions for protecting the valuable water resources of this important aquifer system.

REFERENCES

- Crandall, C.A., Katz, B.G., and Hirten, J.J., 1999, Hydrochemical evidence for mixing between the Suwannee River and Upper Floridan aquifer: *Hydrogeology Journal*, v. 7, p. 454-467.
- Katz, B.G., Bohlke, J.K., and Hornsby, H.D., 2001, Timescales for nitrate contamination of spring waters, northern Florida: *Chemical Geology*, v. 179, Issues 1-4, p. 167-186.
- Katz, B.G., and Bullen, T.D., 1996, Use of $^{87}\text{Sr}/^{86}\text{Sr}$ and other chemical and isotopic analyses to study the hydrochemical interaction between ground water and lakewater in mantled karst: *Geochimica et Cosmochimica Acta*, v. 60, no. 24, p. 5075-5087.
- Katz, B.G., Catches, J.S., Bullen, T.D., and Michel, R.L., 1998, Changes in the isotopic and chemical composition of ground water resulting from a recharge pulse from a sinking stream: *Journal of Hydrology*, v. 211, p. 178-207.
- Katz, B.G., Coplen, T.B., Bullen, T.D., and Davis, J.H., 1997, Use of chemical and isotopic tracers and geochemical modeling to characterize the interactions between ground water and surface water in mantled karst: *Ground Water*, v. 35, no. 6, p. 1014-1028.
- Katz, B.G., Hornsby, H.D., Bohlke, J.K., and Mokray, M.F., 1999, Sources and chronology of nitrate contamination of springwaters, Suwannee River Basin, Florida: U.S. Geological Survey Water-Resources Investigations Report 99-4252, 54 p.
- Katz, B.G., Lee, T.M., Plummer, L.N., and Busenberg, E., 1995a, Chemical evolution of groundwater near a sinkhole lake, northern Florida: 1. Flow patterns, age of groundwater, and influence of lakewater leakage: *Water Resources Research*, v. 31, no. 6, p. 1549-1564.
- Katz, B.G., Plummer, L.N., and Busenberg, E., Revesz, K.M., Jones, B.F., and Lee, T.M., 1995b, Chemical evolution of groundwater near a sinkhole lake, northern Florida: 2. Chemical patterns, mass-transfer modeling, and rates of chemical reactions: *Water Resources Research*, v. 31, no. 6, p. 1565-1584.
- Lee, T.M., 1996, Hydrogeologic controls on the groundwater interactions with an acidic lake in karst terrain, Lake Barco, Florida: *Water Resources Research*, v. 32, p. 831-844.
- Rostad, C.E., Leenheer, J.A., Katz, B.G., Martin, B.S., and Noyes, T.I., 2000, Characterization and disinfection by-product formation potential of natural organic matter in surface and ground waters from northern Florida, in Barrett, S., Krasner, S., and Amy, G. (eds.). *Natural Organic Matter and Disinfection Byproducts: American Chemical Society Symposium Series No. 761*, Washington, D.C., p. 154-172.

Development of a Counterterrorism Preparedness Tool for Evaluating Risks to Karstic Spring Water

By Malcolm S. Field

U.S. Environmental Protection Agency, National Center for Environmental Assessment (8623D), Washington, DC 20460

Disclaimer: The views expressed in this paper are solely those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

Abstract

Terrorist attacks on the nation's drinking-water supplies remains a distinct possibility if not a probability. To guard against an attack, water managers must pursue a preparedness strategy that encompasses a range of operations (e.g., monitoring FBI warnings of potential attacks). One important aspect of a preparedness strategy is the need to define source water boundaries using standard delineation procedures. Of particular value are tracer tests conducted throughout the area for the purpose of defining recharge areas, solute-transport properties, and probable arrival concentrations. Because the hydrologic conditions and the mass of toxic substance (poison) will not be known until a release event actually occurs, release scenario simulations need to be conducted. The recently developed *Efficient Hydrologic Tracer-test Design Program* (EHTD) has been modified to provide water managers with the ability to conduct release scenario simulations. The simulations can be used to predict toxic substance arrival times (time to leading edge, time to peak, persistence), axial dispersion, dilution, and arrival concentrations. By combining the EHTD-simulation results with risk-assessment analyses for acute exposures, water managers can develop a set of alternatives as part of an overall strategy for protecting human health. This set of alternatives could range from no action (i.e., no significant concern) to disconnecting the water-supply system, announcing a no contact warning, and arranging for the supply of an alternative water source.

INTRODUCTION

Terrorist threats to the nations potable water supplies have recently become a major concern for the country. The events of September 11, 2001 (9/11) and subsequent anthrax attacks have proven the vulnerability of basic civilian infrastructures to terrorists. While the past attacks included the physical destruction of large structures housing significant populations by detonation and aerosol attacks on a smaller scale, the potential for a biological or chemical attack on important potable water supplies cannot be discounted (Burrows and Renner, 1999).

Current efforts intended to protect potable water supplies tend to focus on early warning systems (EWS) (Foran and Brosnan, 2000) to detect initial arrival of hazardous biological and

chemical agents. While an improvement over conventional methods of tracking contaminated-water outbreaks (MacKenzie and others, 1994) EWSs may be regarded as inadequate in and by themselves.

Predicting when, and at what concentration a toxic substance released in the respective source area will reach a water-production facility is essential for water managers. The concern for managers of water-supply systems was recently aggravated by the realization that terrorists could deliberately release a toxic poison into their system with the potential to cause widespread illnesses, deaths, and panic before adequate protection measures could be activated. Whereas EWSs will certainly be beneficial when available, knowledge of the source area is critical.

Knowledge of source areas can lead to the installation of typical security apparatus (e.g., fences) and/or atypical security measures (e.g., armed security guards) which is most likely to be applied at large water-supply systems (Reed, 2001). Unfortunately, it appears that much of the country is of the misconception that only very large water-supply systems are threatened (USEPA, 2001) and then really only at the downstream outflow points beyond the water-treatment system. While this situation certainly worthy of concern, it is not a seriously realistic attack scenario.

Smaller municipal water systems where source areas are known to occur at some significant distance from the actual supply are potentially more vulnerable to attack because they are more difficult to define and protect. For example, a karst spring that is used as a municipal water supply and is known to be directly connected to a sinking stream, karst window, or sinkhole several kilometers away should be of significant concern to the local water managers. While these smaller suppliers may only serve a few thousand people at most, the potential for a terrorist attack causing illnesses, deaths, and widespread terror are very realistic.

The threats can be better assessed, however, if water managers have a general sense of potential solute-transport rates and likely receptor concentrations for a given release in a given source area. Reasonable predictions of solute-transport rates and concentrations will allow water managers to (1) provide for a higher level of physical security, (2) plan in advance in the event of a physical attack on their respective water system, and (3) actually implement the plan when an attack does occur.

The purpose of this paper is to outline a method for a proactive approach to protecting ground-water supplies, particularly in karstic terranes. A hypothetical scenario is used to illustrate the value of the approach presented.

SOURCE-WATER PROTECTION

Perhaps the most critical element necessary for protecting the nation's drinking-water supplies is source-water protection. Source-water protection consists of delineating the sources of water, inventorying potential sources of contamination in those areas, and making susceptibility determinations (USEPA, 1997, p. 1-11).

Source-Water Delineation

The most basic aspect of source-water protection is source-water delineation, which is nothing more than mapping out the recharge or catchment area from which the water is derived. This can take the form of mapping surface-water divides on a topographic map for surface-water source delineation to comprehensive quantitative-tracing studies for ground-water source delineation. Detailed guidance's on source-water delineation may be found in USEPA (1987), Bradbury and others (1991), and Schindel and others (1997), but only Schindel and others (1997) provides a detailed guidance on the use of tracer test methods for source-water delineation. Field (2002a) and Mull and others (1988) provide detailed discussions on quantitative tracer testing for more comprehensive evaluations of hydrologic systems.

Quantitative tracer testing is the most reliable method for source-water delineation, especially in karstic terranes. The basic methodology consists of releasing a known quantity of tracer material into a source-water location (e.g., karst sinkhole) and recovering the tracer at a downstream location (e.g., karst spring). By repeating this procedure at several tracer-injection sites and recovering the tracer at all possible recovery locations, a clear delineation of source water is established.

EFFICIENT HYDROLOGIC TRACER-TEST DESIGN

To better facilitate tracer testing in hydrologic systems, a new Efficient Hydrological Tracер-test Design (EHTD) methodology has been developed (Field, 2002b). Application of EHTD to a study site resulted in successful tracer tests and showed that good tracer-test design can be developed prior to initiating a tracer test (Field, 2000, p. 26). Subsequent comparison analyses documented the ability of EHTD to predict tracer test results (Field, 2002c).

Basic Design of EHTD

EHTD is based on the theory that field-measured parameters (e.g., discharge, distance, cross-sectional area) can be combined in functional relationships that describe solute-transport processes related to flow velocity and times of travel. EHTD applies these initial estimates for times of travel and velocity to a hypothetical continuous stirred tank reactor (CSTR) as an analog for the hydrological-flow system to develop initial estimates for tracer concentration and axial dispersion based on a preset average tracer concentration. Root determination of the one-dimensional advection-dispersion equation (ADE) using the preset average concentration then provides a theoretical basis for an estimate of necessary tracer mass. Applying the predicted tracer mass with the hydraulic and geometric parameters in the ADE allows for an approximation of initial sample-collection time and subsequent sample-collection frequency where 65 samples have been empirically determined to best describe the predicted breakthrough curve (BTC).

Range of Capabilities of EHTD

Recognizing that solute-transport processes operative in hydrological systems all follow the same basic theoretical principles suggests that an appropriate model for estimating tracer mass would function effectively for all hydrological systems. However, such a model would need to be able to account for differences in the nature

of the flow systems (e.g., effective porosity) and the manner in which the tracer test is conducted (e.g., tracer-release mode).

Breakthrough curves predicted using the tracer-test design program, EHTD, for various hydrological conditions have been shown to be very reliable (Field, 2002c). The hydrological conditions used to evaluate EHTD ranged from flowing streams to porous-media systems so that the range of capabilities of EHTD could be assessed. Comparisons between the actual tracer tests and the results predicted by EHTD showed that EHTD adequately predicted tracer breakthrough, hydraulic characteristics, and sample-collection frequency in most instances.

PREDICTING THE EFFECTS OF A TOXIC RELEASE

The effect of accidental and deliberate releases of toxic substances to drinking-water supplies need to be predicted if water managers are to initiate appropriate actions should a release occur. EHTD can be used to predict the effects of a toxic-substance release once source-water areas have been established. By using the same measured or estimated parameters intended for tracer-mass estimation and entering a solute mass for EHTD to use, solute-transport parameters and downstream arrival concentrations are predicted.

Prediction methodologies have previously been developed (Kilpatrick and Taylor, 1986; Taylor and others, 1986; and Mull and others 1988), but these previous methods required considerably more time and effort. Additionally, these previous methods tended to overestimated downstream concentrations when attempts were made to reproduce measured results. EHTD, however, reliably reproduces known results.

Methodology

EHTD predicts the effects of a toxic-substance release by initially predicting solute-transport parameters and estimated solute mass as described in Field (2002b). EHTD was modified for a third-type inlet condition to

conserve mass (Toride and others, 1995, p. 5). Additional modifications allow for consideration of continuous initial concentration and exponential production (Toride and others, 1995, pp. 9—14). Entering a solute mass directly causes the preset average concentration C to be overridden and a new C to be predicted.

Upon entering a solute mass, EHTD proceeds using the measured parameters and calculated functional relationships (Field, 2002b). A typical breakthrough curve representing the downstream effects of the release is then produced. For pathogen releases, simple conversions for mass and concentration need to be undertaken, however.

EXPERIMENTAL EXAMPLE

To evaluate the ability of EHTD to predict the effects of a deliberate release of a chemical or biological agent, a karstic aquifer in which a relatively small spring is used for drinking water is investigated. Tracer tests have established the connection between a distant karst window and the spring, which serves to illustrate the vulnerability of such a water supply to a terrorist attack.

Hydrologic System

The example system considered here consists of a karst window in which the stream flowing at the base of the window has been connected through tracing tests to a spring used by a small city for drinking-water supplies. The karst window is not far from a major thoroughfare and is easily accessible. Basic measured field parameters necessary for EHTD prediction are shown in Table 1 with associated functional relationships and related transport parameters. All measured parameters listed in Table 1 were calculated directly from one tracer test in the flow system which may not be representative of the system at different times and hydrologic conditions. Also, it is very unlikely that the solution conduit maintains a straight line so that a sinuosity factor $S_f \sim 1.3$ is usually multiplied to the straight-line distance, but was not done so here. Tracer retardation R_d

and tracer decay μ were subsequently developed to account for delayed arrival times and significant tracer loss ($\sim 35\%$).

Table 1. Tracer-test design parameters

Parameter	Measured	Predicted
<i>Field Parameters</i>		
Release Mode	Impulse ^a	Impulse ^a
Q , m ³ h ⁻¹	1.16×10^2	1.16×10^2
L^b , m	9.14×10^2	9.14×10^2
A , m ²	1.84×10^0	1.84×10^0
C , $\mu\text{g L}^{-1}$	4.10×10^0	4.10×10^0
C_p , $\mu\text{g L}^{-1}$	4.10×10^0	4.10×10^0
<i>Functional Relationships</i>		
t_p , hours	1.45×10^1	1.39×10^1
t , hours	1.72×10^1	1.45×10^1
u_p , m h ⁻¹	6.30×10^1	6.57×10^1
u , m h ⁻¹	5.31×10^1	6.30×10^1
V , m ³	1.99×10^3	1.77×10^3
<i>Axial Dispersion</i>		
D , m ² h ⁻¹	3.28×10^2	6.60×10^2
P_e	1.50×10^2	8.73×10^2
<i>Tracer Reaction</i>		
R_d	1.00×10^0	1.05×10^0
μ , h ⁻¹	0.00×10^0	1.80×10^{-2}

^aInstantaneous release = Dirac (δ) function.

^bTransport distance = straight-line distance.

Cursory examination of the measured parameters and functional relationships shows that transport rates are quite high, dispersion is significant, and transport is strongly dominated by advective forces rather than diffusive forces.

The impact of these parameters is that a release of a toxic substance in this area will arrive quickly at the water-supply spring with relatively little dispersion. Discrepancies between the measured and predicted arrival times were adjusted by setting $R_d = 1.05$ in EHTD.

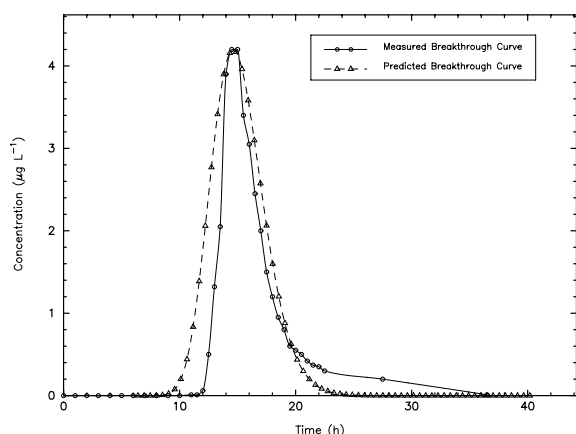


Figure 1. Comparison of measured data for the site tracer test with EHTD predicted results. Circles represent actual sample-collection times and triangles represent EHTD-recommended sample-collection times.

Applying the measured parameters and tracer-reaction values to EHTD resulted in a visually acceptable fit between the EHTD-predicted BTC and the measured BTC (Figure 1). The actual mass of tracer released, 3.57 g, was closely approximated by EHTD (3.56 g) when appropriate tracer reactions were considered.

Chemical/Biological Release Examples

Consider two possible toxic releases into a water-supply system. A potentially deadly pathogen might include *Vibrio cholerae* while a potentially deadly chemical substance that could be released might include Compound 1080 (fluoroacetic acid [CAS NUMBER: 62-74-8]). Compound 1080 is a highly toxic pesticide (NOAEL = 0.05 mg kg⁻¹ d⁻¹; LOAEL = 0.2 mg kg⁻¹ d⁻¹; and human LD₅₀ = 2-5 mg kg⁻¹) used to control rodents and coyotes.

Acquisition of a toxic chemical is not difficult; on May 10, 2002 7.6 tons (6895 kg) of sodium cyanide were hijacked in Hidalgo State, Mexico. Although the majority of the NaCN was recovered and was probably stolen by mistake, this instance serves to illustrate the likelihood that highly toxic compounds may easily fall into the hands of would-be terrorists (Jordan, 2002).

Release of Compound 1080

Suppose just 1 kg of Compound 1080 were to be deliberately released into the flow system. Such a release would result in a significant downstream peak concentration (Figure 2). A peak concentration of 1.18 mg L⁻¹ is sufficiently large as to warrant an acute risk assessment be conducted.

Compound 1080 Risk Assessment

A release 1 kg of Compound 1080 resulting in a peak concentration downstream of the release site equal to 1.18 mg L⁻¹ can be assessed for its impact on human health by conducting a standard risk assessment. An acute exposure assessment for ingestion E_I is

$$E_I = \frac{C_p I_g}{B_w}$$

where $C_p = 1.18 \text{ mg L}^{-1}$, $I_g = 1.4 \text{ L d}^{-1}$, and $B_w = 70 \text{ kg}$. Its associated hazard quotient H_{QI} is estimated from (Field, 1997)

$$H_{QI} = \frac{E_I}{RfD}$$

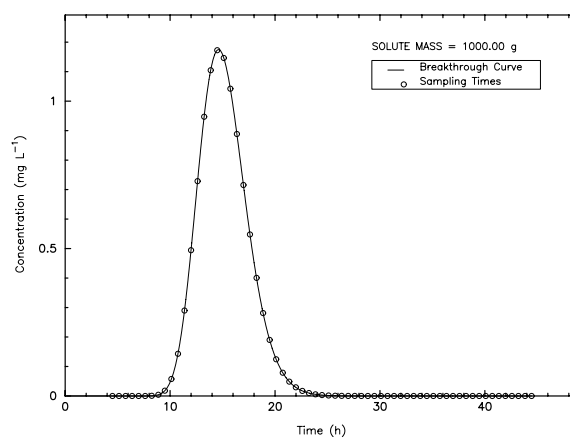


Figure 2. Breakthrough curve results from release of 1 kg of Compound 1080. Circles represent EHTD-recommended sample-collection times.

An acute exposure assessment for inhalation E_2 is estimated from (Field, 1997)

$$E_2 = \frac{C_p I_h W_u S_d}{B_w V_a F_r}$$

where $I_h = 0.6 \text{ m}^3 \text{ h}^{-1}$, $W_u = 719 \text{ L}$, $S_d = 0.17 \text{ h}$, $V_a = 2 \text{ m}^3$, and $F_r = 1$ each day. It's associated hazard quotient, H_{Q2} is estimated from (Field, 1997)

$$H_{Q2} = \frac{E_2 B_w}{RfC I_h}$$

Lastly, an acute exposure assessment for dermal contact E_3 is estimated from (Field, 1997)

$$E_3 = \frac{C_p S_a P_c S_d K_f}{B_w F_r}$$

where $S_a = 1.82 \times 10^4 \text{ cm}^2$, $P_c = 0.074 \text{ cm h}^{-1}$, and $K_f = 10^{-3} \text{ L cm}^{-3}$. It's associated hazard quotient H_{Q3} is estimated from (Field, 1997)

$$H_{Q3} = \frac{E_3}{RfD A_e}$$

where $A_e = 20\%$. The hazard index H_I is then obtained by summing all the previously estimated hazard quotients (Field, 1997)

$$H_I = \sum_1^n H_{Qi}$$

Table 2 shows the basic exposure and risk numbers associated with the Compound 1080 release. The resulting Hazard Index H_I of 2.69×10^3 is high enough to warrant significant concern by a water manager. A $H_I > 1$ is reason for concern so a $H_I > 10^3$ should probably prompt the water manager to issue a no use warning.

Table 2. Acute risk assessment for Compound 1080

Pathway	Exposure Assessment (mg kg ⁻¹ d ⁻¹)	Hazard Quotient (dimen.)
Ingestion ^a	2.35×10^{-2}	1.18×10^3
Inhalation ^b	6.15×10^{-4}	1.50×10^3
Dermal	9.22×10^{-5}	2.31×10^1
Hazard Index, $H_I =$		2.69×10^3

^a $RfD = 2.0 \times 10^{-5} \text{ mg kg}^{-1} \text{ d}^{-1}$.

^b $RfC = 2.0 \times 10^{-6} \text{ mg m}^{-3}$ (assumed).

Release of *Vibrio cholerae*

It has been suggested that it would be very difficult for terrorists to release a deadly pathogen into drinking-water supplies in sufficient quantities to cause serious illness because of the large volume necessary. Consider a one quart thermos (suggested by Hickman, 1999 as a logical container) with a 2.5% concentration of *V. cholerae* (enteric gram-negative rods bacteria ~2-4 μm long). The actual concentration N_p of cholera in the thermos may be calculated by

$$N_p = \frac{2 C_c 10^{12}}{\rho_p \pi a b^2}$$

where $a = 3.0 \mu\text{m}$, $b = 0.5 \mu\text{m}$, and $\rho_p = 1.05 \text{ g cm}^{-3}$. For a $C_c = 2.5\%$ concentration, $N_p = 2.02 \times 10^{10} \text{ mL}^{-1}$. The mass M_p for an individual cholera particle may be calculated by

$$M_p = \frac{\rho_p \pi 10^{-12} a b^2}{2}$$

Which results in $M_p = 1.24 \times 10^{-12} \text{ g}$. The total mass of all the cholera particles M_p^T is then calculated by

$$M_p^T = V N_p M_p$$

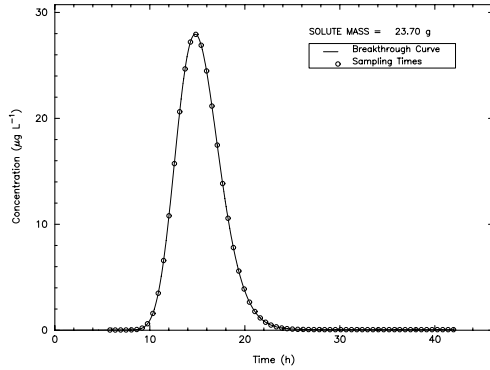


Figure 3. Breakthrough curve results from release of 23.70 g of *V. cholerae*. Circles represent EHTD-recommended sample-collection times.

Where $V = 946$ mL (one quart thermos) results in $M_p^T = 23.70$ g which appears to be a relatively small amount. Applying this value for M_p^T to EHTD with an initial *V. cholerae* concentration of $5.08 \times 10^{-1} \text{ mL}^{-1}$ and allowing for exponential growth results in a $C_p = 27.94 \text{ µg L}^{-1}$ (Figure 3) which translates into a downstream particle concentration $N_p = 2.26 \times 10^4 \text{ mL}^{-1}$.

***Vibrio cholerae* Risk Assessment**

A release 23.70 g of *V. cholerae* resulting in a peak concentration downstream of the release site equal to 27.94 µg L^{-1} can be assessed for its impact on human health by determining the probability of infection P_i by use of the beta-poisson model (Haas, 1983)

$$P_i(d) = 1 - \left[1 + \frac{d}{N_{50}} (2^{1/\alpha} - 1) \right]^{-\alpha}$$

where $\alpha = 0.25$ and $N_{50} = 243$ for *V. cholerae* (Haas and others, 1999, p. 430). Equation (4) may be related to the probability of morbidity $P_{D:I}$ (clinical illness) by (Haas and others, 1999, p. 306)

$$P_{D:I}(d) = 1 - \left[1 + \frac{d}{N_{50}^*} (2^{1/\alpha^*} - 1) \right]^{-\alpha^*}$$

where $\alpha^* = 0.495$ and $N_{50}^* = 3364$ for *V. cholerae* (Haas and others, 1999, p. 308). The probability of mortality $P_{M:D}$ by (Gerba and others, 1996)

$$P_{M:D}(d) = P_{D:I} F_a$$

where $F_a = 0.01\%$ although evidence in support of this equation is conspicuously lacking. Table 3 shows the risks associated with the *V. cholerae* release. While the values for P_i , $P_{D:I}$, and $P_{M:D}$ for a single individual may be taken as fairly low, they are significant given the very small volume (946 mL) released. For an exposed population of 10,000 people, the severity of the risks become apparent where nearly every exposed individual will become infected and will exhibit morbidity (Table 3) if chlorination is shut-down as a result of sabotage or is rendered ineffective through weaponization and/or bioengineering.

Table 3. Acute risk assessment for *V. cholerae*

Population	Risk of Infection, P_i	Risk of Illness, $P_{D:I}$	Risk of Death, $P_{M:D}$
Individual	9.76×10^{-1}	9.95×10^{-1}	9.95×10^{-5}
10,000	9.76×10^3	9.95×10^3	9.95×10^{-1}

Typical water chlorination readily kills *V. cholerae*, but weaponization of *V. cholerae* could make it resistant to chlorination and other disinfectants. *Vibrio cholerae* is well-documented to form biofilms with individual organisms taking a rugose form which increases its resistant to typical chlorination and possibly other disinfectants (Sanchez and Taylor 1997; Wai and others, 1999; Reidl and Klose, 2002). Cholera survival in drinking water may be further exacerbated by inadequate water-treatment plant chlorination (O'connor, 2000, pp. 106—107) or water-treatment plant sabotage (Hickman, 1999).

CONCLUSIONS

Terrorist attacks on drinking-water supplies must be regarded as inevitable. While basic security efforts are useful, it is beneficial to conduct simulation studies of possible releases of toxic substances so as to gain insights into the nature of potential threats. The tracer-test design program, EHTD was modified to use in conducting model simulations of potential attacks. Modifications consisted of conversion to a third-type inlet condition for resident concentrations, inclusion of routines for uniform initial (background) concentration and exponential production (growth) parameters, and the ability to bypass preset C . When run with user-selected solute-mass as input, EHTD bypasses the preset C to allow for prediction of downstream concentrations. Initial solute concentrations and/or exponential production may significantly affect the final concentration estimates if these entered values are substantial.

By conducting basic model simulations studies, water managers can also develop standard risk assessments for chemical and biological attacks on their drinking-water supplies. By developing basic risk assessments, water managers can gain a general sense as to how vulnerable their respective water supplies are to various types toxic contaminants and release amounts. Assessment of the vulnerabilities can then be used to develop human health protection-strategies (e.g., boil water or don't drink health advisories) for use in the event of a terrorist attack.

While not a preventative counterterrorist tool similar to the posting of armed guards, the methodology described is useful for predicting events and for developing protection plans. It is expected, however, that this methodology will be just one small piece in the arsenal of tools available to water managers as they continue to develop protection programs for the nation's drinking-water supplies.

NOTATION

a	long dimension of rod-shaped particle (L)
α	slope parameter for median infection estimate
α^*	slope parameter for median infection estimate
A	cross-sectional area of flow system (L^2)
A_e	estimated adsorption efficiency (dimen.)
b	short dimension of rod-shaped particle (L)
B_w	body weight for an adult (M)
C	mean volume-averaged tracer concentration ($M L^{-3}$)
C_c	concentration for a prepared volume of particulate matter (%)
C_p	peak tracer concentration ($M L^{-3}$)
D	axial dispersion ($L^2 h^{-1}$)
E_1	acute exposure for ingestion of a chemical ($M M^{-1} T^{-1}$)
E_2	acute exposure for inhalation of a chemical ($M M^{-1} T^{-1}$)
E_3	acute exposure for dermal contact with a chemical ($M M^{-1} T^{-1}$)
F_a	fatality rate value (dimen.)
F_r	frequency of showers (T)
H_I	hazard index for all pathways (dimen.)
H_{Q1}	hazard quotient for ingestion (dimen.)
H_{Q2}	hazard quotient for inhalation (dimen.)
H_{Q3}	hazard quotient for dermal contact (dimen.)
I_g	amount of ingested water per day ($L^3 T^{-1}$)
I_h	inhalation rate ($L^3 T^{-1}$)
K_f	volumetric conversion for water ($L^3 L^{-3}$)
L	characteristic distance from point of injection to point of recovery (L)
M	solute mass (M)
M_p	particle mass (M)
M_p^T	mass of total number of particles (M)
n	number of hazard quotients to sum
N_{50}	median infectious dose ($\# T^{-1}$)
N_{50}^*	median morbidity dose ($\# T^{-1}$)
N_p	concentration of particles ($\# L^{-3}$)
n_e	effective porosity (dimen.)
ρ_p	particle density ($M L^{-3}$)
P_c	skin permeability constant ($L T^{-1}$)
P_e	Péclet number (dimen.)
P_I	probability of infection (dimen.)

$P_{D:I}$	probability of morbidity (dimen.)
$P_{M:D}$	probability of mortality (dimen.)
Q	flow system discharge ($L^3 T^{-1}$)
R_d	solute retardation (dimen.)
RfC	reference concentration ($M L^{-3}$)
RfD	reference dose ($M M^{-1} T^{-1}$)
S_a	skin surface area (L^2)
S_d	shower duration (T)
S_f	sinuosity factor
t	mean residence time (T)
t_p	peak arrival time (T)
μ	solute decay (T^{-1})
v	average flow velocity ($L T^{-1}$)
v_p	peak flow velocity ($L T^{-1}$)
V	volume (L^3)
V_a	shower stall volume (L^3)
W_u	water usage (L^3)

REFERENCES

- Bradbury, K. R., Muldoon, M. A., Zaporozec, A., and Levy, J., 1991, Delineation of wellhead protection areas in fractured rocks, U.S. Environmental Protection Agency Tech. Rep. EPA 570/9-87-009, 144 p.
- Burrows, W. D. and Renner, S. E., 1999, Biological warfare agents as threats to potable water, *Environmental Health Perspectives*, 107(12) pp. 975–984.
- Field, M. S., 1997, Risk assessment methodology for karst aquifers: (2) Solute-transport modeling *Environmental Modeling and Assessment*, 47, pp. 23–37.
- _____, 2000, Ground-water tracing and drainage basin delineation for risk assessment mapping for spring protection in Clark County, Virginia, U.S. Environmental Protection Agency Tech. Rep. NCEA-W-0936, 36 p.
- _____, 2002a, The QTRACER2 program for tracer breakthrough curve analysis for hydrological tracer tests, U.S. Environmental Protection Agency Tech. Rep. EPA /600/R-02/001, 179 p.
- _____, 2002b, Efficient hydrologic tracer-test design for tracer-mass estimation and sample-collection frequency, 1. Method development, *Environmental Geology* [in press]
- _____, 2002c, Efficient hydrologic tracer-test design for tracer-mass estimation and sample-collection frequency, 2. Experimental results, *Environmental Geology* [in press]
- Foran, J. A. and Brosnan, T. M., 2000, Early warning systems for hazardous biological agents in potable water, *Environmental Health Perspectives*, 108(10), pp. 979–982.
- Gerba, C. P., Rose, J. B., Haas, C. N., and Crabtree, K. D., 1996, Waterborne rotavirus: A risk assessment, *Water Research* 30(12), pp. 2929–2940.
- Haas, C. N., 1983, Estimation of risk due to low doses of microorganisms: A comparison of alternative methodologies, *American Journal of Epidemiology*, 118, pp. 573–582.
- Haas, C. N., Rose, J. B. and Gerba, C. P., 1999, *Quantitative Microbial Risk Assessment*, John Wiley & Sons, Inc., New York, 449 p.
- Hickman, D. C., 1999, A chemical and biological warfare threat: USAF water systems at risk, <http://www.au.af.mil/au/awc/awcgate/cpc-pubs/hickman.htm>, U.S. Air Force Counterproliferation Center, Air War College, Air University, Maxwell Air Force Base, Ala., 28 p.
- Jordan, M., 2002, Mexicans search for lost cyanide, *Washington Post*, (May 28, 2002), p. A13.
- Kilpatrick, F. A. and Taylor, K. R., 1986, Generalization and applications of tracer dispersion data, *Water Resources Bulletin*, 22(4), pp. 537–548.
- MacKenzie, W. R., Hoxie, N. J., Proctor, M. E., Gradus, M. S., Blair, K. A., Peterson, D. E., Kazmierczak, J. J., Addiss, D. G. and Fox, K. R., Rose, J. B. and Davis, J. P., 1994, A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply, *The New England Journal of Medicine*, 331(3), pp. 161–167.
- Mull, D. S., Liebermann, T. D., Smoot, J. L. and Woosley Jr., L. H., 1988, Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terranes, U.S. Environmental Protection Agency Tech. Rep. EPA/904/9-88-001, 103 p.

- O'Connor, D. R., 2000, Report of the Walkerton inquiry: The events of May 2000 and related issues, Part 1, Ministry of the Attorney General, Toronto, Ont., Canada, 504 p.
- Reidl, J. and Klose, K. E., 2002, *Vibrio cholerae* and cholera: Out of the water and into the host, FEMS Microbiological Letters, 741, pp. 1–15.
- Reed, C., 2001, Security measures on tap, Geotimes, 46(12), pp. 26–28.
- Sanchez, J. L. and Taylor, D. N., 1997, Cholera, The Lancet, 349, pp. 1825–1830.
- Schindel, G. M., Quinlan, J. F., Davies, G. and Ray, J. A., 1997, Guidelines for wellhead and springhead protection area delineation in carbonate rocks, U.S. Environmental Protection Agency Tech. Rep. EPA/904/B-97/003.
- Taylor, K. R., James, R. W. J. and Helinsky, B. M., 1986, Traveltime and dispersion in the Shenandoah River and its tributaries, Waynesboro, Virginia to Harpers Ferry, West Virginia, U.S. Geological Survey Water-Resources Investigations Rep. 86-4065, 60 p.
- Toride, N., Leij, F. J., and van Genuchten, M. Th., 1995, The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments, U.S. Salinity Laboratory Research Report No. 137, 121 p.
- USEPA, 1987, Guidelines for delineation of wellhead protection areas, U.S. Environmental Protection Agency Tech. Rep. EPA 4401/6-87-010, 209 p.
- USEPA, 1997, State source water assessment and protection programs, U.S. Environmental Protection Agency Tech. Rep. EPA 816-R-97-009.
- USEPA, 2001, Protecting the Nation's water supplies from terrorist attack: Frequently asked questions, U.S. Environmental Protection Agency Tech. Rep. At <http://www.epa.gov/safewater/security/secqanda.html>.
- Wai, S. N., Mizunoe, N. Y., and Yoshida, S., 1999, How *Vibrio cholerae* survive during starvation, FEMS Microbiological Letters, 180, pp. 123–131.

Comparison of Methods to Source Track Bacteria in Ground Water in Karst Areas of Berkeley County, West Virginia

By Melvin V. Mathes¹, Donald M. Stoeckel², Kenneth E. Hyer³

¹ U.S. Geological Survey, 11 Dunbar Street, Charleston, West Virginia 25301

² U.S. Geological Survey, 6480 Doubletree Avenue, Columbus, Ohio 43229-1111

³ U.S. Geological Survey, 1730 East Parham Road, Richmond, Virginia 23228

Abstract

Escherichia coli, indicators of fecal contamination, were detected in 16 of 50 domestic water wells sampled during the summer of 2000 in Berkeley County, West Virginia, a region partially underlain by karstic limestone. The combination of diffuse and conduit ground-water flow, as well as the complex interaction of ground and surface water in this area make it difficult to link fecal contamination in ground water to aboveground sources. An emerging technology, bacteria source tracking, can likely identify the sources of fecal contamination in ground water of this region. Knowledge of the sources of fecal contamination will aid in the development of effective source control strategies. Although potentially powerful, the science of bacteria source tracking is relatively new, and no consensus is available regarding the best methods to identify fecal contamination sources in environmental settings. This study will compare seven bacteria source tracking methods for their ability to discriminate *Escherichia coli* isolates from feces of nine different source-animal categories in Berkeley County. The source tracking methods to be compared include ribotyping using HindIII, George Lukasik, University of Florida; ribotyping using EcoRI and PvuII, Mansour Samadpour, University of Washington; antibiotic resistance analysis, Bruce Wiggins, James Madison University; pulsed-field gel electrophoresis using NotI, Kriston Strickler, West Virginia Department of Agriculture; sole source carbon utilization using BIOLOG, Charles Hagedorn, Virginia Polytechnic Institute and State University; rep-PCR using REP primers, Donald Stoeckel, U.S. Geological Survey; and rep-PCR using BOX primers, Howard Kator, College of William & Mary.

The study will be performed by challenging a library of known-source isolates with a library of blind isolates. The identities of the blind isolates are known only to the project manager. The known-source library will be developed using fecal samples that were collected from nine sources: humans, dogs, beef cows, dairy cows, swine, chickens, horses, deer, and geese. The blind collection of challenge isolates will include new isolates from the 9 sources represented in the known library, replicates from the original known-source library, and a collection of new sources that are not represented in the source library (such as mice, cats, goats, and llamas). Method performance will be assessed by the average rate of correct classification for isolates from each source group, the rate of false identification within each source group, and the ability of each method to handle the un-represented sources.

The library of known source isolates was constructed from a minimum of 20 fecal samples that were collected in August and September 2001 in Berkeley County for each of nine source-animal categories. Sterile toothpicks were used to pick apart fresh fecal samples and to extract a small portion from the center of each sample. The sterile toothpick containing the extracted feces was swirled in a vial of sterile buffer that was then wiped with alcohol, chilled, and shipped by overnight mail to the U.S. Geological Survey microbiology lab in Columbus, Ohio. Between 5 and 8 isolates of *Escherichia coli* were cultured and confirmed at the Columbus lab from each fecal sample to build a library of at least 100 isolates for each of the nine source-animal categories for a total known-source library of 900 isolates. The confirmed *Escherichia coli* isolates were distributed to the laboratories performing the seven bacteria source tracking methods. Currently, each lab is in the process of building a source library from these known source isolates.

At the time of writing, the collection of the feces for the challenge isolate set was scheduled for June 2002. Feces collection procedures will be identical to those used to collect feces for the known source isolate set. Approximately 15 feces samples will be collected for eight of the source-animal categories, and approximately 30 feces samples will be collected from human sources. Approximately 25 feces samples will be collected from new animal sources not in the known source isolate library. All feces sampled will be mailed without animal-source identification to the U.S. Geological Survey microbiology lab in Columbus, Ohio, for culturing and confirmation of bacteria isolates. The lab will culture and confirm one bacteria isolate from each fecal sample. These isolates plus selected replicates from the known source library will comprise the challenge set of isolates.

Each of the seven researchers will use his or her particular method of bacteria source tracking analysis to compare the challenge set of isolates to isolates in the known-source library. Each researcher will then offer a presumptive identification for each of the 200 isolates in the challenge set, using a direct match or statistical approach of their choice. The identification of the replicates will test the reproducibility of each method, and the identification of the unknowns will test the predictive accuracy of each method. A robust method of analysis will identify correctly all replicate isolates and all unknown isolates from the challenge set that are from sources included in the known-source library. A robust method of analysis will also correctly identify isolates as “unidentifiable” if they were from animal sources not in the source library.

Karst Aquifers as Atmospheric Carbon Sinks: An Evolving Global Network of Research Sites

Chris Groves¹, Joe Meiman², Joel Despain³, Liu Zaihua⁴, and Yuan Daoxian⁴

¹Hoffman Environmental Research Institute, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky 42101 USA

²Division of Science and Resource Management, Mammoth Cave National Park, Mammoth Cave, Kentucky 42259 USA

³Division of Science and Natural Resources Management, Sequoia and King's Canyon National Parks, Three Rivers, California 93271 USA

⁴Karst Dynamics Laboratory, Institute of Karst Geology, 50 Qixing Road Guilin, Guangxi, 541004, China

Abstract

Karst flow systems formed in carbonate rocks have been recognized as a sink for atmospheric carbon that originates as gaseous carbon dioxide and ends up as dissolved aqueous carbon, primarily as bicarbonate. While measurements of the magnitude of the sink associated with carbonate rock dissolution have assumed that half of the dissolved inorganic carbon leaving a given catchment comes from the mineral and half from the atmosphere, consideration of the kinetics of carbonate mineral dissolution in acid solutions suggests that the ratio is enriched in mineral-source carbon to an extent that depends on the geochemical environment of mineral/fluid contact. After developing a methodology for precise field measurement of both the magnitude of this sink as well as the partitioning of inorganic carbon sources in south central Kentucky, in 2001 we initiated a long-term project to improve understanding and estimates of the sink with a global monitoring network. The first two new stations and methodology are described herein. In addition to the existing Kentucky sites, we are now making high-resolution measurements in the Mineral King Valley, an alpine marble catchment within California's Sierra Nevada, at an elevation from 2,400 to 3,650 m, and at Spring 31 of the Karst Dynamics Laboratory's experimental research site near Guilin, China. This humid-subtropical site drains an area of peak cluster tower karst at an elevation from 150 to 450 m, and is considerably warmer and wetter than south central Kentucky. For relatively remote sites, the importance of data logging equipment redundancy is becoming clear.

INTRODUCTION

Considerable uncertainty exists about detailed mechanisms and rates of some biogeochemical aspects of the global carbon cycle. The global "missing carbon sink", (Siegenthaler and Oeschger, 1978; Joos, 1994; Hesshaimer, *et al.*, 1994), which has remained unsolved through more than a decade of intense scrutiny, highlights this problem. The answer lies in a clearer quantitative description of cycle dynamics. Along with broad-scale "box" cycle models, detailed process/rate studies are required to develop sufficiently precise quantitative evaluation of reservoir dynamics, and to understand how pools with different sizes, residence times, and exchange rates interact. Part of the difficulty has been to

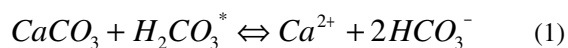
correctly separate and integrate processes and rates associated with short- and long-term carbon cycles, primarily split between those reservoirs and mass-flux terms that would and would not be impacted by human activities, respectively.

Carbonate rock karst aquifer/landscape systems, composed primarily of primarily limestone and dolomite, cover some 12% of the earth's land surface (Ford and Williams, 1989), and weathering of these rocks on the continents has been recognized as a sink term for atmospheric CO₂ (Amiotte Suchet and Probst, 1993, 1995; Berner *et al.*, 1983; Maybeck, 1987; Probst *et al.*, 1994; Liu and Zhao, 2000; Telmer and Veizer, 1999). At the global scale, however, models (Berner and Lasaga, 1989; Berner, 1999)

have assumed that the continental weathering sink is offset by the oceanic CO₂ source that results from the reprecipitation of that carbon as solid mineral phases, and thus the contribution of carbonate mineral weathering to the overall global carbon cycle has thus not received intense attention.

In addition to the biogeochemical interactions that impact carbon transport and cycling in other geological settings, in these areas carbon dynamics are further complicated by fluid/rock interactions (Holland *et al.*, 1964; White, 1988; Ford and Williams, 1989; Dreybrodt, 1989; Palmer, 1991). Along with the typically low, ubiquitous atmospheric background levels, sources of carbon dioxide within carbonate karst systems include microbial respiration, oxidation of organic material, and plant root respiration in the soil (Reardon *et al.*, 1979), as well as carbonate mineral precipitation. Atkinson (1977) and Wood and Petraitis (1984) found evidence of CO₂ production within the vadose zones of both carbonate and noncarbonate aquifers, presumably by oxidation of organic material washed down from the soil zone. The primary sinks include diffusive loss to the atmosphere, uptake by infiltrating recharge waters, and dissolution of carbonate minerals in CO₂-H₂O solutions (Reardon *et al.*, 1979; White, 1988).

Measurements of the atmospheric carbon sink associated with carbonate mineral weathering on the continents (*e.g.* Amiotte Suchet and Probst, 1993, 1995; Berner *et al.*, 1983; Maybeck, 1987; Probst *et al.*, 1994; Liu and Zhao, 2000; Telmer and Veizer, 1999) have generally assumed that of the total inorganic carbon flux from carbonate mineral dissolution leaving a given catchment, often estimated with bicarbonate, half comes from the mineral and half from the atmosphere. This has been based on consideration of the reaction between calcite (or analogously, dolomite) and carbonic acid



where one mole of product carbon is derived from the mineral and one from the atmosphere,

and where H₂CO₃^{*} is equal to the sum of carbonic acid and aqueous carbon dioxide. We define this ratio of inorganic mineral source/atmospheric source carbon as ψ , which in the above case would be unity.

Recent work (Groves and Meiman, 1999, 2000) has shown the possibility of non-unity ψ values based on high resolution monitoring, apparently resulting from the elementary reactions of calcite and dolomite dissolution kinetics in acid solutions (Plummer *et al.*, 1978; Busenberg and Plummer, 1982), suggesting that the details of carbonate mineral dissolution kinetics under varying geochemical environments may influence carbon budgeting. Inorganic carbon leaving the 25 km² Cave City Basin of the humid-subtropical south central Kentucky karst area, for example, had a ψ value of 1.13.

This research is developing along several lines. We are developing theoretical models to try to understand the influences on this ratio, and to develop tools by which it will be possible to make improved global estimates of this carbon flux. The goal of this work is to develop quantitative relationships between the magnitude of this flux and existing, or easily measured, regional climate data. Simultaneously, we are refining our methodology and making additional measurements under different climatic and hydrogeologic conditions to both help us understand the nature of these relationships, as well as to have real, high-resolution data to test the models as they evolve.

We are expanding the work beyond Kentucky (although measurements currently continue at five sites there), and have initiated the development of a global network to make high-resolution measurements of inorganic carbon fluxes and source partitioning. The purpose of this extended abstract is to describe the current status of this network and the methods that we are using to make these measurements. The data are currently being collected at two new sites, a relatively pristine air quality alpine site in California's Sierra Nevada (Mineral King) and at a warm, relatively wet subtropical site in southern China (Guilin)

with recharge acidity impacted by coal burning. We expect to report on the progress at these sites at the third U.S.G.S. Karst Interest Group Conference.

Mineral King, California

The Mineral King valley is the source of East Fork of the Kaweah River within Sequoia National Park in the Sierra Nevada, California (Figure 1). The glaciated valley floor lies at an elevation of approximately 2,400 m. The valley is covered by scattered stands of coniferous trees and meadows of herbaceous annuals. There are permanent snowfields at higher elevations, but no active glaciers.

Mineral King Valley is bounded by Jurassic aged plutonic rocks that outcrop on the margins of the watershed. These form the peaks of the Great Western Divide that reach heights of more than 3,800 m to the east of the main valley. Rocks in the central portions of watershed, including the valley floor and adjacent tributaries, are largely of Mesozoic marine origin. These rocks reveal an altered but intact sub marine volcanic center that forms a vertically-dipping, east-facing homocline with extensive local folding and faulting that is sub-parallel to the bedding (Busby-Spera, 1982).

Karst flow systems have developed within marble outcrops that lie in narrow bands parallel to the valley floor. They are prominent in the White Chief hanging valley, near Timber Gap, along Crystal Creek and in Panorama and Franklin valleys. The marbles are generally white calcite with only minor dolomitization and dark, carbon-rich foliations. Karst has developed in these areas producing dozens of springs, sinking streams, sinkholes and caves in the Mineral King area (Rogers, 1978).

The Mesozoic rocks are largely meta-volcanic and metamorphosed volcanic sediments. They include meta-rhyolite and meta-andesite, phyllites, schists and quartzite, and also marble.

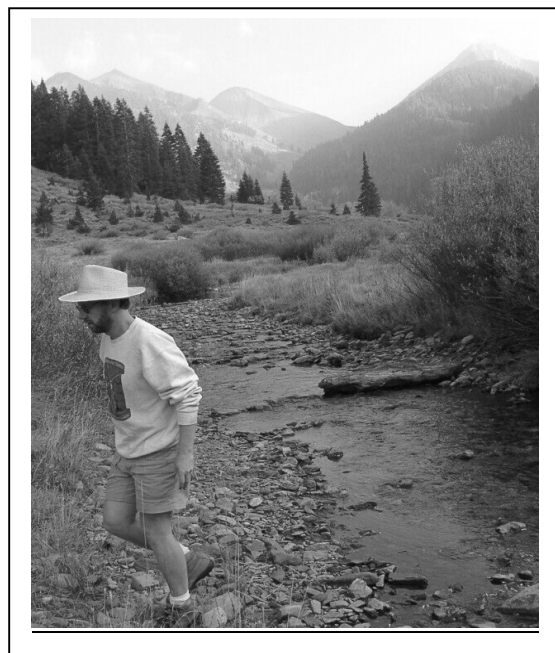


Figure 1. Floor of Mineral King Valley, Sequoia National Park. Photo by J. Meiman.

Along the east side of the Mineral King Valley is the greater White Chief area karst watershed. The upper end of this drainage begins at 3,642 meters on the granitic, glaciated rocks of Vandever Peak. Runoff builds into a small stream and descends to the north and west to an elevation of approximately 3,050 meters. There the stream encounters the White Chief marble and flows into the large southern entrance of 1,200 m-long Cirque Cave. At low flow the stream emerges at a spring below the cave, flows across the surface for 300 m and enters White Chief Cave. White Chief has 2,000 m of passage, much of it adjacent to the cave stream. The stream resurges again at the lower end of the cave, crosses onto schist and plunges over a 30-meter waterfall. (Rogers, 1978). During low flow conditions the stream flows on the surface for another 400 m and sinks yet again into a shallow cave system that is generally not explorable. Underground, the main creek joins the stream from White Chief Lake, resurges and flows through the White Chief Bogaz. Another 500 m across the surface brings the stream to several sinks heavily mantled by plutonic glacial debris. There the White Chief

stream sinks underground to ultimately reappear at Tufa Falls.

North of White Chief Valley the marble is mantled by more than 150 m of Tioga stage glacial debris (Tinsley, 1999). Further north, sinks appear in the surface along the valley of Eagle Creek at an elevation 2,700 m. Eagle Creek disappears into a large sink where fractured pieces of marble, but no bedrock crop out. Beyond Eagle Sink the narrow marble band can be followed on the surface for 1.5 km to the Tufa Falls Resurgence. There the marble and this complex hydrology end in the steep, glaciated wall of the main White Chief Valley. The entire water shed drains approximately 7 km².

Flow at the resurgence varies seasonally with a peak associated with spring snowmelt, generally in late May, and can exceed 1 m³s⁻¹. Late fall flows from the spring are generally much lower and in dry years may drop below 0.03 m³s⁻¹ (Black, 1994; Schultz, 1996). The site is snow covered for several months each winter, with accumulations that can exceed 10 m. Previous work has shown that stream temperatures range between 2° and 9°C, and pH values between 7.3 and 8.0 (Black, 1994; Schultz, 1996). Tinsley (1999) has demonstrated that the water at the spring originates from Eagle Sink and White Chief Valley. Sodium chloride and fluorescein were used in 1989 to document the connection to the White Chief stream. Transit time to the spring was 3.5 days.

The greater White Chief karst offers an excellent opportunity to characterize the chemistry of an alpine karst stream. The well-defined watershed, previously mapped geology (Busby-Spera, 1982; Tinsley, 1999), and reasonable winter access to the spring make this the ideal site for this work in the Sierra Nevada.

We installed equipment in the fall of 2001, and continuous geochemical and flow monitoring began in January, 2002.

Guilin, China

In the 1980's, the Karst Dynamics Laboratory developed the Guilin Karst Hydrogeology Experimental Site close to Yaji Village, near Guilin, China. Guilin, in southern China's Guangxi Province at a latitude of about 24° north, is a well-known tourist city because of the great beauty of its karst landscapes. In early 2002 we installed continuous monitoring equipment at the site's Spring 31 (Figure 2), the largest of four significant springs that occur along a faulted boundary between regions of the two major tower karst landform types in southern China (Droge, 1986; Yuan *et al.*, 1990, Sweeting, 1995) (Figures 3 and 4). These are *fengcong* (peak clusters), and *fenglin* (peak forests). While both have karst towers as a major feature, in this area with heights of up to 300 m, the peak clusters form from groups of peaks joined at their bases, forming enormous dolines between them. In the peak forest areas, in contrast, generally single towers are distinct from one another, separated by a flat floodplain surface.

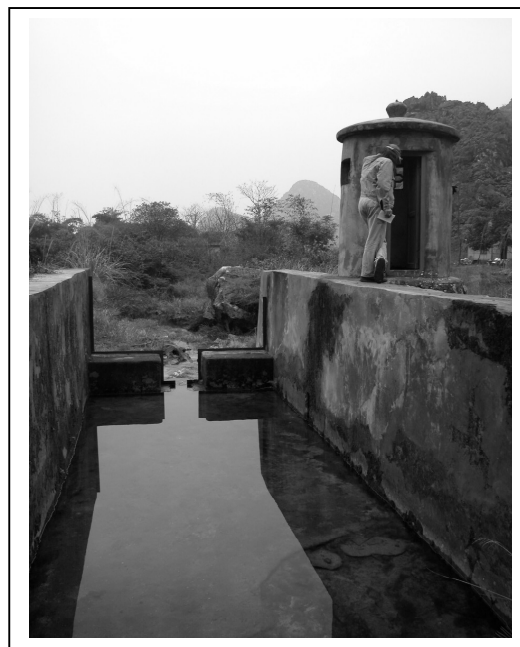


Figure 2. Spring 31 near Guilin, China, showing flume and rectangular weir, prior to equipment installation. Photo by C. Groves.

The experimental site drains an area of peak cluster with a recharge area of about two km², with the springs at the outside base of the peak cluster region (Figure 4). Spring 31, the only perennial spring at the site, drains three large dolines (Chai *et al.*, 1988) and has a discharge that ranges from 10⁻⁴ to 7 m³s⁻¹. There is a distinct rainy season in Guilin--mean annual precipitation there is 1.9 m, with 75% falling from April to August (Yuan *et al.*, 1990). The mean temperature of the waters of Spring 31 is about 19°C.

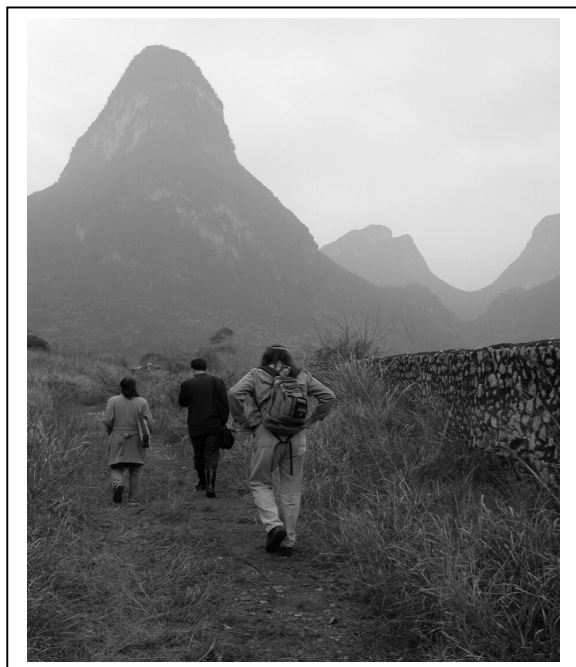


Figure 3. Peak cluster area near Guilin. The experimental site is within the cluster area, and Spring 31 is at the base of the towers, towards the right of the picture. Photo by C. Groves.

The karst of the experimental site is formed within the upper Devonian Rongxian Formation, a relatively pure sparry micrite (Yuan *et al.*, 1990), which in the area dips to the southeast at 5-10°. This is part of an arc shaped, north-south trending synclinorium, which contains a Devonian-Mississippian carbonate rock sequence about 3,000 m in thickness.

The flat plain to the left of the diagram, and in the foreground of Figure 3, is the flood plain of the Li River (*Lijiang* on Fig. 4), which forms

the flat surface separating the isolated karst peaks of the peak forest area.

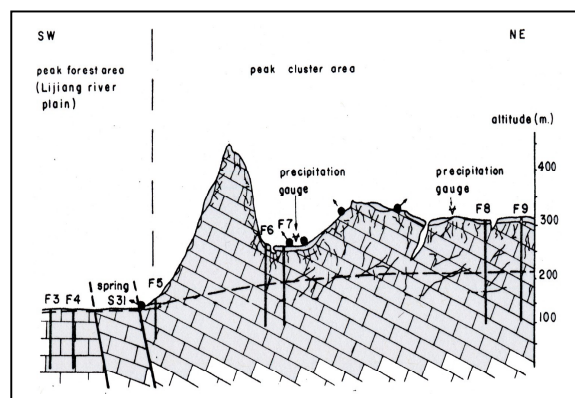


Figure 4. Cross-section through the Guilin experimental site, showing location of Spring 31 (from Yuan, *et al.* 1990). The karst tower adjacent to Spring 31 in the diagram is the tall one in Figure 3.

Methodology

The long-term goal of monitoring is to collect high-resolution data on both flow and chemical characteristics to quantitatively evaluate the magnitudes and rates of change of carbonate chemistry from limestone/dolomite karst flow systems under a variety of climatic conditions including temperature, precipitation, and rainfall acidity. The requirements for the establishment of such research sites depend to some degree on the specific research questions being addressed, as these methods provide data that can be used for a variety of questions in addition to carbon source partitioning. Basic features, however, include a karst flow system with a well-delineated recharge area that can be sampled with reasonable accessibility and local collaborators for site visits (sample collection and analysis and equipment maintenance). There must not be significant amounts of bedded primary gypsum, anhydrite, or other calcium or magnesium sources in addition to calcite and dolomite within the drainage system. The only required analysis that cannot be preserved is for bicarbonate, so resources must be available for titration within a relatively short period. The sites are visited every two weeks (or for especially remote sites as often as is practical)

for maintenance and calibration, to download data loggers, and to collect water samples. Probes are checked and cleaned during visits and readings taken with separate meters to check for instrument drift. We have found that that we are able to get very steady readings over this interval, including pH with recent improvements in pH amplification.

Although details of installation vary from site to site, due to varying hydrologic conditions and the typically remote nature of these sites, we are standardizing the equipment across all sites and typically we use electronic probes at each site to measure temperature, specific conductance, and stage, and pH. Because changes in both flow and chemical conditions in karst flow systems can be very rapid, a Campbell multi-channel data logger queries the probes every thirty seconds, and averages these readings every two minutes.

While discharge measurements are not required for the carbon source partitioning, they are important for total carbon flux estimations, and comparing between different sites in the network. Discharge estimates within the network are made by a variety of methods, depending on the conditions at each site. In the underground Logsdon and Hawkins Rivers in Kentucky we use two-minute direct velocity (electronic velocity sonde) and stage measurements (pressure transducer) to estimate discharge under open channel conditions, using a relationship between the cross section area of flow and stage (Groves and Meiman, 2000). These measurements are limited, however, by measurement at a single location in the center of the flow cross-section in each stream. To account for the vertical velocity distribution, the velocity at 0.6 flow depth, which has been shown to be close to the mean velocity in the vertical profile, was related to the apparent velocity at the fixed-depth point of measurement assuming a logarithmic velocity distribution (Chow, 1959). In order to correct for longitudinal velocity variations, discharge measurements were made on eight occasions using standard wading-rod gaging techniques and a 0.3 meter longitudinal spacing, and the average ratio between mean and maximum

velocity (assumed at the center of each channel, where the velocity sonde is located) was determined. The vertically corrected apparent velocity in each stream was then multiplied by this ratio.

The Mineral King alpine site is in a surface pool between two waterfalls along a very steep stream segment, downstream from the emergence of the flow from Tufa Falls, a large karst spring. Because of the geometry of the site and the highly variable flow conditions, particularly with spring snowmelt, neither a weir nor direct velocity sonde measurement are practical. Here we are developing a rating curve with constant stage monitoring and direct measurements using a salt-slug tracer method. The logger has been programmed with a second routine (in addition to the regular data collection mode) that can be implemented during site visits for very high resolution (1 second) conductivity recording, and salt solutions of known volume and concentration are injected upstream. From the salt slug passing the probe (Figure 5), discharge can be calculated.

In Guilin, discharge is calculated with continuous stage monitoring behind a compound, rectangular weir constructed during the original implementation of the research station (Figure 2).

The data required to determine inorganic carbon source partitioning (Groves and Meiman 2000, 2001) in addition to the pH and temperature from the probes, include calcium, magnesium, and bicarbonate. We currently use ion chromatography and atomic adsorption spectroscopy for ion analyses, and a gran titration for bicarbonate analyses. One additional sample for every ten should be analyzed as a blind duplicate for quality assurance procedures, run for a reasonably complete set of anions and cations for a charge balance check, although in many karst waters these three ions will dominate. Fortunately, the relationship between each of these three and specific conductance is often linear and statistically significant (White, 1988), although the relationship must be established with data from each site. At our Kentucky underground

river sites, for example, we have been able to measure such relationships with r^2 values exceeding 0.95. For this reason, samples are collected during each visit and measured in the laboratory for these three ions, which gives 26 values (plus duplicates) during a year long sampling campaign, typically over a range of storm and seasonal conditions, which can then be used to develop the relations. The high-resolution specific conductance data can thereafter be used as a proxy for the required ions, and calculations made. The same data can be used to study magnitudes and rates of change of mineral saturation indices, dissolution rates, and carbon dioxide partial pressures.

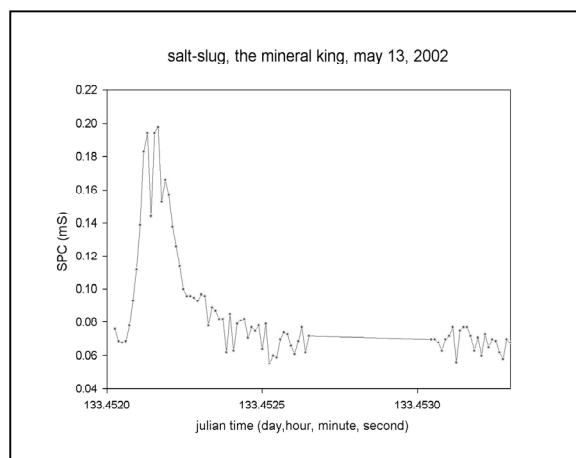


Figure 5. Typical salt slug using second logger program used for discharge calculation, Miner King site.

CONCLUSIONS

The work described here represents the next step in a long-term project to improve the global estimates of, and to better understand, the geological interactions impacting the global carbon cycle. We continue to refine the methods, to a large degree learning from our errors. While we have designed a reasonably robust system for data collection, for example, it has become clear that for remote sites fully redundant data loggers and probes are required.

We have identified a series of additional locations for potential research sites under a

wider variety of rainfall, temperature, and rain pH conditions in the U.S., Caribbean, and Europe, and currently hope to build the network to a total of twelve sites over the next four years. A fringe benefit of this work is that through detailed, quantitative study of a wide variety of karst environments, and through interactions with our colleagues who have long experience in those areas, we are also learning a great deal about karst hydrogeology and geomorphology.

REFERENCES

- Amiotte Suchet, P. and J.L. Probst, 1993, *Modeling of atmospheric CO₂ consumption by chemical weathering of rocks: Application to the Garonne, Congo, and Amazon Basins*. Chem. Geol. 107, 205-210.
- Amiotte Suchet, P. and J.L. Probst, 1995, *A global model for present day atmospheric/soil CO₂ consumption by chemical erosion of continental rocks (GEM-CO₂)*. Tellus 47B, 273-280.
- Atkinson, T.C., 1977, *Carbon dioxide in the atmosphere of the unsaturated zone: An important control of groundwater hardness in limestones*, J. Hydrol. 35, 111-125.
- Berner, R.A. and A.C. Lasaga, 1989, *Modeling the geochemical carbon cycle*. Sci. Amer. 260, 74-81.
- Berner, R.A., 1999, *A new look at the long-term carbon cycle*. GSA Today 9, 1-6.
- Berner, R.A., A.C. Lasaga, and R.M. Garrels, 1983, *The carbonate-silicate geochemical cycle and its effect on atmospheric CO₂*. Amer. J. Sci. 283, 641-683.
- Black, P.B., 1994, *The Hydrogeochemistry of the Mineral King Area, Sequoia National Park, CA*. MS. Thesis, School of Natural Sciences, Fresno State University, 178 p.
- Busby-Spera, C.J., 1982, *Paleogeographic Reconstruction of a Submarine Volcanic Center: Geochronology, Volcanology, and Sedimentology of the Mineral King Roof Pendant, Sierra Nevada, California*. PhD Dissertation, Department of Geological and Geophysical Sciences, Princeton University, 291 p.

- Busenberg, E. and Plummer, L.N., 1982, *The kinetics of dissolution of dolomite in CO₂-H₂O systems at 1.5 to 65°C and 0 to 1 atm PCO₂*. Am. J. Sci. **282**, 45-78.
- Chai, W., A. Dai, D. Yuan, and P. Bidaux, 1988, *Tracing test in karst water-bearing system, using various chemical reagents*. Proceedings of the International Association of Hydrogeologists 21st Congress (Guilin) Part 2. Beijing: Geol. Pub. House 902-909
- Dreybrodt, W., 1988, *Processes in Karst Systems*, New York: Springer-Verlag, 288 p.
- Droge, C., *Fracturing in the Paleozoic carbonate formation of southern China (Guanxi fracture area): Interpretation within the tectonic context of eastern Asia*. Tectonophysics, 121, pp. 295-302.
- Ford, D.C. and P.W. Williams, 1989, *Karst Geomorphology and Hydrology*, Winchester, Massachusetts: Unwin Hyman Ltd., 601 p.
- Groves, C., and J. Meiman, 2000, *Regional atmospheric carbon sink within the south central Kentucky karst*, Proceedings of the Eighth Mammoth Cave Science Conference, pp. 131-141.
- Groves, C. and J. Meiman, 2001, *Inorganic carbon flux and aquifer evolution in the south central Kentucky karst*, U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report, 01-4011, pp. 99-105.
- Hesshaimer V., M. Heimann, and I. Levin, 1994, *Radiocarbon evidence for a smaller oceanic carbon dioxide sink than previously believed*, Nature 370, 201-203.
- Holland, H. D., Kirsipu, T. V., Huebner, J. S., & Oxburgh, U. M., 1964, *On some aspects of the chemical evolution of cave waters*, J. Geol. 72, 36-67.
- Joos, F., 1994, *Imbalance in the budget*, Nature 370, 181-182.
- Liu, Z. & J. Zhao, 2000, *Contribution of carbonate rock weathering to the atmospheric CO₂ sink*. Env. Geol. 39, 1053-1058.
- Meybeck, M., 1987, *Global chemical weathering of surficial rocks estimated from river dissolved load*. Amer. J. Sci. 287, 401-428.
- Palmer, A.N., 1991, *The origin and morphology of limestone caves*, Geol. Soc. Amer. Bull. 103, 1-21.
- Probst, J.L., J. Mortatti, and Y. Tardy, 1994, *Carbon river fluxes and global weathering CO₂ consumption in the Congo and Amazon River basins*. Applied Geochem. 3, 1-13.
- Reardon, E.J., G.B. Allison, and P. Fritz, 1979, *Seasonal chemical and isotopic variations of soil CO₂ at Trout Creek, Ontario*, J. Hydrol. 43, 355-371.
- Rogers, B., *Mineral King Update*, California Caver, Vol. 29, 4-12, 1978.
- Siegenthaler, U. and H. Oeschger, 1978, *Predicting future atmospheric carbon dioxide levels*, Science 199, 388-395.
- Sweeting, M. M., 1995, *Karst in China: Its Geomorphology and Environment*. Berlin: Springer-Verlag, 265 p.
- Telmer, K., & J. Veizer, 1999, *Carbon fluxes, pCO₂ and substrate weathering in a large northern river basin, Canada; carbon isotope perspectives*. Chem. Geol. 159, 61-86.
- Tinsley, J.C., 1990, *New Karst Connection in Mineral King Valley*, California Caver, 210, 22.
- White, W.B., 1988, *Geomorphology and Hydrology of Karst Terrains*, New York: Oxford University Press, 464 p.
- Wood and Petraitis, 1984, *Origin and distribution of carbon dioxide in the unsaturated zone of the southern High Plains*, Water Resources Res. 20, 1193-1208.
- Yuan, D., C. Droge, A. Dai, W. Lao, W. Lao, P. Bidaux, and M. Razack, 1990, *Hydrology of the karst aquifer at the experimental site of Guilin in southern China*. J. Hydrol., 115, pp. 285-296.

STATE AND NATIONAL PROGRAM

Synopsis of Karst Investigations Conducted in Jefferson and Berkeley Counties, West Virginia, by the U.S. Geological Survey, West Virginia District

By Mark D. Kozar

U.S. Geological Survey, 11 Dunbar Street, Charleston, West Virginia 25301

Abstract

The U.S. Geological Survey has been investigating ground-water flow and quality in the karst aquifer system of West Virginia's Eastern Panhandle since the early 1960's. The first study was conducted by Paul P. Bieber in 1961 and primarily described the hydrogeologic setting of the karst aquifer within Jefferson and Berkeley Counties. The study also estimated the potential volume of flow that might be expected from wells drilled within the karst aquifer based on well yield data. Two studies by William A. Hobba (Hobba, W.A., Jr., 1976, and Hobba, W.A., Jr., 1981) in Berkeley and Jefferson Counties concentrated on Cambrian and Ordovician age limestones and dolomites of the Great Valley. Determining the quality of ground water within the karst aquifer system and determining whether agriculture was impacting the quality of ground water within the aquifer were the major objectives of the studies. In 1991 Kozar, Hobba, and Macy investigated whether water-quality problems documented in the 1981 study of Jefferson County had improved or worsened over the ten-year period. Shultz, Hobba, and Kozar (1995) made a similar study in Berkeley County, to address whether temporal changes in ground-water quality had occurred. The later studies, although based on more random criteria for selecting wells, also contained a significant component of research into the effects of agriculture on ground-water quality. A more recent investigation (Mathes, 2000) assessed the effects of septic systems on the occurrence of indicator bacteria in the karst aquifer in Berkeley County. This abstract presents a chronological history of significant findings of these investigations.

Initial investigations by Bieber indicate that large quantities of ground water are available throughout Jefferson and Berkeley Counties. Of 104 wells for which yield data were available, yields ranged from 1 to 630 gallons per minute (gal/min). For wells less than 100 feet in depth, average well yield was found to be less than 20 gal/min. For wells deeper than 150 feet, average well yield was in excess of 60 gal/min. Optimal depths for drilling in the karst aquifer were found to be between 150 and 200 feet. Generally, the quality of ground water available from the karst aquifer was good except many wells produced hard to very hard water.

The first Berkeley County study (Hobba, 1976) found the quality of water available from the karst aquifer generally to be good. Only a few wells had chloride and/or nitrate in excess of drinking-water standards. Eighty to ninety percent of streamflow was found to be attributable to ground-water discharge to streams. On average, 600,000 gallons of water per day per square mile (gal/day/mi²) were estimated to be available from the karst aquifer and 100,000 gal/day/mi² were estimated to be available from shale aquifer within the county.

The first countywide investigation of ground-water quality within Jefferson County documented high concentrations of nitrate in water from a few wells completed within the karst aquifer (Hobba, W.A., Jr., 1981). Of 192 wells sampled and analyzed for nitrate, 27 (14 percent) had concentrations equal to or exceeding the 10 mg/L maximum contaminant level (MCL) drinking water standard. On average, up to 600,000 gal/d/mi² of water were estimated to be available from the karst aquifer.

A more comprehensive investigation was made in the second Jefferson County study. The second study included dye tracer tests to determine rates and directions of ground water flow within the karst aquifer. Results of dye tracer tests indicate that ground water moves parallel to bedrock strike at a rate of 70 to 840 feet per day (ft/day) and perpendicular to bedrock strike at a rate of 30 to 235 ft/day (Kozar and others, 1991). Transmissivity was estimated by using streamflow and water-table gradients to be 3,900 and 4,100 feet squared per day (ft²/day) parallel to strike and 800 and 1,100 ft²/day perpendicular to strike. Spring discharge data indicate that the Chambersburg Limestone, the Beekmantown Group, and the Connococheague Formation have yields of more than 1,300,000; 290,000; and 175,000 gal/day/mi² of water, respectively. Of 62 wells and springs sampled as part of the investigation, water samples from 26 percent of the sites contained nitrate in excess of the MCL. Fecal coliform bacteria were detected in water samples from 53 percent of the sites and fecal streptococcus bacteria were detected in water from 70 percent of the sites.

The second Berkeley County investigation was also more comprehensive than the first. Recharge was estimated to be about 10 inches per year for the karst aquifer (Shultz and others, 1995). Ground-water flow is controlled by geologic structure with bedding planes being major controls on the direction and velocity of ground water flow. Ground-water velocities, based on results of dye tracer tests, ranged from 32 ft/day in the more diffuse portions of the aquifer to 1,879 ft/day in the more conduit-dominated portions of the karst aquifer. The highest mean yield (48 gal/min) was for wells completed in the Beekmantown Group but the highest median yield (20 gal/min) was for wells completed in the Martinsburg Shale Formation. Faults were also found to be important avenues of ground-water flow. Median specific capacity of wells less than 700 ft from a fault was 3.6 gallons per minute per foot of drawdown (gal/min/ft) while wells greater than 700 ft from a fault had median a specific capacity of only .26 gal/min/ft. For wells completed within the karst aquifer, yield generally decreases with depth. The highest median yield (20 to 30 gal/min) generally is for wells less than 150 feet deep. For wells deeper than 150 feet, median yields range from 4.5 gal/min for wells greater than or equal to 400 feet in depth to 15 gal/min for wells between 150 and 199 feet in depth. The quality of water from the karst aquifer in Berkeley County is generally good, but the aquifer is highly susceptible to contamination. Fecal coliform bacteria were detected in water samples from 41 percent and fecal streptococcus bacteria were detected in water samples from 54 percent of wells sampled within the karst aquifer. Nitrate, which was found to be a potential problem in Jefferson County, was detected in concentrations exceeding the MCL in only 3 wells sampled in the karst aquifer within Berkeley County. Bacterial contamination was found to be the primary water-quality problem of concern.

In June of 2000, 50 wells in the karst aquifer of Berkeley County were sampled for total coliform, fecal coliform, and *E. coli* indicator bacteria. The wells were selected to represent areas with differing densities of septic systems within a 5-acre area around the well. A primary objective of the investigation was to assess the impact of septic density on ground-water quality of the karst aquifer. No relation between septic density and indicator bacteria could be determined. A high proportion of wells sampled, however, contained indicator bacteria. Of the 50 wells sampled, 62 percent contained total coliform bacteria, 32 percent contained *E. coli*, and 30 percent contained fecal coliform bacteria. Complicating factors of septic efficiency and/or complexities of the ground-water flow system likely are responsible for the lack of correlation between indicator bacteria and densities of septic systems.

REFERENCES

Bieber, 1961, Ground-Water Features of Berkeley and Jefferson Counties, West Virginia: West Virginia Geological and Economic Survey Bulletin 21, 81 p.

- Hobba, W. A., Jr., 1976, Ground-Water Hydrology of Berkeley County, West Virginia: West Virginia Geological and Economic Survey Environmental Geology Bulletin 13 21 p.
- Hobba, W. A., Jr., 1981, Ground-Water Hydrology of Jefferson County, West Virginia: West Virginia Geological and Economic Survey Environmental Geology Bulletin 16 21 p.
- Kozar, M.D., Hobba, W.A., Jr., and Macy, J.A., 1991, Geohydrology, Water Availability, and Water Quality of Jefferson County, West Virginia, With Emphasis on the Carbonate Area: U.S. Geological Survey Water Resources Investigation Report 90-4118, 93 p.
- Mathes, M.V., 2000, Relation of Bacteria in Limestone Aquifers to Septic Systems in Berkeley County, West Virginia: U.S. Geological Survey Water Resources Investigation Report 00-4229, 12 p.
- Shultz, R.A., Hobba, W.A., Jr., and Kozar, M.D., 1995, Geohydrology, Ground-Water Availability, and Ground-Water Quality of Berkeley County, West Virginia, with Emphasis on the Carbonate-Rock Area: U.S. Geological Survey Water Resources Investigation Report 93-4073, 88 p.

National Karst Map Project, an Update

By Jack B. Epstein¹, David J. Weary¹, Randall C. Orndorff¹, Zelda C. Bailey², and Ronal C. Kerbo²

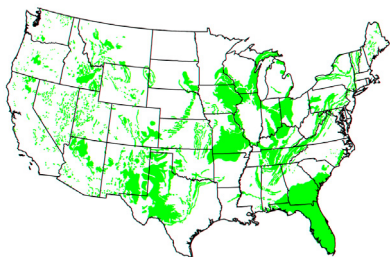
¹US Geological Survey, Reston, VA 20192

² National Park Service, Denver, CO 80225

Abstract

Federal and State agencies, the speleological community, and academia have repeatedly expressed the need for an accurate and detailed national karst map to better understand the distribution of soluble rocks in the United States. Maps at a variety of scales are needed to educate the public and legislators about karst issues, to provide a basis for cave and karst research, and to aid Federal, State, and local land-use managers in managing karst resources.

During the past two years, a diverse group of karst experts discussed a long-term plan for karst mapping on a national scale. The resultant goal is for the US Geological Survey (USGS) to produce a national karst map in digital form, derived primarily from maps prepared by the individual States, and to link that map on a web-based network to State and local scale maps and related data. The newly formed National Cave and Karst Research Institute (Institute; Zelda Chapman Bailey, Interim Director, 303-969-2082; zelda_bailey@nps.gov) will establish a web-based network of karst information that will be used to build the national map.



The National Karst map, which builds upon the "Engineering Aspects of Karst" map by WE Davies and others (1984, scale 1:7,500,000) published in the National Atlas, will be prepared digitally and can be printed at a scale of 1:7,500,000 for educational purposes and 1:2,500,000 for a more detailed view of karst distribution. A digital copy of the map will reside on the Institute web site and be linked to individual states and speleological organizations for state karst maps, detailed information, annotated bibliographies, and outreach products. The USGS will facilitate compilation of the national map by cooperating with State geological surveys to update or produce state karst maps and to establish standards and consistent digital products, and will facilitate the digital compilation and production of the national karst map. Methods of presentation of data in karst maps vary considerably and boundaries of karst between some adjacent states do not match. Some states have a digitized geologic map from which a karst map could be prepared. Outlines of known karst areas, caves and sinkholes, depth of burial of karstic rocks, and areas of "pseudokarst" of several types are among the types of data shown on some maps. The national map will consider the distribution of carbonate and evaporite units, intrastratal karst, karst beneath surficial overburden, and percentage of area covered by karst.

SUPPORT: USGS has initiated programmatic funding for the national karst map, and the ongoing National Cooperative Geologic Mapping Program has long supported mapping in individual states. Some of the geologic mapping provided by State geological surveys in the National Cooperative Geologic Mapping Program has focused on karst. The Institute is providing program coordination, serving the web network, and funding to supplement the USGS mapping program and States that need additional funding to complete mapping or to convert maps to digital form.

The National Map is part of a larger karst project in USGS, under the direction of Randall Orndorff (703-648-4316; rorndorf@usgs.gov). The task leader for the map is Jack Epstein (703-648-6944; jepstein@usgs.gov). Epstein has and will be contacting individual State Surveys as this effort progresses.

STRUCTURE AND GENESIS

Karstification Along an Active Fault Zone in Cyprus

By Richard W. Harrison¹, Wayne L. Newell¹, and Mehmet Necdet²

¹ U.S. Geological Survey, Reston, VA

² Turkish Cypriot Community, Nicosia, Cyprus

Abstract

Karstification is occurring along the trace of an active, left-lateral, strike-slip fault zone at Pergamos, Cyprus due to increased permeability from brecciation, fracturing, and steeply dipping bedding in a carbonate/evaporite sequence. The fault zone consists of a restraining bend segment, which strikes east-west and dips steeply to the south, and two strike-slip segments, both of which strike N30°E and are vertical. Dissolution of subsurface gypsum along all three segments has developed linear trends of sinkholes; no other sinkholes occur in the area. A scarp produced by the fault zone has influenced surface drainage and focused ephemeral stream flow into the sinkholes, further enhancing karstification.

INTRODUCTION

Pergamos is a centuries old, small village in eastern Cyprus (Fig. 1). Present residents report that sinkholes have always existed on the outskirts of the village, and during periods of heavy rain, ephemeral streams will flow into some of the sinkholes, often resulting in additional collapse. Within the past few years, newly formed sinkholes have threatened recent housing developments from the expanding village. Field investigations have determined that the collapses are controlled by a fault system, which cuts through a carbonate/evaporite stratigraphic sequence.

STRATIGRAPHY AND TOPOGRAPHY

Pergamos lies within the circum-Troodos geologic terrane of Cyprus (Fig. 1), comprised of a Cenozoic sedimentary sequence dominated by carbonates (chalks, marls, and calcarenites) and lesser evaporites (Geological Survey Department of Cyprus, 1995). At Pergamos, the near surface stratigraphy (Fig. 2) is flat lying and consists of approximately 4 m of well-indurated calcarenite (Quaternary *Athalassa* Formation), which overlies approximately 30 m of poorly indurated marl (Pliocene *Nicosia* Marl), which overlies more than 60 m of massive gypsum (Messinian *Kalavasos* Formation). Chalks of the Miocene *Pakhna* Formation underlie the *Kalavasos* Formation at an unknown depth.

Calcrete is extensive at the surface throughout the Pergamos area and forms a hard, impermeable, indurated mass of carbonate as much as 1.0 m thick and containing laminae greater than 1 cm thick. This calcrete is interpreted as correlative to the stage V classification of pedogenic calcrete of Machette (1985). Alluvium, up to a few meters thick, occurs in streambeds, which are incised a few meters into a very flat landscape, which is capped by calcrete.

PERGAMOS FAULT SYSTEM

The Pergamos fault system is a left-lateral, strike-slip system, which consists of two, near vertical, right-stepping segments that strike N30°E and are connected by an east-west-striking restraining bend (Fig. 3). A south-dipping thrust fault and related fault-propagation fold characterize the restraining bend (Fig. 4). Brecciation and fracturing are intense along the fault system. Bedding in the restraining bend has been rotated to near vertical from the folding and thrusting (Fig. 4). A topographic scarp, from 1-4 m high and down to the north and northwest, occurs along the fault trace.

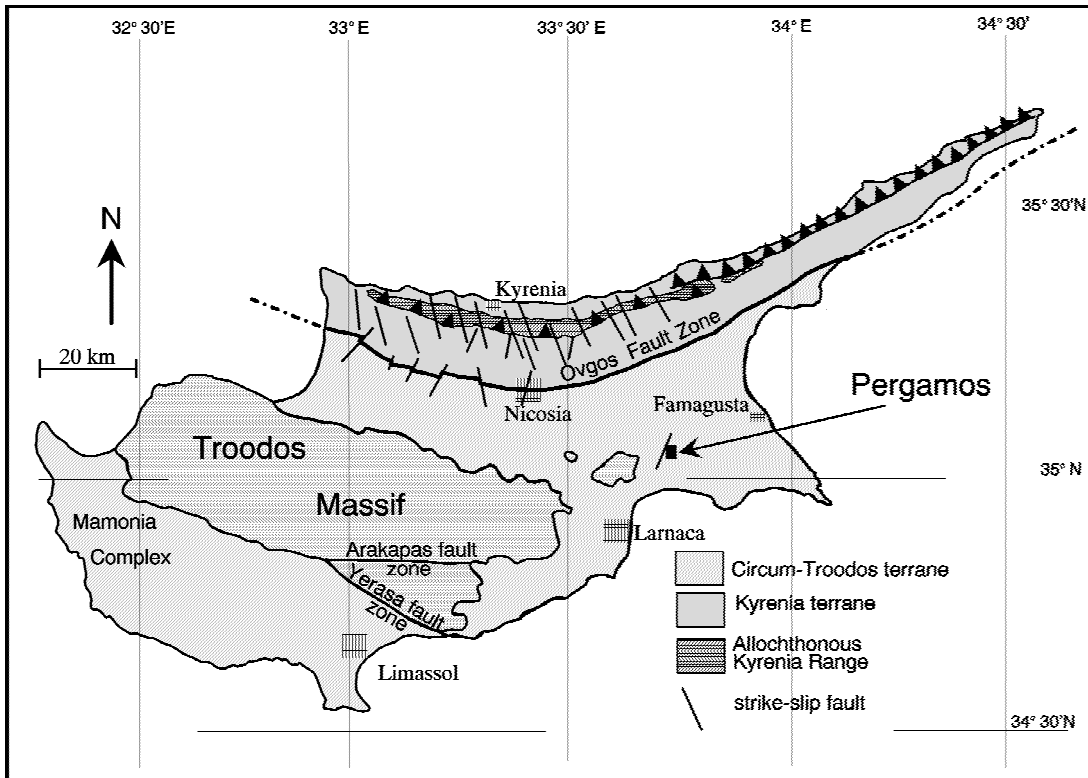


Figure 1. Map showing location of Pergamos, Cyprus.

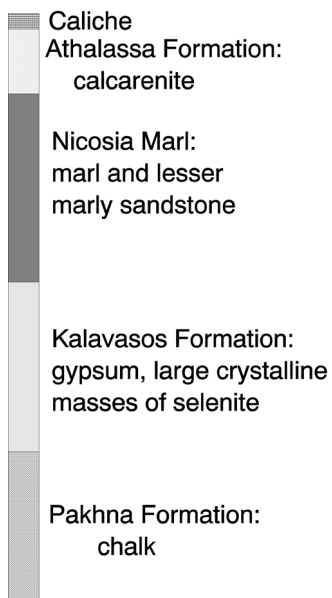


Figure 2. Generalized stratigraphic column for the Pergamos, Cyprus area, based on logs of drilled wells and a hand dug well that penetrated gypsum. Not to scale; see text for approximate thicknesses.

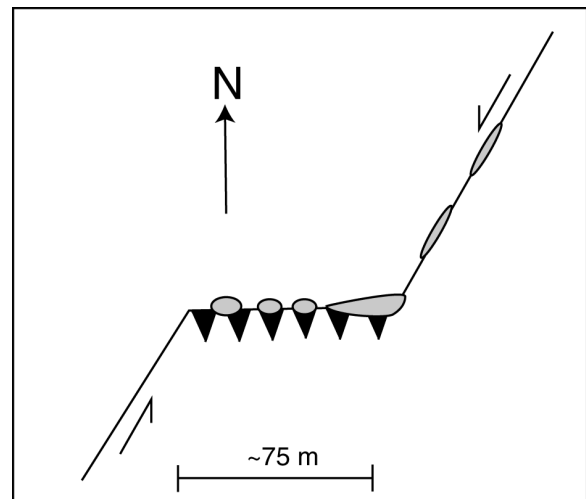


Figure 3. Schematic map of Pergamos fault system. Half arrows indicate relative strike-slip motion; teeth are on hanging wall of east-west-striking thrust fault and related fault propagation fold in restraining bend of fault system. Gray areas are approximate locations and configurations of sinkholes. Photograph in Figure 4 is of the sinkhole furthest to the west.

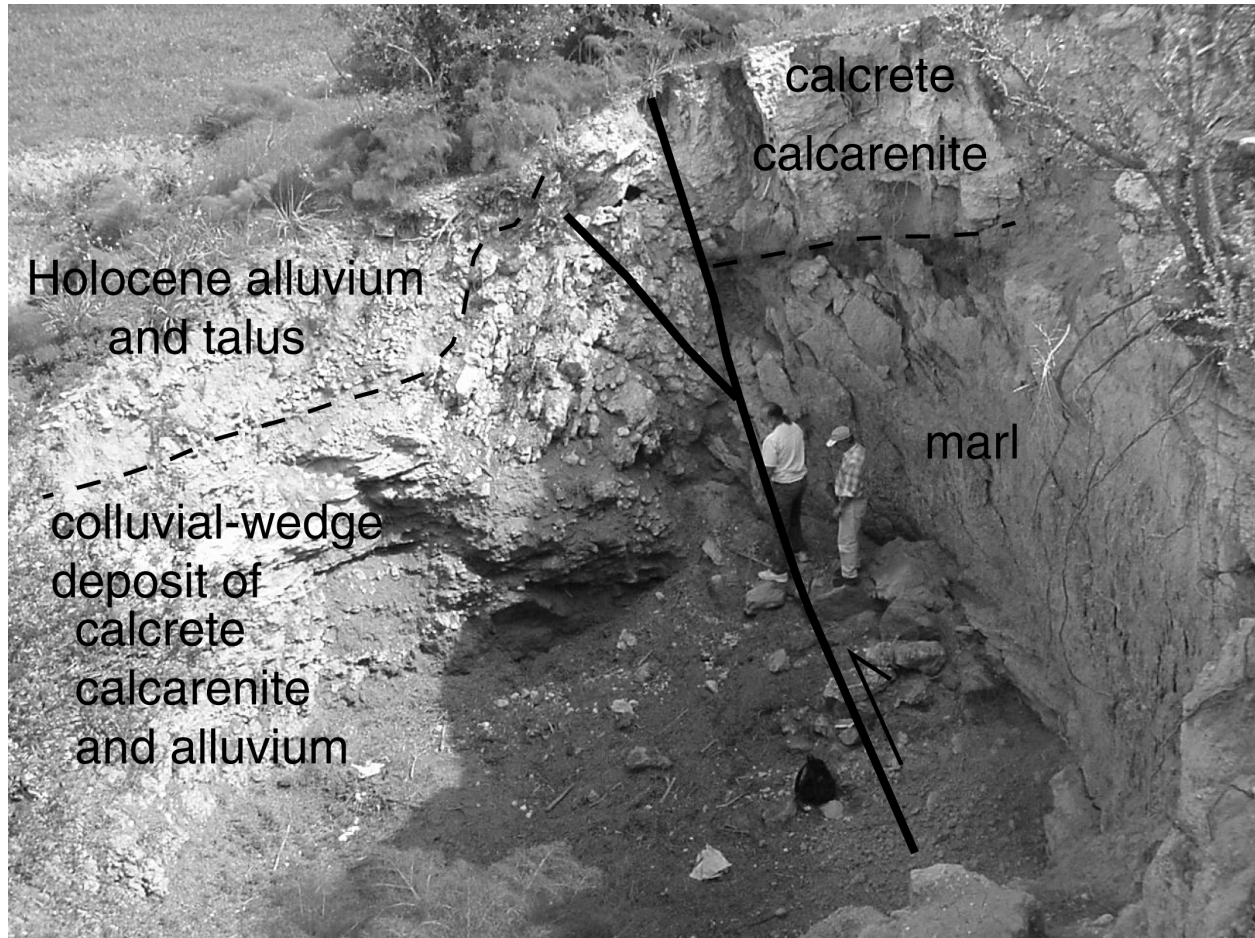


Figure 4. View looking east at sinkhole that developed along the thrust and fault-propagation fold in the restraining bend of the Pergamos fault system. The solid black line marks the approximate location of the thrust; half arrow indicates relative motion.

Deposits in the footwall of the restraining bend consist of deformed bedrock, a Holocene colluvial-wedge derived from the calcrete cap, and Holocene alluvium. Involvement of Holocene alluvium and colluvium in the deformation indicates the active nature of the structure. Also, there is present-day microseismicity along a north-northeast trend in the vicinity of the Pergamos fault system (Makris and others, 2000).

KARST

Sinkholes have developed along the surface trace of the Pergamos fault system (Figs. 3 and 4). These funnel-shaped collapse structures are elliptical in plan view and 10-30 m in elongated dimension. Along the restraining bend they are

typically 5-10 m in short dimension; observable depths are as much as 10 m. The southern strike-slip segment is currently inaccessible, however, along the northern strike-slip segment of the fault system, sinkholes occur as very elongated fissures, which are commonly en echelon, and are open to an unknown depth. Between the open fissures, much of the ground has a hollow sound when traversed and feels spongy. Aside from the sinkholes along the fault zone, there are no other known occurrences in the Pergamos area.

Because of the extensive calcrete encrustation, much of the surface water runoff during rainstorms flows into the sinkholes. In addition, ephemeral streams in the area tend to flow into the sinkholes, prompting the

construction of protective berms to keep water out of the sinkholes.

CONCLUSIONS

From our field investigations, it is concluded that brecciation, fracturing, and steeply dipping bedding produced by recent movement on the Pergamos fault system has lead to a localized increased bedrock permeability in a hydrogeologic setting where much of the surface is relatively impermeable because of calcrete encrustation. Surface waters have thus been focused into subterranean flow along the fault system, resulting in dissolution of gypsum and carbonate at depth, and subsequent surface collapse. Outside of the area of increased

permeability, there appears to be little or no evidence of karstification.

REFERENCES

- Geological Survey Department of Cyprus, 1995, Geological map of Cyprus: 1:250,000 scale, 1 sheet.
- Machette, M.N., 1985, Calcic soils of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.
- Makris, J. Stacker, J., and Kramvis, S., 2000, Microseismic studies and tectonic implications of Cyprus; *in* Panayides, I., Xenophontos, C., and Malpas, J., eds., *Proceeding of the Third International Conference on the Geology of the Eastern Mediterranean*, p. 137-145.

Structural and lithologic control of karst features in northwestern New Jersey

By Donald H. Monteverde and Richard F. Dalton
New Jersey Geological Survey, PO Box 427, Trenton, NJ 08625

Abstract

Development is rapidly replacing farmland in western New Jersey with new housing tracts. Much of this new suburbia is underlain by carbonate bedrock so the understanding of karst formation and control is important in pre-development planning. We have initiated an ongoing study of karst, including sinkholes, caves and springs in an attempt to characterize the karst potential for these carbonate rocks.

Carbonate rocks crop out in the northwestern part of New Jersey along the regional, northeast-southwest Appalachian structural trend. The Wisconsin Terminal Moraine bisects the outcrop belt into a northern glaciated sector and a southern unglaciated sector. The rocks range in age from Middle Proterozoic to middle Paleozoic. The varied structural and metamorphic histories influence their nature of karstification. The Franklin Marble and Wildcat Marble, here combined as Franklin Marble, are of Middle Proterozoic age (Drake and others, 1991) and are at least 350 m thick locally (Drake and Volkert, 1993). They underwent amphibolite-grade metamorphism during the Grenville Orogeny that erased most evidence of original sedimentary features. Calcitic marble dominates the white, very coarse to coarse to locally fine grained Franklin; though dolomitic bands or zones have been identified (Haque and others, 1956). Foliation measurements parallel the transposed dolomitic bands (R Volkert, personal communication 2002). The Taconic and Alleghanian Orogenies also impacted the Franklin. Lower Paleozoic carbonate rocks include the Cambrian and lower Ordovician Kittatinny Supergroup and the unconformably overlying middle Ordovician Jacksonburg Limestone. The Kittatinny is as much as 1312 m thick while the Jacksonburg ranges between 41 and 244 m thick (Drake and others, 1996). The Kittatinny is fine- to medium-grained, thin- to medium-bedded dolomite. Limestone that escaped extensive dolomitization only occurs as isolated lenses. The Jacksonburg contains a lower crystalline limestone that grades upwards into an argillaceous limestone. These rocks experienced two strong deformation events in the Taconic and Alleghanian Orogenies and form a classic fold and thrust belt. Middle Paleozoic carbonates lie along the northwest boundary of New Jersey within parts of the Delaware River National Recreation Area. The carbonates are upper Silurian through lower Devonian in age and record several transgressive-regressive cycles. Limestone is the dominant lithology and the combined carbonate thickness is approximately 290 m (Epstein, 2001). A gentle northwest dipping monocline marks the main outcrop belt but dips steepen and overturn towards both the Pennsylvania and New York borders.

Our work compares cave densities and passage trends, measured from underground surveys (Dalton, 1976) with recorded structural information from recent 1:24,000 scale mapping. New Jersey caves are overall much smaller than Midwestern caves with shorter and narrower passageways. The Franklin Marble contains 22 caves, totaling 775 m of passage length (Dalton and Markewicz, 1972). It shows a strong agreement between foliation strike and passage direction suggesting lithology controls passage development in this unit. Some passageways follow contacts with small interior gneissic layers and further substantiate this trend. None of the known Franklin Marble caves occur at contacts with other Middle Proterozoic units, but form in more interior regions of this thick carbonate unit. Measured outcrop data on joints and fractures indicates that they appear to have little or no control on cavern development. Lower Paleozoic carbonates contain 83 caves with 2252 m of total passageways. The data on these caves show bedding, joints and fractures control. Surface water derived from non-carbonate watershed regions enhances carbonate solution features upon crossing into carbonate bedrock regions. Here, bedding

appears to play a more dominant role in cavern development. Cave passageways locally follow regional fracture trends within select lithologic horizons. Work has not yet reached middle Paleozoic units, which contain 6 caves encompassing 251 m of passageway (Dalton and Markewicz, 1972).

Only 11 of 142 known New Jersey caves are south of the glacial terminal moraine yet Dalton (1996) suggests increased sinkhole development in the south possibly due to a more mature weathering profile. Glacial deposits south of the Wisconsin moraine has been correlated by Stanford and others (2001) to be Late Pliocene age which would yield over 2 Ma of weathering for these carbonates. Work continues to better characterize the karst formation in New Jersey.

REFERENCES

- Dalton, R.F., 1976, Caves of New Jersey, New Jersey Geological Survey, Bulletin 70, 51p.
- _____, 1996, Karst geology of New Jersey and vicinity, in Dalton, R.F., and Brown, J.O., eds., Karst geology of New Jersey and vicinity, Thirteenth annual meeting of the Geological Association of New Jersey, Whippany, NJ, p.21-38.
- Dalton, R.F., and Markewicz, F.J., 1972, Stratigraphy of and characteristics of cavern development in the carbonate rocks of New Jersey, National Speleological Society, Bulletin 34, p. 115-128.
- Drake, A.A., Jr., and Volkert, R.A., 1993, Bedrock geologic map of the Newton East quadrangle, Sussex County, New Jersey, US Geological Survey, Geologic Quadrangle Map GQ-1707, 1:24,000.
- Drake, A.A., Jr., Aleinikoff, J.N., and Volkert, R.A., 1991, The Mount Eve Granite (Middle Proterozoic) of northern New Jersey and southeastern New York, in, Drake, A.A., Jr., ed., Contributions to New Jersey Geology, US Geological Survey Bulletin 1952, p. C1-C10.
- Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1996, Bedrock geologic map of northern New Jersey, US Geological Survey, Miscellaneous Investigations Series, I-2540-A, 1:100,000.
- Epstein, J.B., 2001, Stratigraphy in the region of Delaware Water Gap National Recreation Area, in, Inners, J.D., and Fleeger, G.M., eds., 2001- a Delaware River odyssey, Guidebook, 66th Annual Field Conference of Pennsylvania Geologists, Shawnee-on-Delaware, PA, p. 1-13.
- Haque, J.M., Baum, J.L., Hermann, L.A. and Pickering, R.J., 1956, Geology and structure of the Franklin-Sterling area, New Jersey, Geological Society of America, Bulletin, v. 67, p. 435-474.
- Stanford, S.D., Ashley, G.M., and Brenner, G.J., 2001, Late Cenozoic fluvial stratigraphy of the New Jersey Piedmont: a record of glacioeustasy, planation, and incision on a low-relief passive margin, Journal of Geology, v. 109, p. 265-276.

Three-Dimensional Geologic Framework Modeling for a Karst Region in the Buffalo National River, Arkansas

By Kyle E. Murray, and Mark R. Hudson

U.S. Geological Survey, Box 25046, Mail Stop 980, Denver, CO 80225

Abstract

A detailed geologic framework of surficial and subsurface geology is necessary to understand the ground water hydrologic system in karst regions. In this study, the geologic framework of a karst region adjacent to and within the Buffalo National River, Arkansas was characterized in three-dimensions. Digital geologic map data, structure contours, watershed boundaries, surface water drainage features, and digital elevation models were combined using a Geographic Information System and three-dimensional geologic modeling software to form a volumetric, three-dimensional geologic model. The resulting three-dimensional geologic model contains fourteen lithostratigraphic units, thirty-two faults, and several folds. Comparisons of the computed model to geologic cross-sections indicates that this methodology produced a model that supports the conceptual model of the subsurface. This geologic framework model is useful for visualizing geologic structures, and is an important step for understanding ground water flow, and evaluating potential contaminant transport pathways through the karst system.

INTRODUCTION

Ground water flow rates and subsurface contaminant transport rates are difficult to model and quantify in karst systems due to complex dissolution features and preferential flow. Characterization of these complex geologic features is important for understanding ground water transport processes, but generalization of geologic features are usually necessary for ground water modeling. The basic geologic features, including stratigraphic relationships (i.e. sequence, thickness, and continuity), bedding attitudes, and structural features (i.e. faulting and folding), must be spatially characterized before defining the distribution of more complex features controlling preferential flow. We use the term geologic framework modeling to refer to modeling of these basic geologic features in three-dimensions.

This paper presents the results of geologic framework modeling of a karst system in northern Arkansas, and the methodology used to integrate various types of two-dimensional geospatial data. The model area consists of six 7.5-minute quadrangles in parts of Newton, Boone, and Carroll Counties in northern Arkansas. The model area contains a large portion of the western Buffalo River watershed

(fig. 1), and the Buffalo River is the dominant drainage feature here. The Buffalo River is one of the nation's few remaining undammed

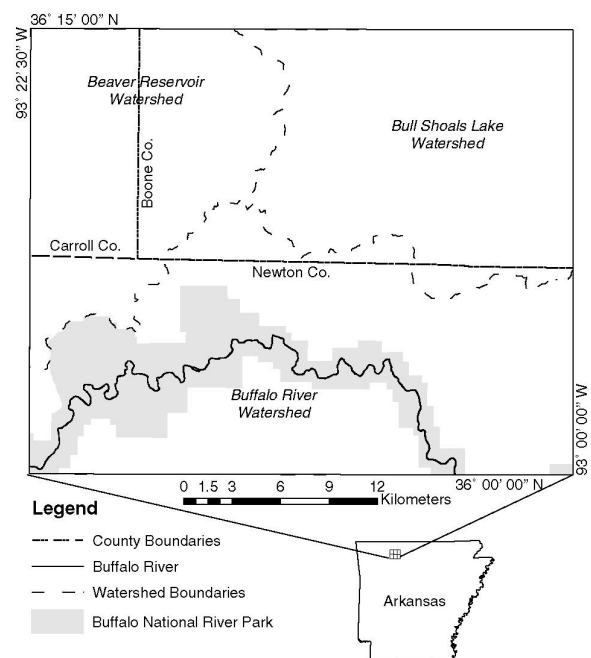


Figure 1: Location and map of the model area; showing county boundaries, the Buffalo River, watershed boundaries, and a portion of the Buffalo National River park.

ivers, and attracts over one million visitors each year for recreational activities (Mott and others, 1999).

The area surrounding the Buffalo River became a protected resource, the Buffalo National River (fig. 1), in 1972 and is managed by the National Park Service. Because baseflow and recharge water from springs constitute a large portion of the flow in the Buffalo River, characterization of ground water flow is essential for protecting the water quality in the Buffalo River hydrologic system.

DESCRIPTION OF THE MODEL AREA

The model area is located in the northeastern part of the Boston Mountains and the southern part of the Springfield Plateau in the Ozark Mountains, northern Arkansas. The model area consists of the Osage NE, Gaither, Harrison, Ponca, Jasper, and Hasty quadrangles (fig. 2) and encompasses approximately 939 square kilometers. Ground surface elevations range from 209 to 740 meters above sea level. The greatest relief is along the Buffalo River in the southern half of the model area, where the river valley is as deep as 415 meters. The climate is humid subtropical, with an average of approximately 108 centimeters of precipitation per year.

Bedrock Geology

Bedrock units largely consist of subhorizontal sequences of alternating carbonates, sandstones, and shales. Five Quaternary alluvial or colluvial units and ten geologic formations of Pennsylvanian, Mississippian, or Ordovician age are exposed at the surface and were mapped by Hudson (1998), Hudson and others (2001b), and Hudson and Murray (2002). These geologic formations were divided by Hudson and Murray (2002) into seventeen geologic map units.

Limestone and dolomite are components of six of the ten mapped geologic formations. The Mississippian Boone Formation, 104 to 129 meters thick (Hudson and others, 2001b), is exposed over 46 percent of the mapped model

area and is the major host of karst features. The chert content of the Boone Formation in the model area is variable but is commonly less than 50 percent, in contrast to higher values typical elsewhere in northern Arkansas. The lower chert content may account for the continuity of karst features throughout the formation in this area.

Structurally, the model area lies in the southern flank of the Ozark Dome. The rock units are mostly gently dipping (<5 degrees) but are broken by a series of faults and monoclinical folds that formed during late Paleozoic time (Hudson, 2000a). Maximum vertical offset across individual faults, indicated by geologic mapping, ranges from 30 to 120 meters. Monoclinical folds that formed over buried faults typically have vertical relief of 20 to 40 meters and contain strata that dip 10 degrees to 25 degrees (Hudson and others, 2001a).

Surface Water Hydrology

Approximately 427 square kilometers or 46 percent of the model area are within the Buffalo River watershed. The Buffalo River originates high in the Boston Mountains, and flows into the model area near the southwestern corner, and flows eastward across the model area (fig.1). Approximately 278 square kilometers or 30 percent of the model area are part of the Bull Shoals Lake watershed. Approximately 230 square kilometers or 25 percent of the model area are part of the Beaver Reservoir watershed. These watersheds are sub basins of the Upper White River that flows to the southeast as a tributary of the Mississippi River.

Karst Features and Ground Water Hydrology

In many geologic settings the area of recharge for a ground water system is contained within the topographic divides that form the watershed boundaries. However, in karst systems ground water flow in the subsurface often crosses the surface watershed boundaries. Knowledge about this component of interbasin flow is important for understanding the interactions of the ground water and surface water hydrologic system, and for evaluating

potential contaminant transport pathways through the karst system.

The stratigraphic distribution of karst in the model area can be inferred from an inventory of caves located within the boundaries of western Buffalo National River, although this inventory may exclude caves in upper formations that lie within the watershed but outside the park corridor. Of 96 inventoried caves, 78 percent are within limestone of the Boone Formation, 17 percent are in limestone or dolomite intervals within the Everton Formation, and the remaining are in limestone of the lower part of the Bloyd Formation (Hudson and others, 2001a). Caves within the Boone Formation are distributed throughout its thickness, but entrances are slightly more common within 12 m of the upper or lower contact. The upper Boone contact is overlain by the 2- to 12-m-thick Batesville Sandstone that is commonly slumped into solution cavities within Boone limestone. The basal Boone limestone unconformably overlies sandstone of the Everton Formation, and the contact is marked by the greatest number of springs within the western Buffalo River watershed. This relation illustrates that the Boone Formation is the main karst aquifer for the region and that the Everton Formation behaves as a confining unit.

Dye-tracer studies documented that some large springs gather recharge from far beyond the surface watershed boundaries (Mott and others, 1999). Erosion of the Buffalo River valley left most karst aquifers perched above the current river level and, consequently, their local base-level elevations are controlled by relief across structures. Down-dropped blocks of Boone Formation host both the largest springs and the most extensive cave systems known within the model area.

Field observations and dye-tracer studies by Mott and others (1999) indicated that water discharged from some springs in the Buffalo River watershed originated in the Bull Shoals Lake watershed. Mott and others (1999) used these data to compute ground water velocities exceeding 640 meters per day. Because much of the Bull Shoals Lake watershed in the model

area is covered by agricultural land, consisting mostly of livestock operations, it is possible that nutrient contaminants from these agricultural activities will reach the Buffalo River by interbasin transfer of water.

DATA COMPILATION

During geologic mapping, locations and elevations of geologic features were recorded using a topographic base map, Global Positioning System (GPS), and altimeter. Geologic features drawn in the field, GPS data points, and aerial photograph information were compiled to form the geologic maps by Hudson (1998), Hudson and others (2001b), and Hudson and Murray (2002). These geologic map data were digitized and attributed in a Geographic Information System (GIS) database. Additional unpublished geologic map data by Hudson (2000b), Lucas (1971), and McMoran (1968) were digitized in GIS and used to supplement more complete geologic map data. A comprehensive GIS database of these geologic map data, extent shown in fig. 2, was developed by the authors for use in geologic framework modeling.

Geologic map units, and major surface water bodies were represented as polygon features. Lithologic contacts, faults, folds, structure contours for the base of the Boone Formation, and minor surface water drainage features were represented as line features. Bedding attitudes and other geologic structure information were represented as point features. Digital elevation model (DEM) data, 10-meter spatial resolution from the U.S. Geological Survey, were used to recreate surface topographic relief and define the watershed boundaries within the model area. Supplemental GIS data (i.e. county boundaries, minor surface water drainage features, and land-use information), used as reference information, were obtained from various on-line data repositories.

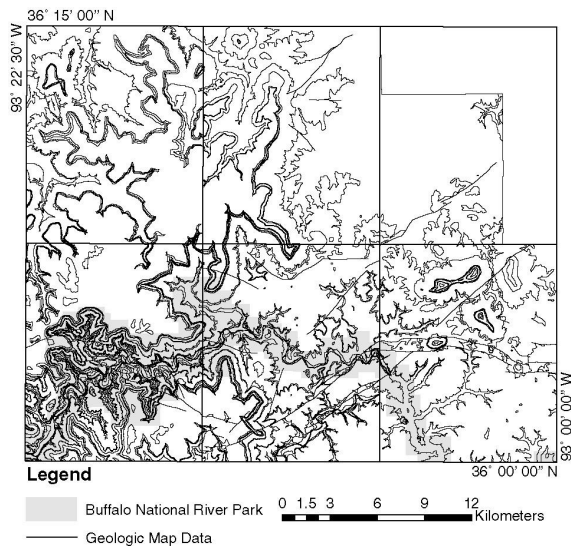


Figure 2: Map showing the extent of published and unpublished geologic map data and quadrangle boundaries.

GEOLOGIC MODELING PROCEDURE

The three-dimensional modeling software requires input of longitude (x), latitude (y), and elevation (z) coordinates of data points on geologic surfaces (lithostratigraphic contacts, faults). These data were obtained during geologic mapping, but took three forms of different quality. The highest quality data were field sites on contacts or faults that were located during mapping via one or a combination of a GPS receiver, altimeter, or distinctive topographic location. These field sites formed the basis from which other data forms were constructed. Secondary data sources were the traces of geologic planes over surface topography. During construction of the geologic maps, these map traces were anchored to the field sites but were often interpolated between sites on the basis of distinctive topographic features (e.g., ledges) that provided further qualitative control on the spatial variation of the planes. Finally, for the Boone Formation, structure contours were interpreted from the control sites on its upper and lower contacts, the formation thickness, measured attitudes of beds and faults and lacking other constraints, geologic interpretations of the structural configuration of the area.

Pre-Processing of Geologic Model Input Data

Geologic map data were digitized and attributed in GIS format for ninety-three percent of the model area (fig. 2). These data were most easily transferred from the GIS database to the geologic modeling software in American Standard Code for Information Interchange (ASCII) format. Points of contact between lithostratigraphic units were exported from the GIS with x and y coordinates. Separate ASCII files were maintained for the top of each lithostratigraphic unit. The z coordinates of these points of contact were calculated from the 10-meter spatial resolution DEM and added to the ASCII files.

Supplementary lithostratigraphic points of contact were derived from structure contours of the elevation of the base of the Boone Formation. Lithostratigraphic points of contact were exported from the GIS with x, y, and z coordinates. These data points were used in addition to the geologic map data to define the top of the Everton Formation in the geologic framework model.

Major mapped faults were also included in the geologic framework model. The surface traces of the major mapped faults were exported as a series of points from the GIS with x and y coordinates. Separate ASCII files were maintained for each major fault. The elevations of these points were calculated from intersections with the 10-meter spatial resolution DEM and added to the ASCII files. The average dip direction (in azimuthal units) and inclination of the faults were added to the respective ASCII fault files. From these data, additional points were calculated in three-dimensional space to represent the shape of the fault surface.

Geologic Units and Structures

Surface topography, fourteen lithostratigraphic units, and thirty-two faults were modeled in three dimensions. The surface topography was modeled as an unconformity at the top of the stratigraphic sequence using DEM data as a continuous surface. The tops of the

following lithostratigraphic units, listed in increasing geologic age, were modeled: Atoka Formation, Upper Bloyd Formation, Lower Bloyd Formation, Prairie Grove Member of the Hale Formation, Cane Hill Member of the Hale Formation, Pitkin Limestone, Wedington Sandstone Member of the Fayetteville Shale, main body of the Fayetteville Shale, Batesville Sandstone, main body of the Boone Formation, St. Joe Limestone Member of the Boone Formation, Everton Formation, Powell Dolomite, and the Cotter Formation.

The relative amount of data used as input for these formations is summarized in Table 1 by showing the length of the upper contact mapped in the model area. The lengths of the mapped contacts for the Boone and Everton Formations were greatest in the model area, thus these geologic formations were well controlled in the geologic framework model. The upper contacts (surfaces) of the lithostratigraphic units were computed by interpolating between data points along the geologic map contacts and extrapolating to the model boundaries using the two-dimensional minimum-tension gridding algorithm (Dynamic Graphics Incorporated, 1998). The thicknesses of these lithostratigraphic units were then calculated as the differences between adjacent surfaces.

Lithostratigraphic units with fewer input data (Atoka, Powell, and Cotter) were modeled using data points that represented the top of the lithostratigraphic units, and by maintaining thicknesses relative to reference lithostratigraphic units (units with higher relative amounts of input data). The Atoka Formation referenced the Upper Bloyd Formation, the Powell Dolomite referenced the Everton Formation, and the Cotter Formation referenced the Everton Formation. Quaternary units and the Ordovician Fernvale Limestone were not modeled because of their thinness and lack of spatial continuity.

Thirty-two major faults were incorporated into the geologic framework model. The fault inclinations ranged from forty degrees to eighty-five degrees from horizontal with an average

Table 1: Summary of modeled lithostratigraphic units

Mapped Unit Name	Length of Mapped Upper Contact (meters)
Atoka	150m-constant thickness
Upper Bloyd	39,985
Lower Bloyd	283,799
Prairie Grove	255,975
Cane Hill	158,955
Pitkin	59,520
Wedington	40,053
Fayetteville	59,555
Batesville	291,551
Boone	453,939
St. Joe	315,198
Everton	382,109
Powell	10,720
Cotter	1,204

fault inclination of seventy-four degrees. Twenty-seven of the thirty-two faults were inclined at angles greater than or equal to seventy degrees.

EVALUATION OF GEOLOGIC FRAMEWORK MODEL RESULTS

The quality of the geologic framework model may be evaluated by comparing cross-sectional views generated from the model to cross-sections published with the geologic mapping. Cross-sectional views through the Jasper quadrangle (Hudson and others, 2001b) were used for these comparisons. The cross-section A-A' (Hudson and others, 2001b) is shown as Figure 3a; and the corresponding cross-sectional view computed from the geologic framework model is shown as Figure 3b. The cross-section B-B' (Hudson and others, 2001b) is shown as Figure 4a; and the corresponding cross-sectional view computed from the geologic framework model is shown as Figure 4b.

The geologic framework model includes two formations that were not recognized during geologic mapping in the Jasper quadrangle. These formations, the Atoka Formation (youngest Pennsylvanian unit) and the Cotter Formation (oldest Ordovician unit), were identified during mapping of the Ponca

Figure 3a: Cross Section A-A' from Hudson and others (2001b).

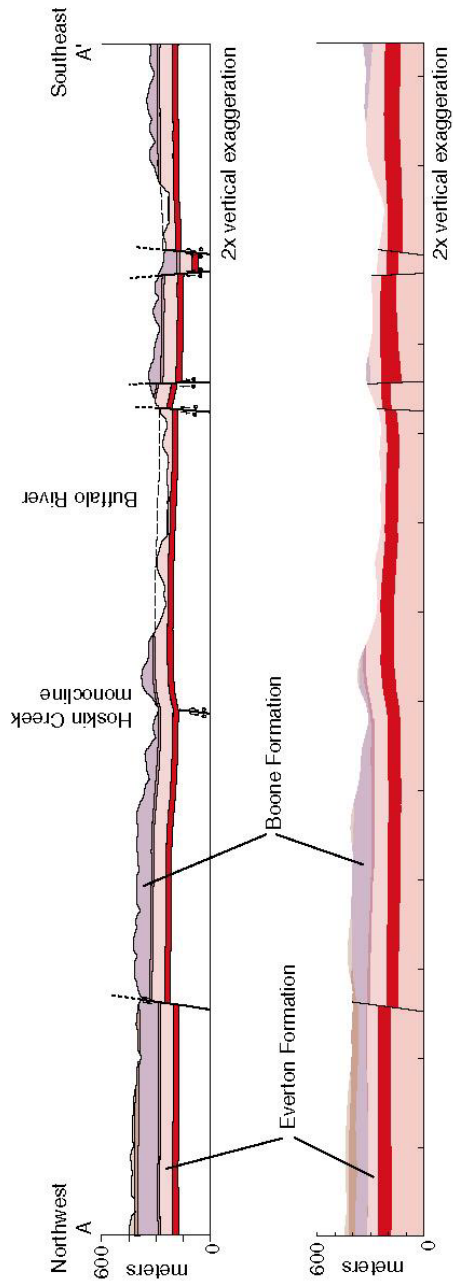


Figure 3b: Cross Section A-A' computed from the Geologic Framework Model.

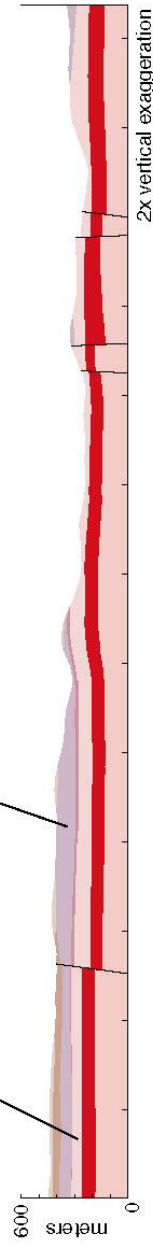


Figure 4a: Cross Section B-B' from Hudson and others (2001b).

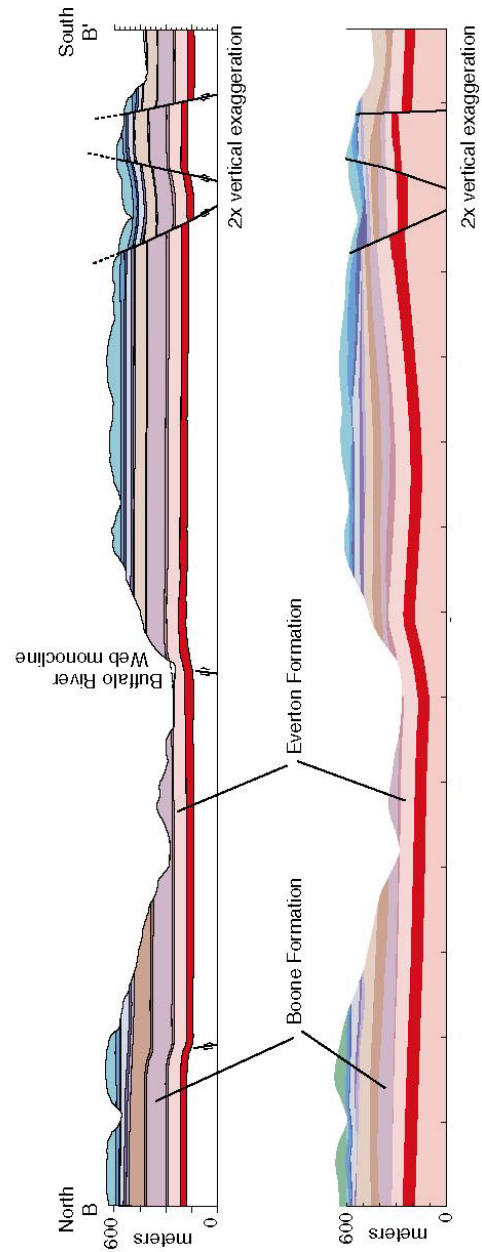
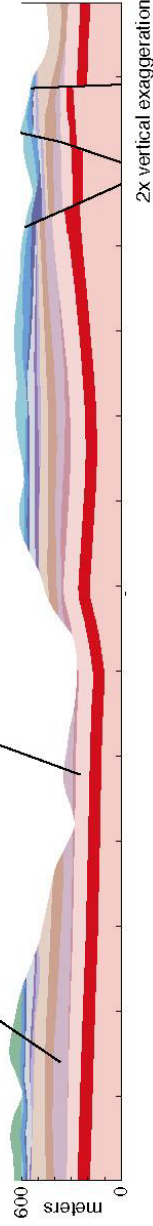


Figure 4b: Cross Section B-B' computed from the Geologic Framework Model.



quadrangle by Hudson and Murray (2002), and added to the geologic framework model.

Visual inspection of these cross-sections indicates that the thicknesses of the Boone Formation, and the Everton Formation are similar between the published cross-sections and the geologic framework model. Slight variations in lithostratigraphic unit thicknesses occur near A', the southeastern portion of the Jasper quadrangle, and are probably due to a sparse distribution of points of lithostratigraphic contact in this area. Thicknesses of the thinner lithostratigraphic units are not as well maintained in the geologic framework model, but may be less important for understanding this karst system. Structural features and offset of lithostratigraphic units along the fault surfaces are captured very well by the geologic framework model. Offset direction along 4 out of 5 faults in A-A', and 2 out of 3 faults in B-B' are correctly built by the geologic framework model. The Hoskin Creek monocline, in A-A', and the Web monocline, in B-B' are correctly captured by the geologic framework model.

In the model area, the Boone Formation is the most significant karst aquifer unit. Accurately modeling the distribution of this geologic unit is an important step for understanding ground water flow in the model area. The distribution of the Boone Formation (main body and St. Joe Limestone Member), computed in geologic framework modeling, is shown as Figure 5. The resulting geologic framework model indicates that the Boone Formation is continuous throughout most of the model area, with the exception of the Buffalo River valley where the main body of the Boone was eroded away.

CONCLUSIONS

The methodology described in this paper was effective for constructing a three-dimensional digital geologic framework model in northern Arkansas. These procedures may be useful in other areas where there are substantial topographic relief, surface exposures of several relatively flat-lying lithostratigraphic units, and normal or strike-slip faults. Successful

development of the geologic framework model in this study relied on high quality geologic map data. Fault dip directions and fault inclinations were required to accurately capture structural geologic features. Use of this procedure required careful digitization and attribution of geologic map data in a GIS format.

The geologic framework model indicates that extensive surface exposures of the Boone Formation are located in the northeastern part of the model area where agriculture is the dominant land-use. The model also indicates that the channel of the Buffalo River is below the main body of the Boone Formation along its entire length, therefore springs from the base of the Boone could directly recharge the Buffalo River. The areas where the Boone is exposed should be the focus of studies to characterize the distribution of dissolution features, and dye-tracer studies to define pathways of travel between dissolution features and springs recharging the Buffalo River.

Additional lithologic data or property data (e.g. distribution of permeability) acquired during the installation of ground water wells would be valuable additions to this model. Borehole geophysical logs or surface geophysics could also contribute control points for lithostratigraphic contacts in the subsurface. These data would be useful for refining the modeling methodology and adding control points to computations in the subsurface.

REFERENCES

- Dynamic Graphics Incorporated, 1998, EarthVision User's Guide 5.1, Alameda, California.
- Hudson, M.R., 1998, Geologic map of parts of the Jasper, Hasty, Ponca, Gaither, and Harrison quadrangles in and adjacent to Buffalo National River, northwestern Arkansas: U.S. Geological Survey Open-File Report 98-116, 1:24,000 scale.
- Hudson, M.R., 2000a, Coordinated strike-slip and normal faulting in the southern Ozark dome of northern Arkansas: Deformation in a late Paleozoic foreland: *Geology*, v. 28, p. 511-514.

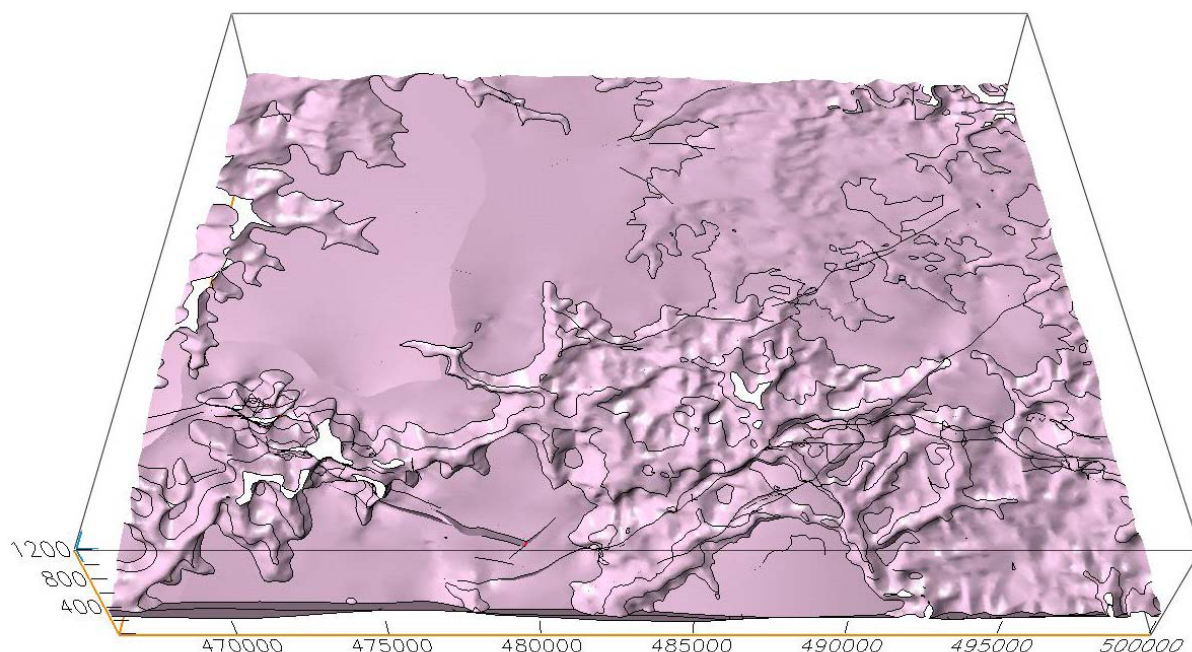


Figure 5: Distribution of the main body and St. Joe Limestone member of the Boone Formation computed by Three-Dimensional Geologic Modeling.

- Hudson, M.R., 2000b, Geologic map of the Hasty quadrangle, Boone and Newton Counties, Arkansas: Unpublished geologic map data, 1:24,000 scale.
- Hudson, M.R., Mott, D.N. and Bitting, C.J., 2001a, Geologic framework of karst features in western Buffalo National River, northern Arkansas, in Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011, p. 16-17.
- Hudson, M.R., Murray, K.E., and Pezzutti, D., 2001b, Geologic map of the Jasper quadrangle, Boone and Newton Counties, Arkansas: U.S. Geological Survey Miscellaneous Field Studies 2356, 1:24,000 scale.
- Hudson, M.R., and Murray, K.E., 2002-in review, Geologic map of the Ponca quadrangle, Newton, Boone, and Carroll Counties, Arkansas: U.S. Geological Survey Miscellaneous Field Studies, 1:24,000 scale.
- Lucas, P.E., 1971, Geology of the Osage NE quadrangle, Arkansas, Unpublished Masters thesis, University of Arkansas, Fayetteville, Arkansas, 78 pp.
- McMoran, W.D., 1968, Geology of the Gaither quadrangle, Boone County, Arkansas, Unpublished Masters thesis, University of Arkansas, Fayetteville, Arkansas, 86 pp.
- Mott, D.N., Hudson, M.R., and Aley, T., 1999, Nutrient loads traced to interbasin groundwater transport at Buffalo National River, Arkansas, in Harmon, D., ed., Proceedings of the 10th Conference on Research and Resource Management in Parks and Public Lands, George Wright Society, Hancock, Michigan, p. 114-121.

Stratigraphy-Karst Relationships in the Frederick Valley of Maryland

By David K. Brezinski and James P. Reger

Maryland Geological Survey, 2300 St. Paul Street, Baltimore, Maryland 21218-5210

Abstract

Karst features are present in strata of Triassic, Ordovician, and Cambrian age in the Frederick Valley of Maryland. While the Triassic Leesburg Member of the Bull Run Formation and Rocky Spring Station Member of the Cambrian Frederick Formation have large numbers of surface depressions developed within their outcrop belts, it is the Lime Kiln Member of the Frederick Formation and the overlying Ordovician Grove Formation that present the greatest danger for active sinkhole development. Springs are most likely to develop in the Adamstown Member of the Frederick Formation. The relative susceptibility of the different units of the Frederick Valley appears to be related to the relative purity of the individual units. Those units with abundant clay and silt are less likely to have active sinkhole develop than those units with greater carbonate purity.

INTRODUCTION

The Frederick Valley of Maryland's western Piedmont represents the state's second largest karst terrane. Although the largest is located in eastern Washington County and is known as the Hagerstown Valley or Great Valley, the Frederick Valley has had more incidences of catastrophic collapse and active subsidence than its larger neighbor. The Frederick Valley is a lowland region that stretches from the Potomac River northward to Woodsboro in northern Frederick County, an area of approximately 400 km². The Maryland Geological Survey, in conjunction with the Maryland State Highway Administration, has been conducting detailed geologic mapping along with karst feature identification. This report is the preliminary results of that study which is currently in progress.

REGIONAL SETTING

The Frederick Valley is a broad synclinorium that is overturned along its eastern flank. It lies near the western edge of the Piedmont Physiographic Province of Maryland. The western Piedmont encompasses a number of geologic subdivisions including the Frederick Valley, the Triassic Basins, and the western edge of the metamorphosed phyllites and schists that characterize the Piedmont proper. The Frederick Valley is composed of Cambrian and Ordovician

limestones that, beyond their intense folding, exhibit very little metamorphism. The eastern boundary of the Frederick Valley is commonly placed at the contact between the limestones of the Frederick Valley and sandstones and siltstones of the subjacent Araby Formation.

The Frederick Valley is bounded on the south by the Potomac River and is overlapped to the west and north by Triassic rocks. In Maryland, parts of two separate Triassic basins are present. From the Potomac River north to U.S. Route 40, Triassic rocks were deposited in the Culpeper Basin. From just north of the northern terminus of the Culpeper Basin at U.S. 40 northward to the Pennsylvania State Line and beyond, the Triassic sediments were deposited in the Gettysburg Basin. Because there is very little topographic relief between the Frederick Valley proper and the Triassic sediments, discerning between the two separate subdivisions of the western Piedmont can be difficult. Moreover, because extensive areas underlain by Triassic strata are carbonate, and are prone to similar types of dissolution and erosion as the limestones of the Frederick Valley, the Triassic sediments are included as part of the Frederick Valley within the current study. The western limit of the Triassic rocks is along a linear fault that is presumably of Triassic age and places the Triassic against the edge of the Blue Ridge Province.

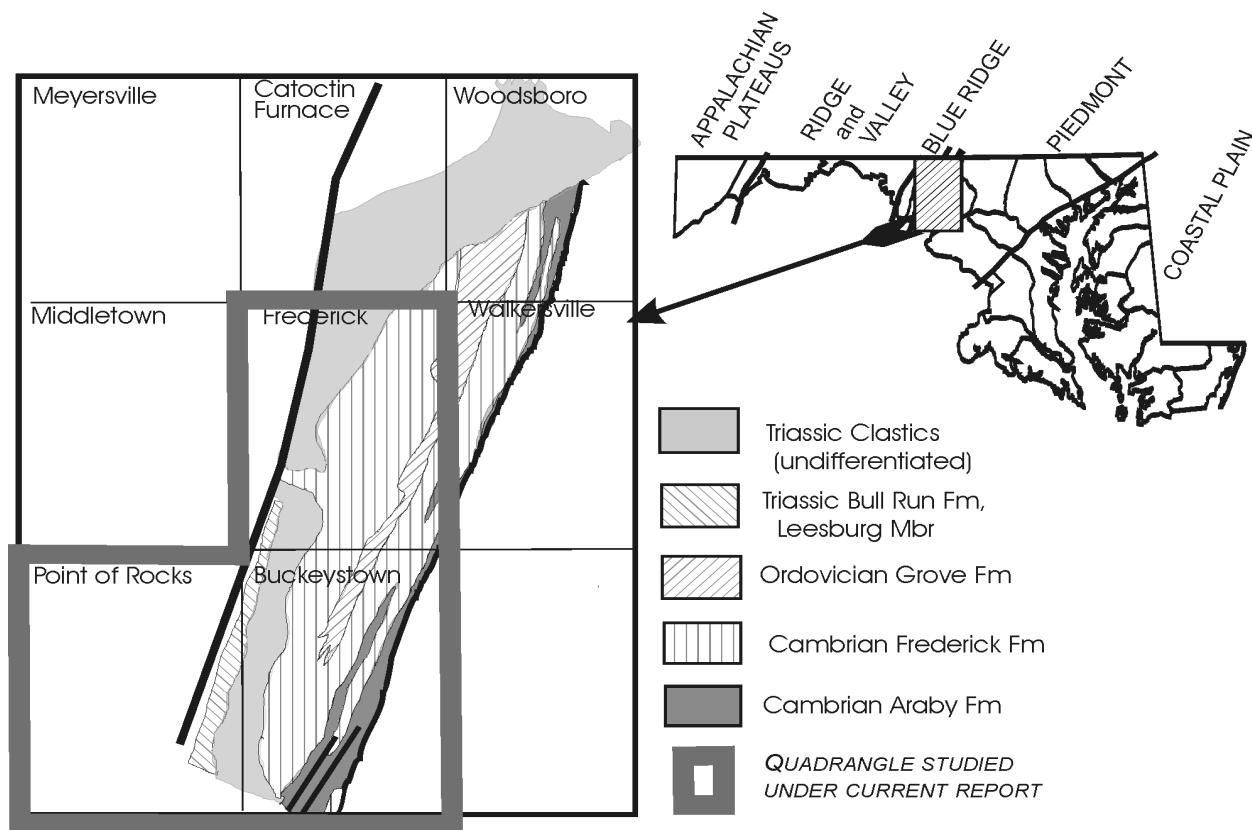


Figure 1. Location map of the Frederick Valley and the location of the Buckeystown, Point of Rocks, and Frederick quadrangles.

STRATIGRAPHY

Triassic Units

Bull Run Formation: Leesburg Member

The Leesburg Member is characterized by a light reddish gray, cobble to boulder, limestone and dolomite conglomerate. Locally, thin layers of reddish brown, sandy siltstone partings are interbedded with the conglomerate. Most of the clasts are rounded to subangular and poorly sorted. The average size of the clasts that make up the conglomerate varies widely, from pebbles less than 1 cm in diameter to cobbles more than 30 cm across. The clasts are cemented by light reddish brown to reddish gray, silty carbonate cement. Although no detailed size analysis was conducted, there appears to be a relative

decrease in cobble size from the western edge of the outcrop belt toward the east.

Bull Run Formation: Balls Bluff Siltstone Member

Lee (1979) interpreted the Balls Bluff Siltstone to be a fine-grained lateral equivalent to the conglomerates that constitute the Leesburg Member. The Balls Bluff Siltstone consists of reddish-brown to brownish-red, thin- to medium-bedded, argillaceous, sandy siltstone to silty mudstone. Locally, thin beds of argillaceous, silty, micaceous sandstone are present. Many of the mudstone intervals are characterized by strata that are pervaded by carbonate nodules and blebs. The extensive rooting and abundance of carbonate nodules are interpreted as caliche horizons.

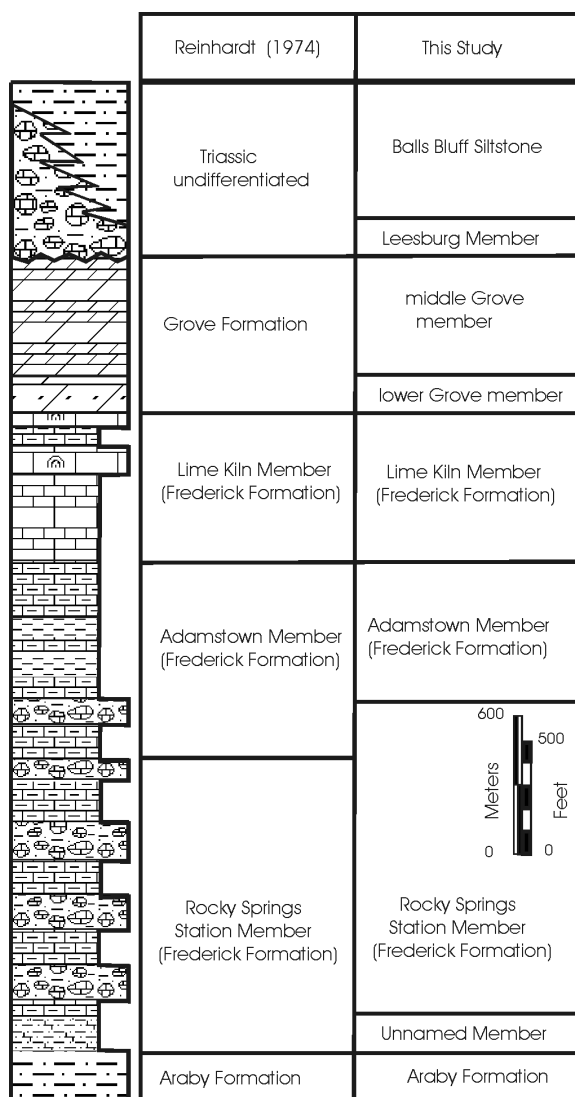


Figure 2. Generalized bedrock stratigraphy of the Frederick Valley, Frederick County, Maryland.

Manassas Formation

The Manassas Formation consists of four members in Virginia, but only two, the Poolesville and the Tuscarora Creek members are present in Maryland (Lee, 1979; Lee and Froelich, 1989). The Poolesville Member consists of thick intervals of reddish-brown, coarse-grained, sandstone interbedded with red, and reddish-brown, silty mudstone, and laminated, micaceous siltstone.

The Tuscarora Creek Member, a thin carbonate conglomerate, crops out along the

eastern margin of the Triassic belt at the base of the Manassas Formation. The Tuscarora Creek Member consists of thickly bedded, light gray weathering carbonate conglomerate to breccia. The clasts range in size from 1 to 8 cm in diameter and are typically well rounded.

Cambrian Units

Araby Formation

Creating the eastern border of the Frederick Valley is a ridge of Lower Cambrian clastics assigned to the Araby Formation. This unit consists of thickly bedded, medium gray to dark greenish gray, fine-grained sandstone and sandy siltstone with numerous interbeds of greenish gray to dark gray, slaty shale. In fresh outcrop the sandstone intervals commonly exhibit an anastomosing network of burrows; in some intervals this so pervades the strata that all indications of bedding have been obliterated. Furthermore, because of the Araby's fine-grained character, secondary cleavage further penetrates the rocks, making recognition of stratification extremely difficult.

Frederick Formation: *Unnamed* member

Along the eastern margin of the Frederick Valley is an interval of limestone interbedded with black shale. This interval will herein be termed the *Unnamed* member. The *Unnamed* member of the Frederick Formation consists of a knotty lime mudstone with angular carbonate clasts surrounded by dark gray, dolomitic shale. The carbonate clasts within this knotty-appearing lithology have a tendency to weather more rapidly than does the surrounding siliciclastic matrix. Interbedded with this knotty lithology are intervals of very dark gray to black, platy, calcareous shale ranging from 1 to 8 m thick.

Frederick Formation: Rocky Spring Station Member

Reinhardt (1974) named the Rocky Spring Station Member for approximately 300 m of interbedded very thinly bedded dark gray shaly limestone, medium bedded, sandy gray

limestone, and thick bedded, medium gray, polymictic (multiple lithology) limestone breccias the occur near the base of the Frederick Formation. The Rocky Spring Station Member is characterized by dark gray, very thinly bedded lime mudstone interbedded and interlaminated with black calcareous shale, sandy limestone, flaggy limestones and very thick, to massively bedded limestone breccia. These polymictic breccia beds are diagnostic of this member and are key characteristics to the origin and recognition of this member

Frederick Formation: Adamstown Member

Overlying the Rocky Spring Station Member is an interval characterized mainly by dark gray, very thinly bedded, lime mudstone with shaly partings. Reinhardt (1974) named this interval the Adamstown Member.

Reinhardt (1974, p. 24) estimated the thickness of the Adamstown at nearly 325 m. This thickness was verified by measured sections along the Monocacy River, along the eastern side of the Frederick Valley synclitorium.

Frederick Formation: Lime Kiln Member

The youngest and stratigraphically highest member of the Frederick Formation is named the Lime Kiln Member (Reinhardt, 1974). The Lime Kiln Member consists of thinly interbedded dark gray, thinly bedded lime mudstone and black calcareous shale with a few thicker layers up to 30 cm in thickness in the lower part of the member. The scattered thicker layers become more prominent and abundant up-section at the expense of the thinly interbedded limestone and shale intervals. Also appearing and becoming common near the middle and top of the member are lenticular, medium gray, sandy, lime grainstone and packstone that exhibit a sharp, presumably erosional base, and gradational upper contacts. These sandy intervals are up to 10 m thick. The upper 65 m of the member is marked by thick intervals of medium to dark gray, crudely bedded, algal thrombolite lime mudstone and stromatolitic lime mudstone interbedded with thinly bedded lime mudstone. The Lime Kiln Member is approximately 250 m thick at the type section.

Ordovician Units

Grove Formation: *lower* member

Jonas and Stose (1938) recognized and mapped a quartzose dolomitic unit at the base of the Grove Formation. This unit, which comprises the basal 30 to 70 m of the Grove Formation, is herein informally termed the *lower* member. This member consists of light gray, fractured, sandy, dolomite that is interbedded with intervals of very light gray, fractured, fine-grained dolomite. At least one of these non-sandy interbeds is interpreted to be a dolomitized algal thrombolite. The sand which characterizes the dolomitic intervals of this member vary from fine-grained to very coarse-grained and make up between 5 to 45 percent of the rock. Most of the larger sand grains are well rounded. Some sandy layers exhibit abundant cross-bedding, some of which is herringbone.

Grove Formation: *middle* member

Overlying the distinctive lower member, and making up the bulk of the formation's thickness is an interval composed of thickly bedded, thrombolitic lime mudstone, tan, laminated, dolomitic lime mudstone to dolostone, and light gray, sandy, intraclastic lime packstone to grainstone. This member, while attaining a thickness of more than 700 m in the vicinity of Woodsboro, Maryland, is probably represented in the southern part of Frederick Valley by no more than 60 to 120m of stratigraphic thickness.

KARST FEATURES

This study recognized and recorded three types of karst features: closed depressions, active sinkholes, and karst springs. By far the most common feature recognized were closed depressions, otherwise known as dolines. These features are recognizable topographic lows towards which the surrounding area is inclined and can be from a few meters to 100 m across. The second category of karst features recorded is active sinkholes. These features are differentiated from depressions by the recognition of

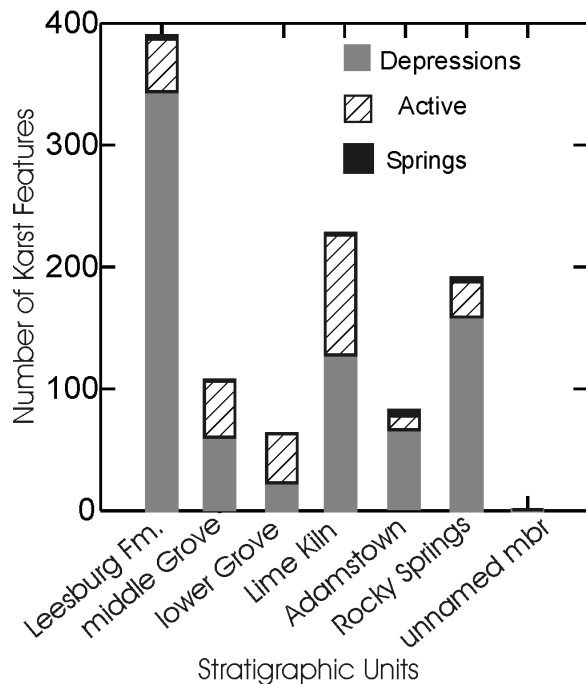


Figure 3. Stacked bar chart of karst features recorded from the Buckeystown, Point of Rocks, and Frederick quadrangles.

recent activity, or an open throat. The third category of karst features recognized is springs.

Data for the current study were attained through detailed geologic mapping of both geology and karst features for the southern part of the Frederick Valley. Such field analysis allowed for both the exact locations of geologic outcrops as well as karst features. While geology was plotted on a 7.5-minute topographic quadrangle map, all karst features were recorded utilizing Trimble GeoExplorer II and GeoExplorer III Global Positioning System (GPS) receivers. All GPS files were post-processed, an office procedure whereby the locations taken in the field are differentially corrected to increase the locations' precision. These corrected locations typically gave a precision of less than 1 m.

SUMMARY OF KARST FEATURES

One thousand and seventy-nine karst features have been identified in the southern part of the Frederick Valley (Buckeystown, Point of Rocks and Frederick 7.5 minute quadrangles).

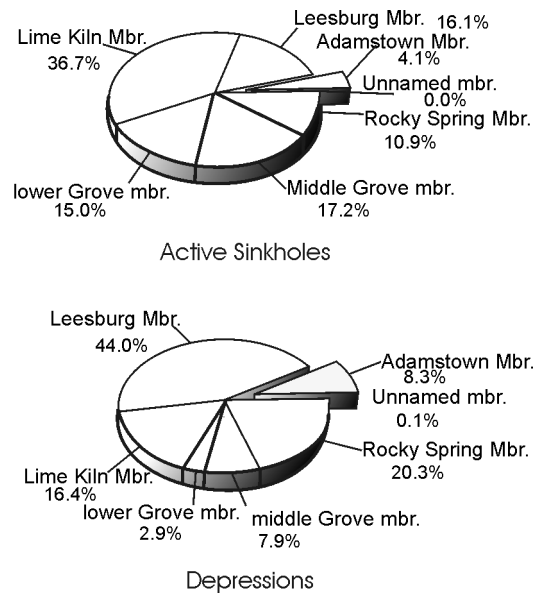


Figure 4. Pie diagrams illustrating break-down of active sinkholes (A) and depressions (B) for the Buckeystown, Point of Rocks, and Frederick quadrangles.

Figure 3 gives a breakdown of the types of features in a stacked bar chart. Depressions are by far the most common feature recorded, making up nearly 74 percent of all the readings. While active sinkholes comprised nearly 25 percent of the features, springs were a distant third making up only 1.3 percent of all karst features.

As one might suspect karst features were not distributed evenly throughout the Frederick Valley carbonate units. Some geologic units appear to have greater numbers of features than do others. Clearly, the Triassic Leesburg Formation has the greatest number of depressions (344), the Lime Kiln Member of the Frederick Formation has the largest number of active sinkholes (98), and the Adamstown Member the largest number of springs (5). These data are summarized more thoroughly in Table 1. One can see that most active sinkholes (69%) are contained within the Lime Kiln Member of the Frederick Formation (36.7%), lower Grove (15%), middle Grove (17.2%), and Leesburg (16.1%) (Figure 4). Although the Lime Kiln, lower Grove, middle Grove, and Leesburg contain the largest number of active sinkholes, most of the depressions (>80%) are

Table 1. Summary of karst feature distribution within susceptible stratigraphic units and their relative areal distributions

Unit	Depressions	Active	Springs	Area (sq.mi.)	Features/mile	Active/mile
Unnamed mbr.	1	0	0	2.72	0.37	0.0
Rocky Springs Station Mbr.	159	29	3	29.39	6.50	0.99
Adamstown Mbr.	65	11	5	9.4	8.6	1.17
Lime Kiln Mbr.	128	98	2	5.94	38.38	16.5
lower Grove mbr.	23	40	0	2.44	25.82	16.39
middle Grove mbr.	62	46	1	2.65	41.13	17.37
Leesburg Mbr.	344	43	3	8.72	44.72	0.96
Totals	782	267	14	61.26		

contained in the Leesburg Formation (44%), Rocky Springs Station Member of the Frederick Formation (20.3%), and Lime Kiln Member of the Frederick Formation (16.4%) (Figure 4). Only the Lime Kiln Member has large numbers of both active sinkholes and depressions. This summary illustrates that not all karst-prone units in the Frederick Valley are equally susceptible. However, it does little to tell why this is so.

KARST FEATURE DISTRIBUTION

One of the main purposes of this study is to both map the distribution of karst features and to examine their distribution with respect to the stratigraphic unit. As discussed above a general pattern of karst features and can be gleaned from the data now at hand. The comparatively high incidence of karst features within the Lime Kiln is again illustrated in Table 1.

It would appear, utilizing raw numbers of Table 1, that the most karstic unit studied is the Leesburg Formation with almost 400 features recorded within its outcrop belt. Likewise, dividing the area (in square miles) underlain by that unit by the number of karst features recorded for that unit gives an average of 44.72 karst features per square mile. This is the most of any unit discerned. Conversely, the Rocky Spring Station Member, which has nearly 200 karst features recognized within its outcrop belt

has an average of only 6.5 features per square mile, because the area underlain by this unit is so large.

When one normalizes the number of sinkholes in a similar fashion as above, by dividing the number by the area underlain by each unit, a slightly different image develops. The Leesburg Formation, with an average of 44.72 features per square mile, has only 0.96 active sinkholes per square mile. The Rocky Springs Station likewise has a low 0.99 active sinkholes per square mile. However, the Lime Kiln Member of the Frederick Formation, which has a relative high 38.38 karst features per square mile, has a relatively high 16.5 active sinkholes per square mile. The two Grove members produce some of the highest numbers of any of the units with 16.39 and 17.37 active sinkholes per square mile, respectively. Consequently, from unit to unit there are notable differences between the likelihood of encountering depressions and active sinkholes (see Table 1).

KARST SUSCEPTIBILITY

Figure 5 gives the general relationships of the susceptibility of the stratigraphic units of the Frederick Valley of Maryland that were utilized in this study. While this curve on the right is general and empirical, it is meant to give a

relative susceptibility of the individual stratigraphic units. From this graph one can see that the relative susceptibility for the lower units of the Frederick Formation is low, with the exception of some of the purer breccia beds of the Rocky Springs Station Member. The upper Frederick (Lime Kiln Member) and the lower Grove member are rated as highly susceptible based upon the large number of active sinkholes recorded in these units. The Triassic Leesburg is relatively low in its susceptibility even though there are large numbers of depressions recorded within its outcrop belt. It is rated low because very few active sinkholes have been identified within it.

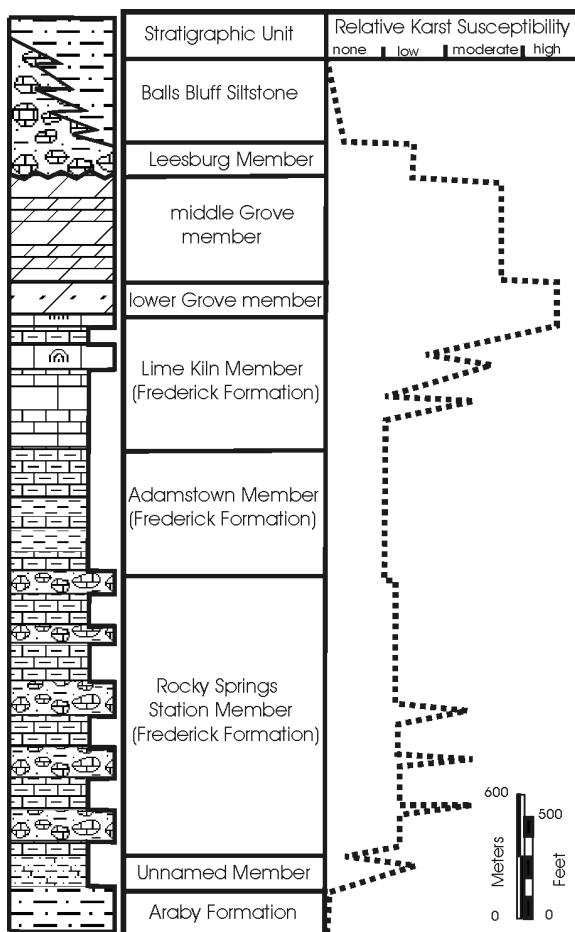


Figure 5. Relative karst susceptibility of the stratigraphic units of the Frederick Valley.

REFERENCES

- Bassler, R.S., 1919, Cambrian and Ordovician: Maryland Geological Survey Systematic Report, 424 p.
- Boyer, B.W., 1997, Sinkholes, soils, fractures, and drainage: Interstate 70 near Frederick, Maryland: Environmental and Engineering Geoscience, 3-469-485.
- Jonas, A. I. and Stose, G. W., 1938, Geologic map of Frederick County, and adjacent parts of Washington and Carroll Counties: Maryland Geological Survey Geologic Map, scale 1:62,500.
- Lee, K.Y., 1979, Triassic-Jurassic geology of the northern part of the Culpeper Basin, Virginia and Maryland: U.S. Geological Survey Open File Report 79-1557, 19 p., 16 sheets scale 1:24,000.
- Lee, K.Y., and Froelich, A. J., 1989, Triassic-Jurassic stratigraphy of the Culpeper and Barboursville basins, Virginia and Maryland: U.S. Geological Survey Professional Paper 1472, 52 p.
- Reinhardt, J., 1974, Stratigraphy, Sedimentology and Cambro-Ordovician paleogeography of the Frederick Valley, Maryland: Maryland Geological Survey Report of Investigations 23, 73 p.
- Stose, A. J. and Stose, G. W. 1946, Geology of Carroll and Frederick Counties, in The physical features of Carroll County and Frederick County: Maryland Geological Survey County Report, p. 11-131.

POSTER SESSION ABSTRACTS

Evaluating Travel Times and Transient Mixing in a Karst Aquifer Using Time-Series Analysis of Stable Isotope Data

By Andrew J. Long¹ and Larry D. Putnam¹

¹U.S. Geological Survey, 1608 Mountain View Road, Rapid City, SD 57702

Abstract

Stable-isotope samples were collected at about 6-week intervals over a 6-year period at a streamflow-loss zone that recharges the karstic Madison aquifer and at a well located near or within a main ground-water flowpath. Time-series analysis of isotope data indicates that the well is in direct and rapid response to recharge from a sinking stream during climatically wet periods. The hydraulic connection between the loss zone and well primarily results from karst conduits. During dry periods when streamflow is small, isotopes in the well samples primarily are influenced by aquifer-matrix water that has been stored for many months or years. These data were analyzed by correlation and linear-systems analysis for a 34-month period of high recharge rates. The two data sets correlate most closely when the stream data are lagged 22 days, which may approximate the traveltime from the loss zone to the well. Linear-systems analysis estimates a traveltime to the well of about 15 days and a system memory of 2-3 years resulting from diffuse matrix flow. Based on these analyses, conduit-flow velocity is estimated at 380–800 ft/day (120–240 m/day). A log-normal distribution approximates the distribution of traveltimes of a plume for conduit flow.

INTRODUCTION

Stable isotopes of oxygen (¹⁸O) and hydrogen (D, deuterium) can be used as naturally-occurring tracers for evaluating traveltimes and mixing conditions in ground water. Stable-isotope data for samples from a well and a sinking stream that recharges the Madison aquifer indicate that the well water exhibits a rapid response to recharge from the stream. Time-series analysis, including a linear-systems approach, is used to evaluate traveltimes, transient mixing, and the relation between conduit and matrix flow. Linear-systems analysis of tracer data also provides valuable information regarding the movement, traveltimes, and residence times of potential contaminants.

The study area is located on the eastern flank of the Black Hills uplift in western South Dakota (fig. 1). The Madison aquifer primarily is contained in the upper part of the Madison Limestone where numerous fractures and solution openings provide

extensive secondary porosity (Greene, 1993). The Madison Limestone in this area ranges from about 300 to 450 feet thick and is part of a series of sedimentary units that generally dip away from the uplifted Black Hills. Because of the dipping sedimentary units, the Madison aquifer is confined in most of the study area with a narrow unconfined area near the outcrop.

In the study area, the Madison aquifer receives recharge primarily from streamflow loss to the Madison Limestone outcrop and secondarily from infiltration of precipitation on the outcrop. On the eastern flank of the Black Hills near Rapid City (fig. 1), streamflow loss is the dominant form of recharge (Naus and others, 2001). Greene (1997) concluded that part of the recharge from Spring Creek loss flows north toward Rapid City and makes up a large portion of the water that is discharged at Jackson-Cleghorn Springs, which is located about 5 miles north-northeast of the Spring Creek loss zone.

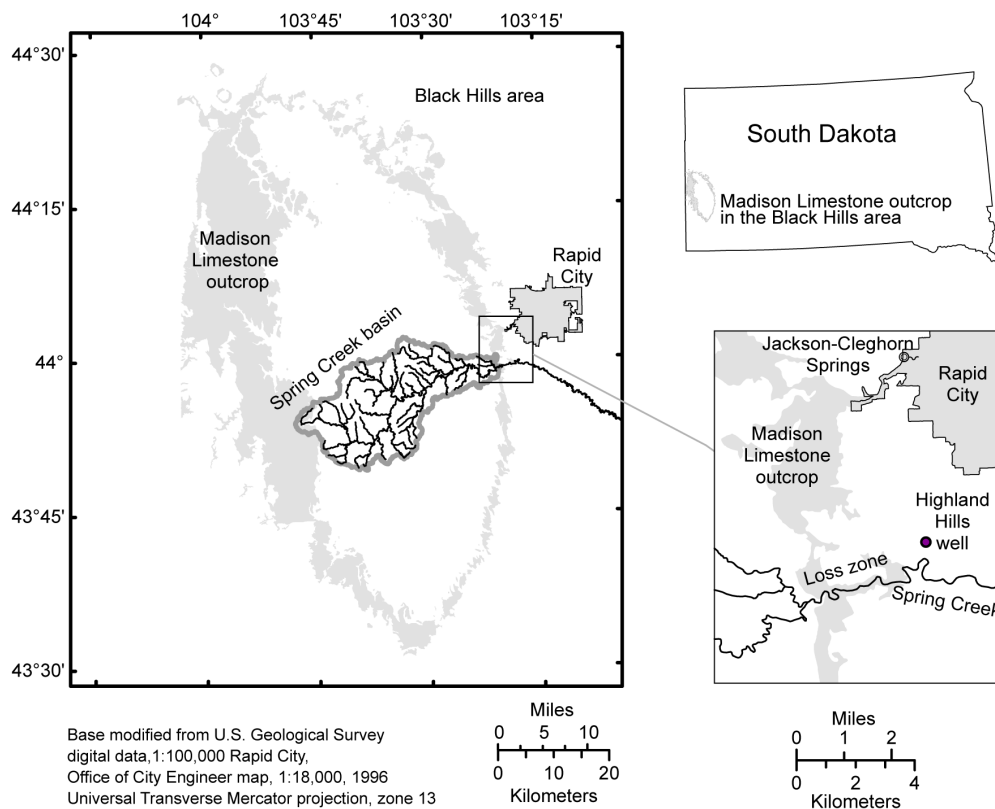


Figure 1. Location of the study area.

In western South Dakota the Madison aquifer has been extensively studied by collecting and analyzing stable isotope data. Anderson and others (1999) described the use of stable isotopes to characterize ground- and surface-water interactions in the Rapid City area. Greene (1993) used stable isotopes to evaluate the spatial distribution of recharge from sinking streams in the Madison aquifer in the Rapid City area. Naus and others (2001) described the regional distribution of stable isotopes for the Black Hills area and provided a general characterization of ground-water flow in the Madison aquifer. Naus and others (2001) also discussed the influence of orographic and climatic conditions on stable isotopes. Long and Derickson (1999) applied a linear-systems analysis to study the hydraulic-head response of the Madison aquifer to streamflow recharge from Spring Creek.

STABLE ISOTOPE DATA

Delta (δ)¹⁸O and δ D are a measure of the concentrations of stable isotopes of oxygen and hydrogen, respectively, compared to a standard and are expressed in parts per thousand or per mil (Clark and Fritz, 1997). Isotope concentrations are referred to as isotopically heavier for higher concentrations and isotopically lighter for lower concentrations. Oxygen and hydrogen isotopes were sampled in Spring Creek above the loss zone from 1993 through 2001. Because a nearly linear relation exists between δ^{18} O and δ D in the Black Hills (Naus and others, 2001), the following analysis uses only δ^{18} O for simplicity. This data set includes a period of above-average precipitation beginning in the spring of 1995 extending through the spring of 2000. The cumulative departure of precipitation from average during this extended wet period is

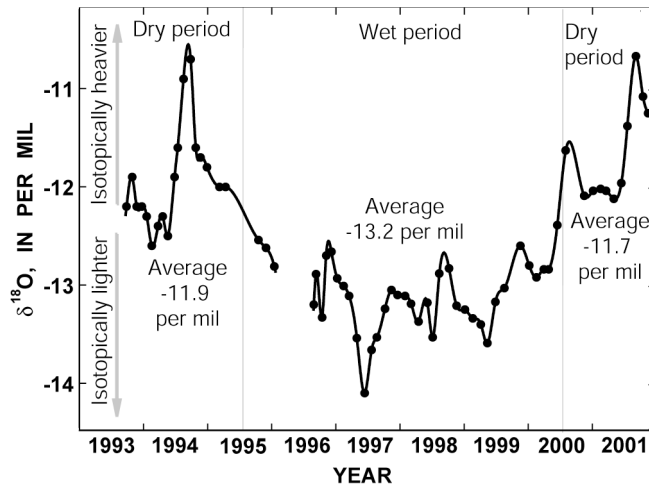


Figure 2. Measured $\delta^{18}\text{O}$ values for Spring Creek above streamflow-loss zone. Periods of generally dry or wet climatic conditions are noted. The curved line through the $\delta^{18}\text{O}$ data points was interpolated by a cubic spline.

about 25 inches (National Oceanic and Atmospheric Administration, 1993-2001). The resulting change in isotope fractionation during the wet period produced a lighter $\delta^{18}\text{O}$ in Spring Creek. The average $\delta^{18}\text{O}$ values in Spring Creek for the two dry periods are -11.9 and -11.7 per mil compared to -13.2 per mil during the wet period (fig. 2).

Stable isotopes were sampled in the Highland Hills (HH) well (fig. 1) beginning in the fall of 1996 to observe the response of the Madison aquifer to changes in Spring Creek isotope concentrations (fig. 3). The HH well is 780 feet deep and is open only to the upper 135 feet of the Madison Limestone. The well produces about 30 gallons per minute and serves a suburban development of about 10-15 homes. All analyses for this study include daily values for $\delta^{18}\text{O}$ interpolated by a cubic spline approximation, which is represented by the curved lines connecting sampled data points (fig. 3). The streamflow-recharge rate to the Madison aquifer (fig. 3), which varies with flow in Spring Creek up to a maximum estimated rate of $21 \text{ ft}^3/\text{s}$ (Hortness and Driscoll, 1998), must be considered because of its influence on transient mixing. Response of $\delta^{18}\text{O}$ in the HH well also may

be influenced by other aquifer dynamics caused by hydraulic head changes or well withdrawals.

EVALUATION OF TRAVEL TIMES AND TRANSIENT MIXING

The $\delta^{18}\text{O}$ values in samples from the HH well indicate a response to variable recharge rates and $\delta^{18}\text{O}$ values in Spring Creek (fig. 3). During extended periods when Spring Creek recharge is at or near the maximum loss rate, the $\delta^{18}\text{O}$ trend for the HH well is similar to that of Spring Creek (A sections, fig. 3), and ground water moves from the conduits into the matrix because conduits have reached capacity. During periods of low recharge (B sections, fig. 3), the influence of conduit flow diminishes, and ground water moves from matrix to conduits. Matrix water moves slowly compared to conduit water and, thus, probably has an isotope signature closer to the average recharge water from several years prior. The average $\delta^{18}\text{O}$ for Spring Creek during the dry period prior to the summer of 1995 was -11.9 per mil (fig. 2), and a single sample in 1986 was -11.2 per mil (Naus and others, 2001). Furthermore, $\delta^{18}\text{O}$ for samples from Madison aquifer

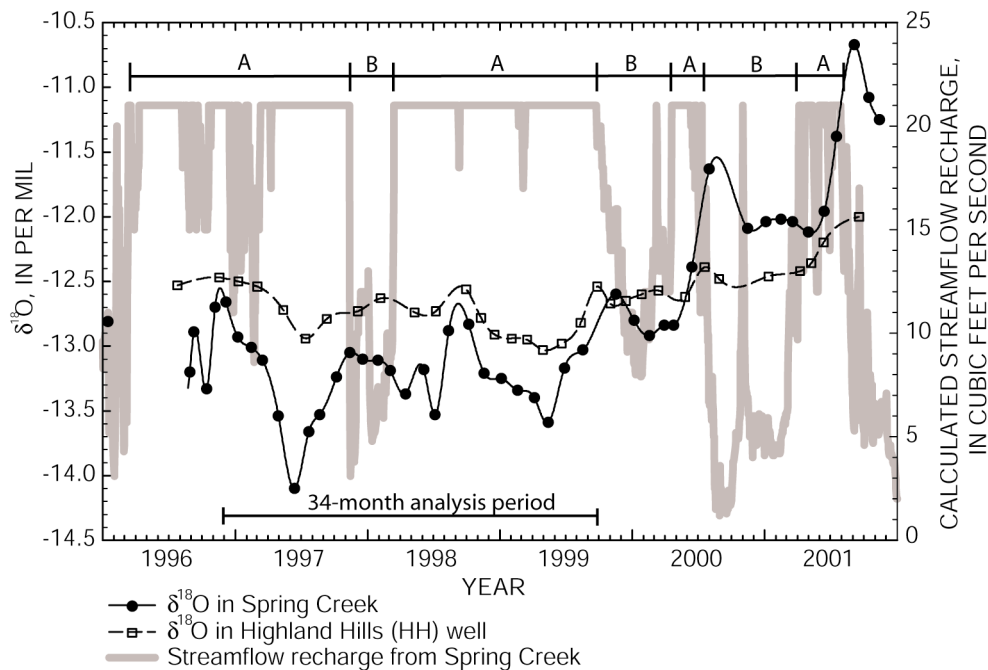


Figure 3. $\delta^{18}\text{O}$ data and streamflow recharge to the Madison aquifer from Spring Creek for 1996 through 2001. The curved line through the $\delta^{18}\text{O}$ data points was interpolated by a cubic spline. The A sections indicate periods of near-maximum recharge, whereas B sections indicate periods of lower recharge. The streamflow recharge has a maximum estimated rate of 21 ft^3/s (Hortness and Driscoll, 1998).

wells south of Rapid City in 1986-87 generally were about -12 per mil (Anderson and others, 1999). Based on these data, the average $\delta^{18}\text{O}$ for the period of 1986-95 probably was about -12 per mil or heavier, which also may approximate the aquifer-matrix value later than 1995. The movement of water from matrix to conduits is illustrated in figure 3, where $\delta^{18}\text{O}$ for the well in every B section increases toward the assumed matrix value of -12 per mil, even when $\delta^{18}\text{O}$ in Spring Creek decreases, which indicates a larger contribution from the matrix during periods of low recharge.

An analysis of correlation of the $\delta^{18}\text{O}$ daily time-series data for Spring Creek and the HH well is used to approximate the ground-water traveltime from the loss zone to the well. The analysis includes a 34-month time period from December 1996 through September 1999 (fig. 3) when the recharge rate from Spring Creek was relatively steady and generally was at or

near the maximum loss rate of 21 ft^3/s . The Spring Creek data were consecutively lagged from 0 to 40 days in relation to the HH data with a correlation coefficient calculated for every lag time (fig. 4). Thus, for the period of analysis, traveltime is

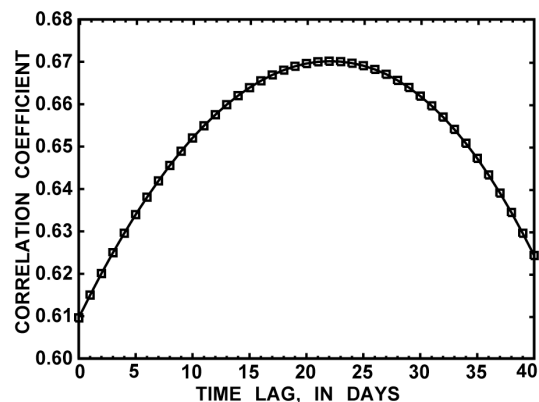


Figure 4. Correlogram of $\delta^{18}\text{O}$ time-series data for Spring Creek and Highland Hills (HH) well. The Spring Creek data were lagged from 0 to 40 days for correlation.

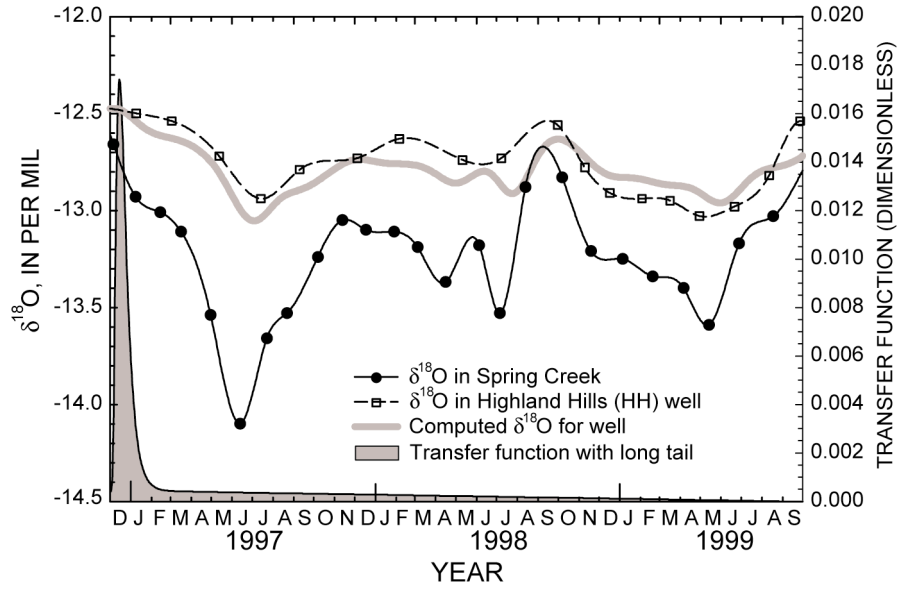


Figure 5. Results of linear-systems analysis including the computed $\delta^{18}\text{O}$ data for the sampled well and the transfer function used in the analysis. The curved line through the $\delta^{18}\text{O}$ data points was interpolated by a cubic spline.

estimated to be approximately equal to the lag time corresponding to the maximum correlation of about 0.67, which occurs at a lag of 22 days.

Linear-systems analysis was applied to the daily $\delta^{18}\text{O}$ data of Spring Creek and the response of $\delta^{18}\text{O}$ at the HH well for the 34-month analysis period (fig. 3). A time-invariant transfer function can be estimated as a translation of the forcing function (Spring Creek) and the observed response (HH well). The method assumes that the system is linear, time invariant, and stationary, meaning the character of the response does not change with magnitude of the forcing function or with time, and that the physical characteristics of the system do not change. In this case, the assumption is valid for periods of streamflow recharge that generally are near the maximum loss rate. A linear, time-invariant system is described by the convolution integral:

$$y(t) = \int_0^t h(t - \tau)x(\tau)d\tau$$

where $y(t)$ is the system response, $x(\tau)$ is the forcing function, $h(t - \tau)$ is the transfer function, and $(t - \tau)$ represents the delay time from forcing function to response (Dooge, 1973; Singh, 1988). Convolution for this analysis was calculated in the Fourier-transform domain.

The response in $\delta^{18}\text{O}$ at the HH well to $\delta^{18}\text{O}$ in Spring Creek was modeled by convolution with a time-invariant transfer function, which represents the statistical distribution of travel times. A log-normal distribution, which is used to model many kinds of environmental contaminant data (Gilbert, 1987), was used for this transfer function. However, the log-normal curve was only adequate to represent the short-term response and, therefore, a long tail was added in the form of a straight line with a declining slope to represent the long-term response. Convolution of the Spring Creek $\delta^{18}\text{O}$ data with this composite transfer function produced modeled output for the HH well that matched the observed data fairly well (fig. 5).

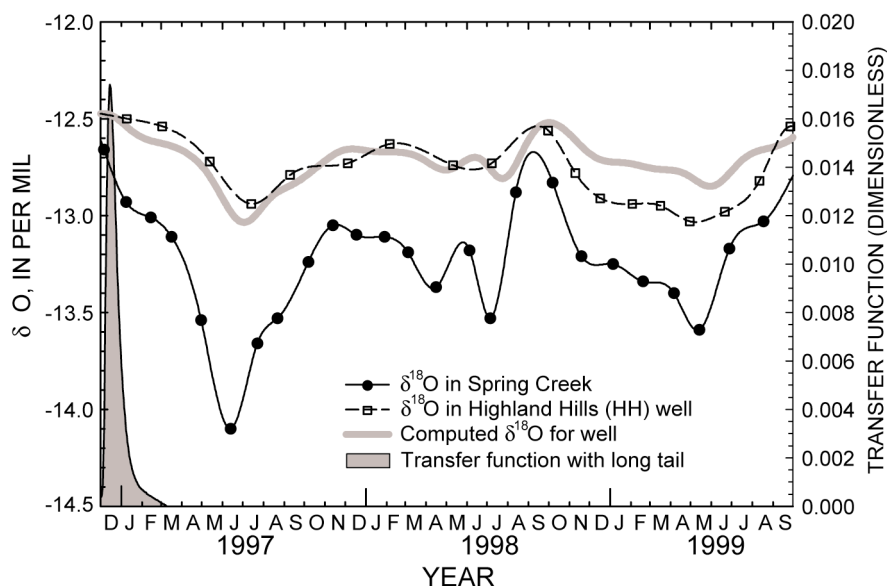


Figure 6. Results of linear-systems analysis using a shortened transfer-function tail, which produced a poorer fit to observed data than did the long-tail transfer function. The curved line through the $\delta^{18}\text{O}$ data points was interpolated by a cubic spline.

To illustrate the necessity of the extended tail, figure 6 shows the results of convolution using the same transfer-function except with a shortened tail, which produced a poorer fit to the observed data. Using the short tail, the computed data for the HH well have a more upward sloping trend (fig. 6) compared to that produced by the long tail (fig. 5). The observed $\delta^{18}\text{O}$ data (spline interpolated) for the well appear to have a general slope that is similar to the system response computed by the long-tail transfer function (fig. 5). The long tail of the transfer function (fig. 5) has a very small height compared to the log-normal part of the function, but extends for a great length. The character of this tail indicates a long system memory; however, the tail has minor effects compared to that of the log-normal part of the function.

The shape of the transfer function (fig. 5) characterizes the system and represents the form of response of any 1-day pulse from the input function. The peak response occurs about 15 days after a pulse and declines rapidly, whereas the system memory is 2-3 years, as indicated by the tail's length. The log-normal part of the transfer function describes conduit flow,

whereas the linear tail describes diffuse matrix flow. The sharp contrast in the transfer function between peak response (log-normal) and long-term memory (linear tail) probably results from the dominant influence of conduit flow during periods of high recharge.

The transfer function also represents the statistical distribution of traveltimes for a contaminant plume. If a contaminant were to spill into the stream above the loss zone, the contaminant concentration in the well could be predicted by the transfer function (fig. 5). Peak concentration would occur about 15 days later, and the main body of the plume would be expected to leave the well area within about 100 days (fig. 5); however, minor contaminant concentrations could linger for 2-3 years or more depending on specific contaminant characteristics. In areas farther along the flowpath, the main plume body could become larger because of dispersion, with a greater fraction of the total contaminant contained within the matrix. This transfer function (fig. 5) applies to periods of prolonged high-recharge conditions similar to those present during the analysis period; aquifer response and traveltimes

might be different during low-recharge conditions.

The lighter $\delta^{18}\text{O}$ values in Spring Creek during the wet period of the late 1990's (fig. 2) was gradually influencing matrix concentrations, which consequently affected $\delta^{18}\text{O}$ values in the HH well. However, $\delta^{18}\text{O}$ in the matrix probably was decreasing much more gradually than in water sampled from the well, which represented primarily conduit water during that period. Therefore, when the influence of the matrix is introduced by adding a long tail to the transfer function, the result is to lessen the otherwise upward trend because $\delta^{18}\text{O}$ in the matrix had been declining. The particular mixture of conduit and matrix water may have been influenced by pumping of the HH well; the transfer-function tail might have a different character had the well not been pumped.

Long and Derickson (1999) determined a transfer function for the response of hydraulic head in the Madison aquifer to streamflow recharge from Spring Creek. These authors concluded that a logarithmic curve best approximated the transfer function and determined that the system has a time to peak response of less than 1 month and a system memory of about 6 years. The results of this previous research are consistent with the results of time-series analysis of stable isotopes described in this article.

SUMMARY AND CONCLUSIONS

Stable-isotope data indicate that isotope concentrations in the Highland Hills well respond rapidly to stream loss that recharges the Madison aquifer during climatically wet periods; during dry periods when streamflow is low, aquifer-matrix water primarily influences concentrations in the well. The time-series data were analyzed by correlation and linear-systems analysis for a 34-month period of high recharge rates. The two data sets correlate most closely when the stream data are lagged by 22 days, which indicates the approximate traveltime from the loss zone to the well. Linear-systems analysis of the time-series data indicates that

traveltime to the well is about 15 days and that the system has a memory of 2-3 years resulting from diffuse matrix flow. Based on these analyses, conduit-flow velocity is estimated at 380–800 ft/day (120–240 m/day). A log-normal distribution approximates the distribution of traveltimes of a plume for conduit flow. This time-series analysis is valid for periods of prolonged, high recharge rates and may produce different results for low-recharge periods. Characterizing flow by correlation and linear-systems analysis of natural-tracer data can provide useful information for interpretation of dye-tracer tests, monitoring long-term water-quality trends, and managing potential aquifer contamination.

REFERENCES

- Anderson, M.T., Driscoll, D.G. and Williamson, J.E., 1999, Ground-water and surface-water interactions along Rapid Creek near Rapid City, South Dakota: U.S. Geological Survey Water-Resources Investigation Report 98-4214, 99 p.
- Clark, I.D. and Fritz, Peter, 1997, Environmental isotopes in hydrogeology: Lewis Publishers, New York, 328 p.
- Dooge, J.C.I., 1973, Linear theory of hydrologic systems: U.S. Department of Agriculture and Technical Bulletin, Washington, D.C., 1468 p.
- Gilbert, R.O., 1987, Statistical methods for environmental pollution monitoring: New York, Van Nostrand Reinhold, 320 p.
- Greene, E.A., 1993, Hydraulic properties of the Madison aquifer system in the western Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 93-4008, 56 p.
- _____, 1997, Tracing recharge from sinking streams over spatial dimensions of kilometers in a karst aquifer: *Ground Water*, v.35, no.5, p. 898-904
- Hortness, J.E., and Driscoll, D.G., 1998, Streamflow losses in the Black Hills of western South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4116, 99 p.
- Long, A.J. and Derickson, R.G., 1999, Linear systems analysis in a karst aquifer: *Journal of Hydrology (Elsevier)*, v. 219, p. 206-217.

National Oceanic and Atmospheric Administration,
2001, Climatological data for South Dakota,
annual summary: Asheville, North Carolina,
U.S. Department of Commerce (issued
annually).

Naus, C.A., Driscoll, D.G., and Carter, J.M., 2001,
Geochemistry of the Madison and Minnelusa

aquifers in the Black Hills area, South Dakota:
U.S. Geological Survey Water-Resources
Investigations Report 01-4129, 118 p.

Singh, V.P., 1988, Hydrologic systems, rainfall-
runoff modeling –Vol. I: Prentice Hall,
Englewood Cliffs, NJ, 480 p.

Changes in Nitrate Concentrations in Spring Waters Due to Mixing of Surface and Ground Water in the Woodville Karst Plain, Northern Florida

By B. G. Katz¹, A. R. Chelette², and T.R. Pratt²

¹U.S. Geological Survey, 227 N. Bronough St., Tallahassee, FL 32301

²Northwest Florida Water Management District, 81 Water Management Drive, Havana, FL 32333

Abstract

Ground water in the Woodville Karst Plain is highly susceptible to contamination as a result of the numerous sinkholes and other karst features that allow for direct interactions with surface water. Since the early 1970's, nitrate-N concentrations have increased from 0.26 to 0.89 mg/L in Wakulla Springs and 0.06 to 0.19 mg/L in Riversink, major ground water discharge locations for the Upper Floridan aquifer. Two methods were used to better understand the hydrochemical response of springs in this area to changes in rainfall/recharge during 2000: (1) in-situ water-quality multi-parameter instruments that logged hourly measurements of specific conductance and temperature were installed in both springs, and (2) water samples were analyzed for chemical and isotopic tracers during baseflow conditions (February) and after a high-rainfall period (October). Following most small rainfall events (2.5 cm or less) during January through July, specific conductance values in Wakulla Springs and Riversink showed little or no change. However, following several large rainfall events in August and September (57 cm total), specific conductance decreased from 310 to 250 uS/cm in Wakulla Springs and from 250 to 60 uS/cm in Riversink. Correspondingly, concentrations of nitrate decreased in both springs, but dissolved organic carbon increased, indicating an increased contribution from surface water. Based on binary mass-balance models, the maximum amount of surface water that mixed with ground water was estimated to be 20% for Wakulla Springs and 95% for Riversink during the high-flow period.

Use of Dye Tracing To Determine Conduit Flow Paths Within Source-Protection Areas of a Karst Spring and Wells in the Bear River Range, Northern Utah

By Lawrence E. Spangler

U.S. Geological Survey, 2329 Orton Circle, Salt Lake City, Utah 84119

Abstract

Drinking-water source-protection areas for wells and springs in fractured-rock terranes are often delineated by using analytical models and time-of-travel methods based on Darcian concepts. These methods, however, generally assume that the aquifers in these terranes behave as uniform, porous media at the scale of the study area. Source-protection areas and time-of-travel zones delineated for Dewitt Spring and two wells discharging from carbonate rocks in the Bear River Range in northern Utah were compared to results of dye tracing. Results of five tracer tests indicate that time of travel based on porous-media concepts can be substantially overestimated in hydrogeologic terranes where conduit flow paths are present. Ground-water travel times of less than 8 days and average velocities of as much as 2,000 feet per day were documented within the delineated areas. Source-protection areas in these terranes also may be under or over estimated when surface-water divides are assumed to be ground-water divides. As a result, dye tracing can be used to help delineate areas that do not contribute to springs or wells, and thus, minimize the area that is necessary for source-protection management.

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) established guidelines for the delineation of wellhead-protection areas in unconfined, porous, granular aquifers such as unconsolidated sand and gravel (U.S. Environmental Protection Agency, 1987). Methods for delineating wellhead-protection areas in these types of hydrogeologic settings generally assume porous-media (Darcian) flow and are not intended to be applicable in ground-water systems in which water movement is mostly along fractures. Subsequently, the Wisconsin Geological and Natural History Survey (1991), in conjunction with the EPA, produced a document concerning the delineation of wellhead-protection areas in fractured rocks. Although the study sites included a carbonate (dolomite) aquifer, it was assumed that the flow systems functioned similar to those in a uniform, porous medium at the scale of the study area. Eckenfelder, Inc. (1996), again in conjunction with the EPA, produced a definitive document detailing guidelines for delineation of wellhead- and springhead-protection areas in carbonate terranes, where nonporous-media flow predominates.

Drinking-water source-protection areas for wells in fractured-rock terranes are often delineated by using analytical models and time-of-travel methods based on Darcy flow equations. Aquifers in these terranes, however, generally are assumed to behave as uniform, porous media at the scale of the study area. Fractured-rock aquifers that do not behave as porous media, such as those in carbonate (karst) terranes, generally cannot be studied with the same methods used to characterize porous-media aquifers. In these hydrogeologic settings, delineation of source-protection areas or zones of contribution for wells and particularly springs, often can be done only by integration of hydrogeologic mapping techniques such as water-level measurements, estimates of ground-water basin size by comparison of normalized base flow of springs (discharge balancing), and dye-tracer tests (Eckenfelder, Inc., 1996). In addition, analysis of water chemistry can provide useful information with regard to sources of water and potential flow paths (Jensen and others, 1997). Dye tracing used in conjunction with water-table contour maps derived from water-level measurements have proven to be the most effective methods for

determining zones of contribution (recharge areas), general directions of ground-water flow, and residence times for water in fractured-rock aquifers that are characterized by nonporous-media flow (Mull and others, 1988).

Carbonate Aquifers

Most aquifers in carbonate rocks (limestone and dolomite) consist of integrated components of both diffuse and conduit flow (Shuster and White, 1971 and table 1). Consequently, these aquifers are typically dual or triple porosity and include both discrete fracture as well as conduit (solutionally-enlarged fracture) flow paths. Diffuse-flow components may function very similar to porous-media flow on a regional scale, with ground-water movement typically along poorly integrated fractures and other pathways where movement is comparatively slow. Conduit-flow (karst) components are characterized by solutional enlargement of fractures and bedding-plane partings, promoting rapid ground-water movement along complex pathways. As a result, porous-media concepts (Darcian flow) generally do not apply.

Carbonate-rock aquifers generally are highly anisotropic, and hydraulic-conductivity values can range over several orders of magnitude (table 1). Thus, ground-water velocities and travel times can vary considerably. In addition, travel times typically decrease with increases in discharge. Although average values for hydraulic properties determined from well tests may be representative of carbonate aquifers on a regional scale, solutional enlargement of fractures and bedding-plane partings typically results in preferred pathways with increased ground-water velocity that need to be considered when source-protection areas are delineated.

Delineation of Source-Protection Areas

Dewitt Spring near Logan, Utah (fig. 1), provides an example of the use of dye tracing to determine conduit flow paths and recharge areas in comparison to source-protection areas delineated by methods based largely on porous-media (Darcian) concepts. Dewitt Spring

discharges from Paleozoic-age carbonate (limestone and dolomite) rocks to the Logan River, which is base level for ground water that discharges from this alpine region. Discharge from the spring ranges from a low flow of about 10 cubic feet per second during the winter to a peak flow of as much as 35 cubic feet per second in late spring during snowmelt runoff (Dennis Corbridge, City of Logan, written commun., 1998). Dewitt Spring discharges along the axis of a regional syncline where the Logan River breaches the structure. On the basis of discharge variation, structural geology, and dye-tracing studies, ground-water flow to the spring is probably down dip to the axis of the syncline, along solutionally-enlarged bedding planes and fractures.

The source-protection area for Dewitt Spring was delineated by using hydrogeologic mapping methods, including stratigraphic relations and structural geology (Eckoff, Watson, and Preator Engineering, 1996). Time-of-travel zones determined from calculated average linear velocity and representing 250-day and 3-year ground-water travel times were established within the delineated area (State of Utah, 1995 and fig. 1). Time-of-travel distance to the spring within these zones was determined to be about 2,300 and 10,200 feet, respectively, based on an average linear velocity of about 9.3 feet per day. Beyond the 3-year time-of-travel boundary and within the area delineated by hydrogeologic mapping, ground-water travel times were assumed to be as long as 15 years. Because time-of-travel methods are not applicable in this hydrogeologic setting, the source-protection area for Dewitt Spring was subsequently revised (1997) and all of the zones were combined into one zone delineated on the basis of hydrogeologic mapping (fig. 1).

Subsequent dye tracing to the spring indicates flow paths with considerably faster travel times than those determined by time-of-travel calculations. Maximum ground-water travel times ranging from 22 to almost 31 days were determined for losing stream reaches 3.0 to 7.2 miles upgradient from Dewitt Spring (table 2) and within the delineated source-protection area (fig. 1). These travel times also indicate that

Table 1. Hydrogeologic characteristics of diffuse- and conduit-flow components of carbonate aquifers

Aquifer characteristic	Diffuse flow	Conduit flow
Porosity	Discrete fractures; macropores; intergranular	Solutionally-enlarged fractures and partings
Ground-water movement	Dominantly laminar	Dominantly turbulent
Residence time	Months to years	Days to weeks
Hydraulic conductivity	10 ⁻³ to 10 feet per day	10 ² to 10 ⁴ feet per day
Hydraulic gradient	Moderate to high	Low; typically nearly horizontal along principal flow paths
Water table	Can be similar to that in porous media, following surface topography	Irregular; often poorly defined
Storage	Moderate to large	Small; water levels can fluctuate rapidly over large range
Discharge variability	Generally low; springs may respond to seasonal effects	High; springs respond rapidly to precipitation; peak flow typically 10 to 50 times base flow
Chemical variability	Seasonal variations in pH, water temperature, and specific conductance; water often saturated with respect to calcite	Variations in chemical parameters occur with changes in discharge; water generally unsaturated with respect to calcite
Turbidity	Generally low	Can be high with increasing discharge
Recharge	Infiltration through soils and fractures	Point-source recharge through sinkholes and sinking streams

Table 2. Summary of dye traces to Dewitt Spring, Logan Canyon, northern Utah[ft/d, feet per day; ft³/s, cubic feet per second]

Maximum travel time: Travel time calculated from initial dye recovery on activated charcoal; actual travel time probably substantially less.

Linear distance: Straight-line distance between dye-injection and dye-recovery site; actual distance probably substantially greater.

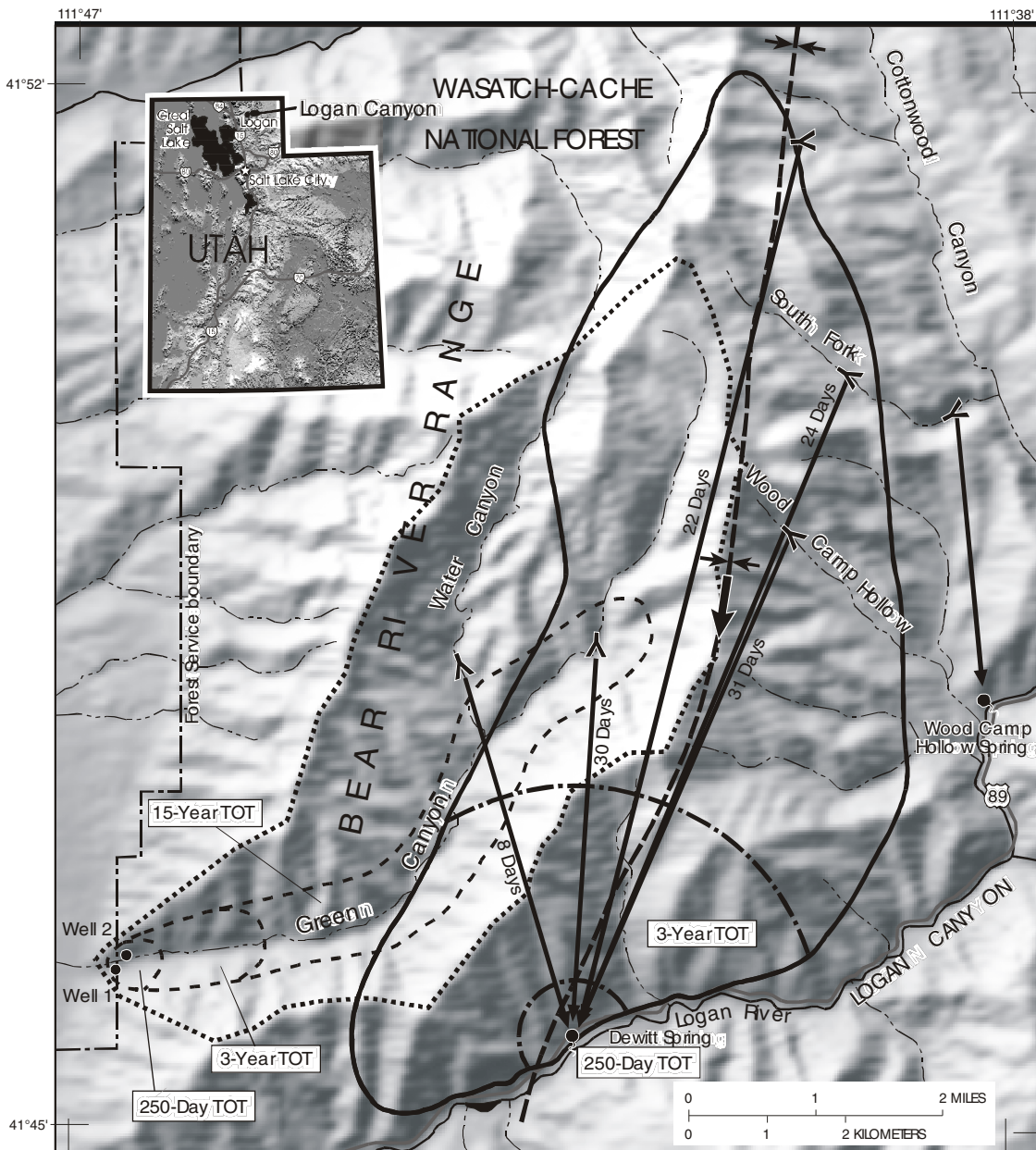
Minimum average velocity: Velocity determined from maximum travel time and linear distance; actual average velocity probably greater.

Vertical distance: Difference between altitude of dye-injection and dye-recovery site.

Spring discharge: Estimated/measured discharge of spring at time of dye injection.

Dye-injection site	Altitude (feet)	Altitude of spring (feet)	Date and time of dye injection		Amount of fluorescein dye (pounds)	
South Fork, Cottonwood Canyon	7,160	5,040	09-15-1995	1700	2.4	
Upper Wood Camp Hollow	7,120	5,040	09-13-1996	1800	2.0	
Upper Cottonwood Canyon	7,920	5,040	07-05-1998	1800	4.4	
Water Canyon	6,320	5,040	11-11-1999	1500	2.0	
Green Canyon	6,560	5,040	05-18-2002	1830	2.5	

Dye-injection site	Date and time of dye recovery		Maximum travel time (days)	Linear distance (feet)	Minimum average velocity (ft/d)	Vertical distance (feet)	Spring discharge (ft ³ /s)
South Fork, Cottonwood Canyon	10-09-1995	1745	24.0	29,550	1,230	2,120	25
Upper Wood Camp Hollow	10-14-1996	1415	30.8	22,700	735	2,080	23
Upper Cottonwood Canyon	07-27-1998	1740	22.0	38,200	1,740	2,880	28
Water Canyon	11-19-1999	1500	8.0	15,840	1,980	1,280	20
Green Canyon	06-17-2002	1935	30.0	15,940	530	1,520	33



Base from US Geological Survey, 1:100,000, Digital Line Graph data, 1984
 Digital Elevation Model 1:24,000, 1993D1998
 Universal Transverse Mercator projection, Zone 12

EXPLANATION

- Delineated source-protection area (Eckhoff, Watson, and Reator Engineering)
- - - Dewitt Spring, based on hydrogeologic mapping (1996, 1997)
- · · Dewitt Spring, based on Time-of-Travel (TOT) calculations (1996)
- - - Green Canyon wells, based on Wellhead Protection Area (WHPA) model (1999)
- · · Green Canyon wells, based on watershed topographic divide (2000)
- ↔ Axis of Logan Peak syncline — Arrows show direction of dip and plunge (from Dover, 1987)
- 8 Days ↔ Generalized direction of ground-water flow from dye-injection site and maximum travel time
- ↔ Dye-injection site (losing stream reach)

Figure 1. Source-protection areas for Dewitt Spring and Green Canyon wells and results of dye tracing.

minimum average ground-water velocities ranged from about 530 to 1,740 feet per day (table 2). Because passive (cumulative adsorption) dye-tracing methods were used, however, ground-water travel times are probably substantially shorter and velocities are greater.

Source-protection areas for two wells completed in fractured dolomite at the mouth of Green Canyon, near Logan, Utah (fig. 1), also were delineated on the basis of time-of-travel concepts (Eckoff, Watson, and Preator Engineering, 1999). The EPA semi-analytical Wellhead Protection Area (WHPA) model (Blandford and Huyakorn, 1991) was used to delineate three zones around the wells, representing 250-day, 3-year, and 15-year ground-water travel times (State of Utah, 1995 and fig. 1). Time-of-travel zones for well 2 were delineated within the zone of contribution for well 1. This model assumes that the aquifer is homogenous, and therefore, approximates a uniform, porous medium. As in the case with Dewitt Spring, time of travel based on porous-media assumptions is not applicable in this carbonate terrane, and the source-protection areas for the wells were revised (2000) and combined to include the entire Green Canyon watershed (fig. 1). The revised source-protection area for both wells was determined mostly by using topographic divides that correspond to a sixth level hydrologic unit (sub-watershed) boundary (Natural Resources Conservation Service, 2002).

Dye tracing in the mapped zone of contribution for these wells indicates that ground water flows, in part, to the southeast away from the wells, and discharges at Dewitt Spring, in the adjacent surface-water basin (fig. 1). Results of dye tracing also show that a large part of the source-protection area delineated for the Green Canyon wells probably lies within the recharge area for Dewitt Spring. Maximum travel time of ground water to the spring from the Green Canyon area during base flow was less than 8 days, with a minimum average velocity of almost 2,000 feet per day (table 2).

CONCLUSIONS

Dye tracing shows that time of travel based on porous-media (Darcian) concepts can be substantially overestimated in hydrogeologic settings where conduit flow paths are present. Although slower components of flow along diffuse pathways are present within the recharge (contributing) areas of the springs and wells and may simulate porous-media flow on a regional scale, recognition of conduit pathways is crucial in predicting the transport and fate of contaminants to public-water supplies developed in these settings. Further, source-protection areas for springs and wells in these terranes may be under or over estimated when ground- and surface-water divides are assumed to be the same. As a result, dye tracing can be used to help delineate areas that do not contribute to springs or wells, and thus, minimize the area that is necessary for source-protection management.

REFERENCES

- Blandford, T.N., and Huyakorn, P.S. 1991, WHPA 2.0: A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas: U.S. Environmental Protection Agency, Office of Ground-Water Protection, Washington, D.C.
- Dover, J.H., 1987, Geologic map of the Mount Naomi Roadless Area, Cache County, Utah, and Franklin County, Idaho: U.S. Geological Survey Miscellaneous Field Studies Map MF-1566-B, scale 1:100000.
- Eckenfelder, Inc., 1996, Guidelines for wellhead and springhead protection area delineation in carbonate rocks: U.S. Environmental Protection Agency, Groundwater Protection Branch, Region 4, Atlanta, Georgia, 127 p., 1 pl.
- Eckoff, Watson, and Preator Engineering (consulting firm), 1996; revised 1997, Drinking water source protection plan for Dewitt Spring, city of Logan, Utah; prepared for the city of Logan and submitted to the Utah Department of Environmental Quality, Division of Drinking Water, Salt Lake City, Utah.

- Eckoff, Watson, and Preator Engineering (consulting firm), 1999; revised 2000, Drinking water source protection plan for Green Canyon wells no. 1 and 2, city of North Logan, Utah; prepared for the city of North Logan and submitted to the Utah Department of Environmental Quality, Division of Drinking Water, Salt Lake City, Utah.
- Jensen, M.E., Lowe, M., and Wireman, M., 1997, Investigation of hydrogeologic mapping to delineate protection zones around springs; report of two case studies: National Risk Management Research Laboratory, U.S. Environmental Protection Agency Technical Report 600/R-97/023, 60 p.
- Mull, D.S., Smoot, J.L., and Liebermann, T.D., 1988, Dye tracing techniques used to determine ground-water flow in a carbonate aquifer system near Elizabethtown, Kentucky: U.S. Geological Survey Water-Resources Investigations Report 87-4174, 95 p.
- Natural Resources Conservation Service, 2002, Federal standards for delineation of hydrologic unit boundaries, version 1.0.
- Shuster, E.T., and White, W.B., 1971, Seasonal fluctuations in the chemistry of limestone springs; a possible means for characterizing carbonate aquifers: *Journal of Hydrology*, v. 14, p. 93-128.
- State of Utah, Department of Environmental Quality, Division of Drinking Water, 1995, Drinking water source protection rule, R309-113, 17 p.
- U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: Office of Ground-Water Protection, Washington, D.C., 186 p.
- Wisconsin Geological and Natural History Survey, 1991, Delineation of wellhead protection areas in fractured rocks: U.S. Environmental Protection Agency, Ground-Water Protection Division, Office of Ground Water and Drinking Water, Washington, D.C., 144 p.

FIELD TRIP GUIDE

Hydrogeologic Framework of the Northern Shenandoah Valley Carbonate Aquifer System

By Randall C. Orndorff¹ and George E. Harlow, Jr.²

¹ U.S. Geological Survey, MS926A National Center, Reston, VA 20192

² U.S. Geological Survey, 1730 East Parham Road, Richmond, VA 23228

Abstract

The carbonate aquifer system of the northern Shenandoah Valley of Virginia and West Virginia provides an important water supply to local communities and industry. This is an area with an expanding economy and a growing population, and this aquifer is likely to be further developed to meet future water needs. An improved understanding of this complex aquifer system is required to effectively develop and manage it as a sustainable water supply. Hydrogeologic information provided by a detailed aquifer appraisal will provide useful information to better address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on ground-water levels and instream flows, (3) the relation between karst features and the hydrology and geochemistry of the surface- and ground-water flow systems, and (4) the quality of the ground-water supply and its vulnerability to current and potential future sources of contamination. To answer these questions, a hydrogeologic framework is necessary to look at the relationship of water resources to the geology.

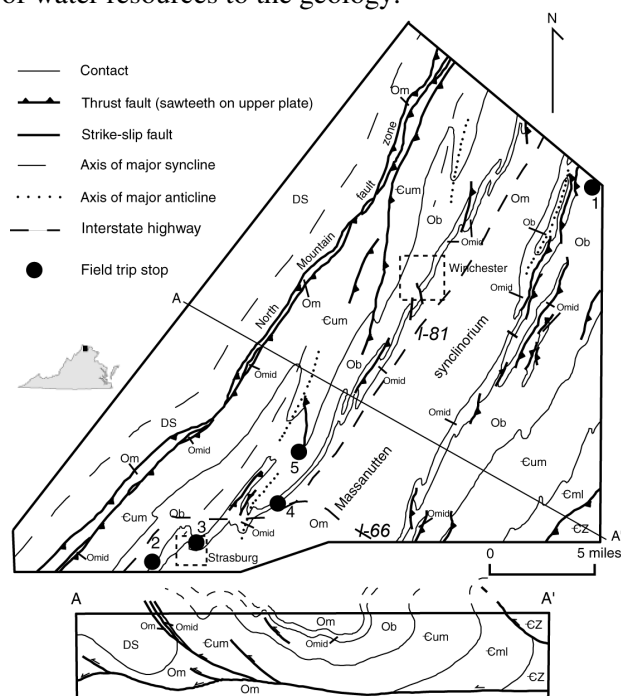


Figure 1. Generalized geologic map, and cross section of the Shenandoah Valley of northern Virginia and location of field stops. DS-Devonian and Silurian rocks; Om-Upper and Middle Ordovician rocks of the Martinsburg Formation; Omid-Middle Ordovician carbonate rocks; Ob-Middle and Lower Ordovician rocks of the Beekmantown Group; Cum-Upper and Middle Cambrian carbonate rocks of the Conococheague and Elbrook Formations; Cml-Middle and Lower Cambrian rocks of the Waynesboro and Tomstown Formations; CZ-Cambrian and Neoproterozoic rocks of the Blue Ridge Province.

INTRODUCTION

In October 2000, the U.S. Geological Survey began an investigation to better characterize the carbonate aquifer system of Frederick County, Virginia (fig. 1) and provide relevant hydrogeologic information that can be used to guide the development and management of this important water resource. This investigation forms the foundation of a regional study of the karst system that will use hydrologic and geologic information to improve the understanding of the aquifer system, its relationship to surface features, and potential hazards over a multi-county area of Virginia and West Virginia. A geologic and karst framework will aid in the understanding of how water enters the aquifer system and how ground water moves through it. Detailed geologic mapping along with fracture analyses, conduit analyses, and mapping of karst features will form this framework. This field trip will visit surface features such as sinkholes, springs, and streams, and venture into a commercial cave to look at the conduit system. We will also look at a stratigraphic section of carbonate rock to examine the various rock formations and fracture system.

GEOLOGIC SETTING

The northern Shenandoah Valley lies between the mountains of the Blue Ridge Province on the east and North Mountain to the west (fig. 1). Carbonate rocks exposed in the Valley range from Early Cambrian to Middle Ordovician in age and can be divided into belts of the eastern and western limbs of the Massanutten synclinorium. The Middle and Upper Ordovician Martinsburg Formation underlies the axis of the synclinorium. The Blue Ridge Province to the east is comprised of rocks of Proterozoic and Cambrian age that are folded and thrust faulted over the younger strata of the Shenandoah Valley. To the west, the Valley is bounded by the North Mountain fault zone; a complex thrust fault system that places the Cambrian and Ordovician units

over Silurian and Devonian units to the northwest. The rocks of the Shenandoah Valley are folded and faulted, and contain numerous joints and veins of calcite and quartz. Folds are northeast trending and are generally overturned to the northwest in the eastern limb and upright in the western limb of the synclinorium. The geology of the area of this field trip has been mapped at various scales by Butts and Edmundson (1966), Edmundson and Nunan (1973), Rader and others (1996), and Orndorff and others (1999).

KARST FEATURES

Karst in the study area is expressed by sinkholes, caves, springs, and areas of poorly developed surface drainage on carbonate rock. Lithologic characteristics, fracture density of the bedrock, and proximity of carbonate rock to streams are controlling factors in sinkhole development (Orndorff and Goggin, 1994). Sinkholes are more abundant and increase in size near incised streams. This relationship can be seen along Cedar Creek (stop 3) and the Shenandoah River. Hubbard (1983) attributed the greater development of sinkholes near streams to the steepened hydraulic gradient and increased rate of ground-water flow in these areas.

Springs in the Shenandoah Valley mostly are structurally controlled, occurring where fault planes intersect the surface. Several springs within the city of Winchester and Vacluse Spring (stop 5) are examples of this relationship. Travertine deposits are associated with many springs in the Shenandoah Valley and in areas where stream waters are supersaturated in respect to calcium carbonate.

GEOLOGIC CONTROLS ON SINKHOLE AND CAVE DEVELOPMENT

Although hydraulic gradient is the primary control on the development of sinkholes, lithostratigraphy plays a role. In

areas where the hydraulic gradient is low, carbonate rocks of the Rockdale Run Formation, Pinesburg Station Dolomite, New Market Limestone, Lincolnshire Limestone, and Edinburg Formation show higher occurrences of sinkholes than the Elbrook Dolomite, Conococheague Formation, and Stonehenge Limestone (Orndorff and Goggin, 1994). In areas with a high hydraulic gradient, this lithologic control on sinkhole development is less evident.

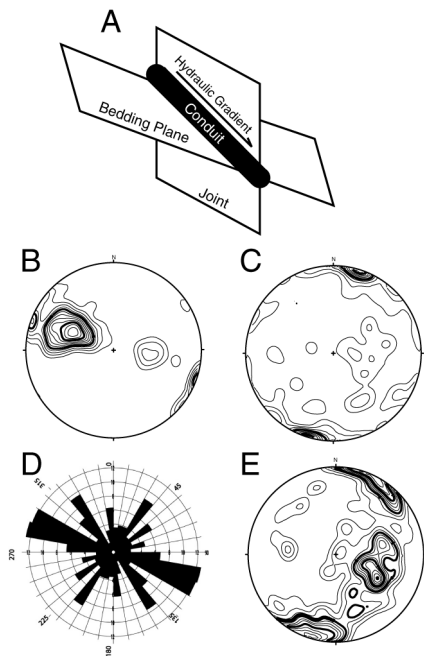


Figure 2. Diagrammatic representations of the importance of the intersection of bedding planes and joints to conduit development. A) Three dimensional diagram of the preferred location of a conduit at the intersection of two planes; B) Lower hemisphere equal area stereographic projection of poles to bedding in the Winchester area of Frederick Co., Virginia contour interval is 1 percent of 1 percent area, n=72; C) Lower hemisphere equal area stereographic projection of poles to joints in Winchester area; contour interval is 1 percent of 1 percent area, n=284; D) Compass-rose diagram showing orientation of joints in the Winchester area, circle interval is 2 percent of total, n=284; E) Lower hemisphere equal area stereographic projection of lineation defined by the intersection of bedding and joints showing shallow plunging northeast and southwest trend to the lineation and a steep southeast trending lineation, contour interval is 0.5 percent of 1percent area, n=259.

Caves occur in all of the carbonate units in the Shenandoah Valley and have formed in both limestone and dolostone. Preliminary results show that some caves form along the intersection of bedding planes with joints (fig. 2a). Therefore, it may be important to look at these linear features as a factor in conduit development locally and regionally. Geologic mapping for this study includes collecting data on fracture orientation, persistence, and intensity. Stereographic and compass-rose depiction of the orientation of bedding and joints (figs. 2b, 2c, and 2d) can be used to determine the orientation of the intersection of bedding and joints (fig. 2e). It is important to understand that conduits in conjunction with various fractures form a network that transports the water vertically to the water table and laterally through the ground-water system.

FIELD TRIP STOP DESCRIPTIONS

Field trip stops will show karst hazards (stop 1), stratigraphic sections of karstic rock (stop 2), sinkholes related to high hydraulic gradient (stop 3), relationship of structural geology to conduit development (stop 3), real-time stream gaging (stop 4), and a karst spring (stop 5).

Stop 1 – Collapse Sinkhole, Clarke County, Virginia

In November 1992, a collapse sinkhole developed in northern Clarke County that caused extensive property damage and completely engulfed a home in less than two months (fig. 3). The bedrock at this locality is limestone of the Rockdale Run Formation of the Beekmantown Group and is less than ¼ mile east of a thrust fault that places the Rockdale Run over the Martinsburg Formation (fig. 1). This collapse sinkhole is one of a series of subsidence sinkholes that form a line that trends north-northeast for nearly one mile. This sinkhole exposes 20 to 30 feet of residuum over the bedrock. Periodic visits over the years to the site has shown that the sinkhole has enlarged

laterally by several tens of feet, deepened by about 10 feet, and has exposed ever increasing amounts of bedrock along its wall.



Figure 3. Collapse sinkhole with remains of house, Clarke Co., Virginia.

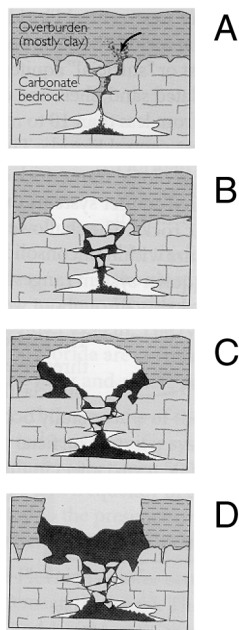


Figure 4. Diagrammatic evolution of a collapse sinkhole (from Galloway and others, 1999). A) Residuum spalls into cavity; B) Resulting void in clayey residuum produces arch in overburden; C) Cavity migrates upward by progressive roof collapse; D) Cavity breaches the ground surface creating sinkhole.

Collapse sinkholes, such as this one, occur due to failure of a soil arch in the residuum above the bedrock (fig. 4). A drop in the water table by drought or excessive

water-well pumping, can cause these mass movements. As ground water moves sediments away from the bedrock-residuum interface through enlarged fractures or conduits, a void develops in the residuum and migrates to the surface as more and more soil is removed (fig. 4). At the point where the soil arch can no longer sustain itself, the collapse occurs. Other causes of sinkhole collapse are from extended drought when adhesive properties of water are no longer active, and from extreme rainy periods when the increased soil moisture adds too much weight to the soil arch. In the case of the Clarke County collapse, about one week prior to the collapse a well driller pumped much mud from a new well in the front yard.

Stop 2 – Tumbling Run Stratigraphic Section

Rocks exposed along the road cuts at Tumbling Run, near Strasburg, VA (fig. 1), have been studied for many years as a classic stratigraphic section of Middle Ordovician carbonate rocks. This section of rock records both a tectonic and paleoenvironmental history of the Middle Ordovician and gives us the opportunity to look at the differences in some of the rock units that karst features form. This road cut also shows fractures that are instrumental in forming voids in the rock in which dissolution can occur.

The Middle Ordovician rocks at this stop record a major change in the tectonic history of North America (fig.5). Dolostone of the upper part of the Beekmantown Group exposed on the west side of the bridge over Tumbling Run was deposited in a shallow water, restricted marine (tidal flat or lagoon) environment during a time when the east coast of North America was a passive margin on the trailing-edge continental plate boundary. An unconformity occurs between the rocks of the Beekmantown Group and the overlying New Market Limestone several feet above creek level just north of the bridge. This unconformity marks the change from a

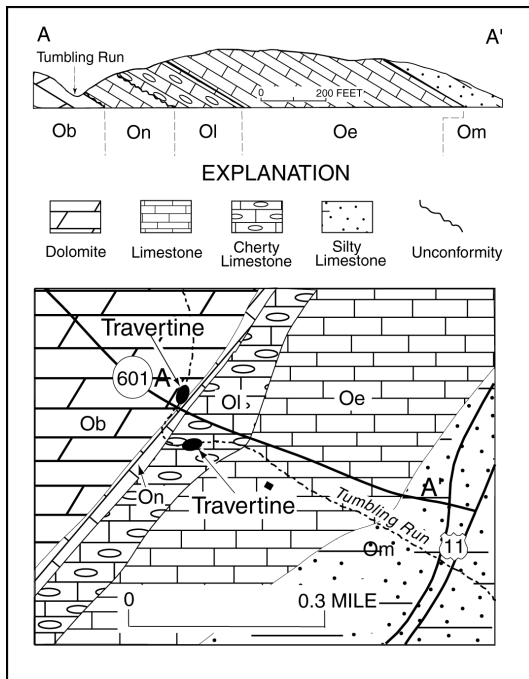


Figure 5. Cross section and geologic map of the Tumbling Run Middle Ordovician stratigraphic section. Ob, Beekmantown Group; On, New Market Limestone; Ol, Lincolnshire Limestone; Oe, Edinburg Formation; Om Martinsburg Formation.

passive margin to an active margin of a convergent plate boundary. Up section to the southeast are rocks that were deposited in progressively deeper water environments, from tidal flat and shallow subtidal marine (New Market Limestone), to open marine, shallow ramp (Lincolnshire Limestone), to deep ramp and slope (nodular facies of the Edinburg Formation), and to anoxic slope and basin (mudstone facies in the Edinburg Formation) (Rader and Read, 1989; Walker and others, 1989) (fig. 5). The overlying rock of the Martinsburg Formation were deposited in a foreland basin that was positioned between North America and a volcanic arc to the east. Volcanic ash or bentonite beds in the Edinburg Formation are evidence for the volcanic activity. A modern analog to this geologic setting is the Java Sea and other seas that exist between mainland Asia and the Indonesian volcanic arc.

Sinkholes and caves form in all of the units exposed at Tumbling Run. Although dolomite is generally less soluble than limestone, karst features do occur in the dolomite of the Beekmantown. Fractures in the carbonate rocks of the Shenandoah Valley occur as bedding plane partings and joints. The joints formed from folding and faulting associated with the Alleghanian orogeny of the Pennsylvanian and Permian. These joints, along with inclined bedding planes, form the pathways for water to move through the aquifer system and initiate dissolution.

One karst feature that occurs in the streambed of Tumbling Run is deposits of travertine. Travertine is usually associated with springs, where water supersaturated with respect to calcium carbonate reaches the surface. A combination of increased temperature and aeration as surface streams flow over rough beds causes degassing of carbon dioxide and loss of calcite supersaturation, resulting in the deposition of calcite (White, 1988). Travertine can be seen in the streambed up stream from the bridge over Tumbling Run and further down stream where water cascades over these deposits. Travertine occurs here due to small springs and seeps that occur in and near Tumbling Run (fig. 5).

Stop 3 – Crystal Caverns, Strasburg, Virginia

The area around Crystal Caverns has many sinkholes and a cave to examine the relationship of stratigraphy and structure to the conduit system (fig. 6a). The area sits on a topographic high north of the confluence of Cedar Creek with the North Fork of the Shenandoah River and the karst is related to the high hydraulic gradient. Seven sinkholes occur within a couple of hundred feet of the parking area for the caverns, many with open throats and soil piping. These sinkholes are generally subsidence sinkholes with gradual movement of

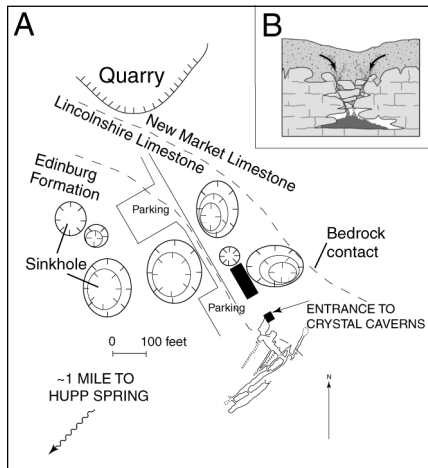


Figure 6. A) Map of Crystal Caverns area showing location of entrance, outline of cave passages projected to surface, and location of sinkholes; B) Diagram showing evolution of a subsidence sinkhole (from Galloway and others, 1999).

sediments into the underground system (fig. 6b) as opposed to the catastrophic collapse type seen at stop 1 (fig. 4). Two of the sinkholes have entrances to small caves that are developed along vertical joints in the bedrock. The active nature of these sinkholes can be attributed to their topographic position in relation to Cedar Creek, and also to the close proximity to a large abandoned quarry to the north that previously had lowered the water table in the local area. Although no dye tracing has been done here, these sinkholes are probably linked in the subsurface to Hupp Spring, which is located about one mile to the south.

The geology of this area is gently dipping Middle Ordovician limestone of the New Market Limestone, Lincolnshire Limestone, and Edinburg Formation that occur near the nose of a southward plunging anticline (Orndorff and others, 1999) (fig. 1). High calcium limestone (as much as 98 percent calcium carbonate (Edmundson, 1945)) of the New Market Limestone was mined from the quarry to the north. The contact between the Lincolnshire Limestone and Edinburg Formation runs northwesterly across the Crystal Caverns property. Like all karst regions, sinkholes can be entrance points for contamination into the

ground-water system that may include agricultural runoff (pesticides, herbicides, and animal waste), industrial pollution, underground storage tanks, landfills, and private septic systems, all of which can be found in the Shenandoah Valley. Historically, sinkholes have been used by land owners as dumping sites for waste. Slifer and Erchul (1989) estimated that there are nearly 1400 illegal dumps in sinkholes and 4600 in karst areas of the Virginia

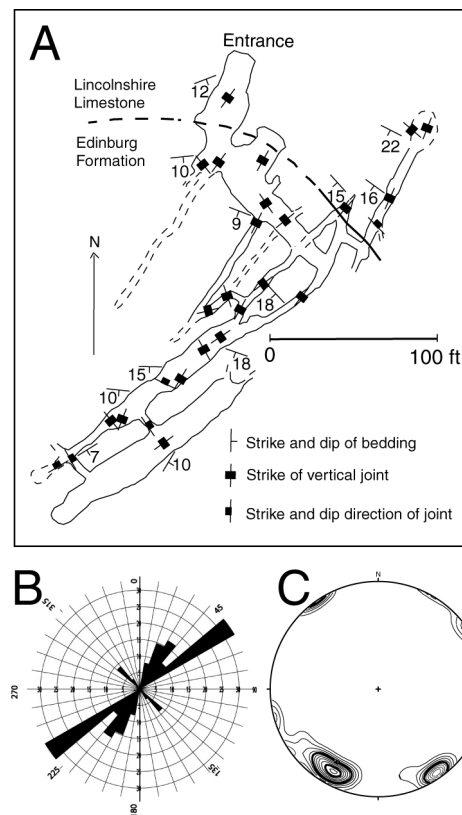


Figure 7. A) Geologic map of Crystal Caverns; B) Compass-rose diagram showing azimuth of cave passages, circle interval is 5 percent of total, n=224 ft; C) Lower hemisphere equal area stereographic projection of the lineation defined by the intersection of bedding planes and joints in Crystal Caverns, contour interval 2 percent of 1 percent area, n=28.

Valley and Ridge Province. An example of this can be seen in the sinkhole north of the caverns entrance.

The passages of Crystal Caverns are part of a conduit system that has developed mostly along joint planes and to a lesser extent along bedding planes (fig. 7a). The major northeast-trending passages parallel the local northeast-trending joint set (fig. 7b). The intersection of the joints with the bedding planes must be important to conduit development because this lineation has a major southwest trend and shallow plunge, and a secondary southeast trend and plunge that are consistent with cave passage orientations (fig. 7c).

Stop 4 – Cedar Creek Gaging Station

As part of the Frederick County carbonate aquifer appraisal, stream gages were constructed on both Opequon and Cedar Creeks in November of 2000. The gages were situated proximal to the contact between the carbonate rock formations and the shale of the Martinsburg Formation. The Cedar Creek gage at US Highway 11 near Middletown, Virginia is situated on the Stickley Run Member (Epstein and others, 1995) of the Martinsburg Formation, which is the transitional unit between the underlying limestone of the Edinburg Formation and the overlying shale of the Martinsburg Formation.

Knowledge of the base-flow characteristics of streams provides insight into the hydrogeologic flow systems of an area (Nelms and others, 1997). Mean base flow provides a measure of the long-term average contribution of ground water to streams and is commonly referred to as either ground-water discharge or ground-water runoff. The contribution to streamflow from ground-water discharge can be referred to as effective recharge (total recharge minus riparian evapotranspiration, Rutledge, 1992) (fig. 8).

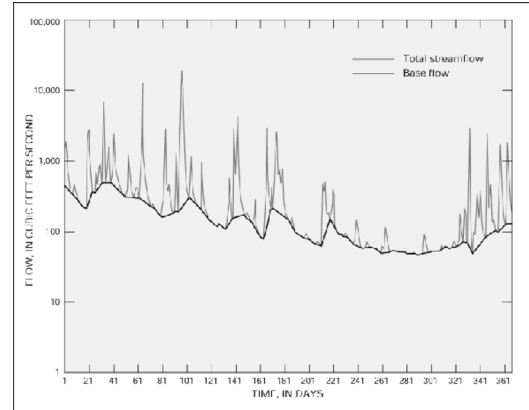


Figure 8. Example of a hydrograph showing the results of the streamflow partitioning method used to provide an estimate of effective recharge (Rutledge, 1992).

Stop 5 – Vacluse Spring

A number of large springs issue from the carbonate rock formations in the Northern Shenandoah Valley. In the past, many of these springs served as public water supplies. Until recent times, the City of Winchester obtained its water supply from a variety of springs that have included Old Town Spring, Rouss Spring, Shawnee Spring, and Fay Spring. As noted by Cady (1938, p. 67), the occurrence of many of these springs near the contact between carbonate formations of the west limb of the Massanutten synclinorium and the shales of the Martinsburg Formation suggests, "the shale obstructs the eastern movement of the ground water from the limestone and may act as a dam." Additionally, springs commonly occur near lithologic contacts and faults between carbonate rock formations. Springs are natural discharge points for water draining from the ground-water system and provide much of the base flow to streams in the area.

Vacluse Spring is a large spring issuing from the Beekmantown Group near Vacluse, Frederick County, Virginia (Cady, 1938, Pl. 4B) (fig. 9) and provides a major component of flow to Meadow Brook. Recent mapping by Orndorff and others (1999) indicates that the spring occurs

proximal to a section of the Vaucluse Spring fault where rocks of the Conococheague Formation are thrust over rocks of the Rockdale Run Formation of the Beekmantown Group (fig. 10). Several discharge measurements have been conducted at Vaucluse Spring (Table 1).



Figure 9. Vaucluse Spring issuing from the Beekmantown Group near Vaucluse, Frederick County, Virginia.

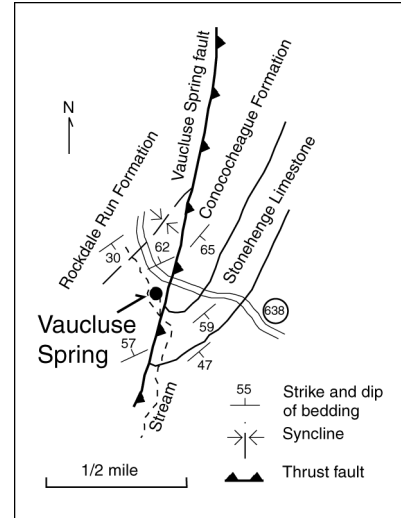


Figure 10. Geologic map of the area around Vaucluse Spring, Frederick County, Virginia (from Orndorff and others, 1999).

REFERENCES

- Butts, Charles, and Edmundson, R.S., 1966, Geology and mineral resources of Frederick County: Virginia Division of Mineral Resources Bulletin 80, 142 p., scale 1:62,500.
- Cady, R.C., 1938, Ground-water resources of northern Virginia: Virginia Geological Survey, Bulletin 50, 200 pp.
- Edmundson, R.S., 1945, Industrial limestones and dolomites in Virginia; northern and central parts of the Shenandoah Valley: Virginia Geological Survey Bulletin 65, 195 p.
- Edmundson, R.S., and Nunan, W.E., 1973, Geology of the Berryville, Stephenson, and Boyce quadrangles, Virginia: Virginia Division of Mineral Resources Report of Investigations 34, 112 p., scale 1:24,000.
- Epstein, J.B., Orndorff, R.C., and Rader, E.K., 1995, Middle Ordovician Stickley Run Member (new name) of the Martinsburg Formation, Shenandoah Valley, northern Virginia, in Stratigraphic notes, 1994: U.S. Geological Survey Bulletin 2135, p. 1-13.

Table 1: Discharge measurements at Vaucluse Spring, Frederick County, Virginia

Date	Discharge (ft ³ /sec)	Discharge (gpm)
1981/07/09	1.92*	860
1984/04/09	5.93*	2,660
1984/10/16	3.04*	1,360
1985/04/18	3.79*	1,700
2001/08/03	1.95	875
2001/08/16	1.98	890
2001/09/26	1.78	800
2001/11/27	1.56	700
2002/03/27	1.29	580
2002/05/01	1.71	770

*Historic unverified measurement.

- Galloway, Devin, Jones, D.R., and Ingebritsen, S.E., 1999, Land subsidence in the United States: U.S. Geological Survey Circular 1182, 177 p.
- Hubbard, D.A., Jr., 1983, Selected karst features of the northern Valley and Ridge province, Virginia: Virginia Division of Mineral Resources Publication 44, scale 1:250,000.
- Nelms, D.L., Harlow, G.E., Jr., and Hayes, D.C., 1997, Base-flow characteristics of streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia: U.S. Geological Survey Water-Supply Paper 2457, 48 p., 1 pl.
- Orndorff, R.C., Epstein, J.B., and McDowell, R.C., 1999, Geologic map of the Middletown quadrangle, Frederick, Shenandoah, and Warren Counties, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1803, scale 1:24,000.
- Orndorff, R.C., and Goggin, K.E., 1994, Sinkholes and karst-related features of the Shenandoah Valley in the Winchester 30' X 60' quadrangle, Virginia and West Virginia: U.S. Geological Survey Miscellaneous Field Studies Map MF-2262, scale 1:100,000.
- Rader, E.K., McDowell, R.C., Gathright, T.M., II, and Orndorff, R.C., 1996, Geologic map of Clarke, Frederick, Page, Shenandoah, and Warren Counties, Virginia: Lord Fairfax Planning District: Virginia Division of Mineral Resources Publication 143, scale 1:100,000.
- Rader, E.K., and Read, J.F., 1989, Early Paleozoic continental shelf to basin transition, northern Virginia, 28th International Geological Conference, Field Trip Guidebook T221: Washington, D.C., American Geophysical Union, 9 p.
- Rutledge, A.T., 1992, Methods of using streamflow records for estimating total and effective recharge in the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic province, in Hotchkiss, W.R., and Johnson, A.I., eds., Regional Aquifer Systems of the United States, Aquifers of the Southern and Eastern States: American Water Resources Association Monograph Series, no. 17, p. 59-74.
- Slifer, D.W., and Erchul, R.A., 1989, Sinkhole dumps and the risk to ground water in Virginia's karst areas, *in*, Beck, B.F., Engineering and environmental impacts of sinkholes and karst: Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, St. Petersburg, Florida, October 2-4, 1989, p. 207-212.
- Walker, K.R., Read, J.F., and Hardie, L.A., 1989, Cambro-Ordovician carbonate banks and siliciclastic basins of the United States Appalachians, 28th International Geological Conference, Field Trip Guidebook T161: Washington, D.C., American Geophysical Union, 88 p.
- White, W.B., 1988, Geomorphology and hydrology of karst terrains: New York, Oxford University Press, 464 p.

ⁱ Ek, David, report to the 2001 Geologic Resources Division Annual Report