Proceedings of the 18th National Cave and Karst Management Symposium

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Missouri Caves & Karst Conservancy

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World Karst	Bern Szukalski
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Banquet Speaker	Blaine Schubert
Managing Caves on Public Lands	James R. Goodbar
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Front cover logo	Bryan McAllister

Back cover photos by Michael Carter of restoration work in Fisher Cave, Meramec State Park:
Matt Tenny and Jason Hardinger clean a stalagmite to be reattached.
Jonathan Beard glues a stalagmite together.

Volunteers:

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Philip Moss
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Eugene Vale
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Joe Walsh
David Webster
Shawn Williams

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SYMPOSIUM OVERVIEW

William R. Elliott, Chairman & Editor

The 18th National Cave & Karst Management Symposium was held October 8 to 12, 2007 at the **Holiday Inn SW & Viking Conference Center**, St. Louis, Missouri. On the following pages are selected photos contributed by the editor and participants.

This was a well-attended symposium with 182 participants and a large Proceedings. Speakers presented a wide variety of talks, from the basic history of cave management in Missouri to the latest high-tech research—something for everyone! I was gratified to see cavers, managers, scientists, show cave operators, conservationists, and the public mingling all week.

On Monday Philip Moss led an **Illinois Karst trip**, and two workshops were given by Bat Conservation International's Jim Kennedy and Project Underground's Carol Zokaites. In the evening we had a welcome party with *hors d'oeuvres* and free beer from Schlafly Beer.

On Tuesday the main session began with a welcome from Bill Elliott and Jim Kaufmann, followed by a keynote address by Director John Hoskins of the Missouri Department of Conservation (MDC). Paper sessions were punctuated with ample breaks and refreshments. Lunch was served in the lobby, where sponsors displayed exhibits. Speleobooks brought a complete store. Tuesday afternoon concluded with Cave Management by Cavers and a panel discussion. On Tuesday evening we bused to MDC's **Powder Valley Nature Center**, where we held a free public event, including the *Caves in Crisis* photo exhibit and a speaker panel on the subject of *Managing Caves & Karst in the 21st Century*. Then refreshments were served in the lobby, including a "cave cake." This photo exhibit has since traveled to other Missouri nature centers, and it is available for exhibit by educators and cave conservation groups.

On Wednesday we took a bus trip to **Meramec State Park**, with a geology narrative by Jo Schaper and walking tours of **Fisher Cave** led by Brian Wilcox, park naturalist, and his staff. We also had a speleothem repair demonstration by Jon Beard and Paul Hummel, caving at **Mushroom Cave** and karst geology tours in the Hamilton Valley. We concluded the afternoon with *hors d'oeuvres* and refreshments. Some folks canoed down the Meramec River to meet us for a tour of nearby commercial **Meramec Caverns,** led by experts Tom Aley, Paul Hauck, and Dwight Weaver along with cavern guides Lee West and Ricky Barnes. A delicious dinner was served in the cave ballroom, prepared by caverns staff and owners Judy and Les Turilli, followed by a slide show about the restoration of nearby Bat Cave #1. Readers should know that Meramec Caverns was backflooded by the Meramec River in the spring of 2008, severely affecting their business. Feel free to send Judy and Les a note of appreciation at jat@fidnet.com, Meramec Caverns, Hwy W, Stanton, MO 63079, phone 573-468-3166.

Evenings at the hotel were full of convivial discussions and fun. We had a full day of sessions on Thursday, ending with a special showing of the video *Caves: Life Beneath the Forest*. There was a big poster session, then a banquet that evening with a wonderful speaker, Dr. Blaine Schubert, East Tennessee State University, who spoke on *Cave and Karst Paleontology in North America*. Marcelo Kramer was recognized as having the most comprehensive student poster on the caves of Rio Grande do Norte State, Brazil. Two of the posters were developed into papers for this volume.

Friday concluded with an Urban Karst session and an afternoon **Urban Karst field trip**, led by Dr. Bob Criss, Washington University. We carpooled and visited points around St. Louis, which sits on a karst that has been generally poorly managed for 200 years. We visited springs, sinkholes, and the entrance of **Cliff Cave**, ending up at the Mississippi River. This visit later prompted me to conduct bat studies in the cave in cooperation with St. Louis County Parks.

This Proceedings volume has a photo album and other new features. Besides the printed index for this symposium, the included CD contains my general index and annotated bibliography of all NCKMS conferences since they began in 1975. To date, NCKMS has published 769 papers and abstracts and more than 3,700 pages of scientific and management information, an important body of literature for cave and karst managers, conservationists, and scientists. One might think that all has been said on this subject, but over the years new technologies have been brought to bear on management problems, so many of the papers have become more technical and less conceptual/philosophical. Earlier authors pondered basic questions like "What is cave management?," "What is cave wilderness?," and how to classify caves or define the limits on the number of visitors ("carrying capacity"). Today's authors are working to actually measure, evaluate, and control human-caused changes in cave and karst resources. Please check the summaries of the symposia in the bibliographic spreadsheet to see how we have progressed.

Many thanks to all our sponsors, staff and participants for a wonderful symposium! Please feel free to contact the editor for further information.

William R. Elliott

A PHOTO ALBUM OF THE 2007 SYMPOSIUM

Photos by William R. Elliott, Marcus Buck, Bob Currie, and Brian Andrich.

Philip Moss at Falling Spring Cave, during the Illinois Karst Field Trip, NCKMS, Oct. 8, 2007. By Marcus Buck.

Lunch was served in the lobby outside our meeting room.

The Caves in Crisis Photo Exhibit was shown at Powder Valley Conservation Nature Center.

Bryan McAllister displays his artwork

Participants and the public listen to the Speaker Panel: Managing Caves & Karst in the 21st Century.

Panelists left to right: George Veni, Tom Aley, Jim Kennedy, Jim Kaufmann, David Ashley and Conservation Commissioner Don Johnson. Photo by Bill Elliott, moderator.

The introductory panel for the photo exhibit.

The photo exhibit has traveled to other nature centers.

Wednesday, Oct. 10, field trip to Meramec State Park. These cavers went in Mushroom Cave.

Our cave cake, cooked up by Powder Valley.

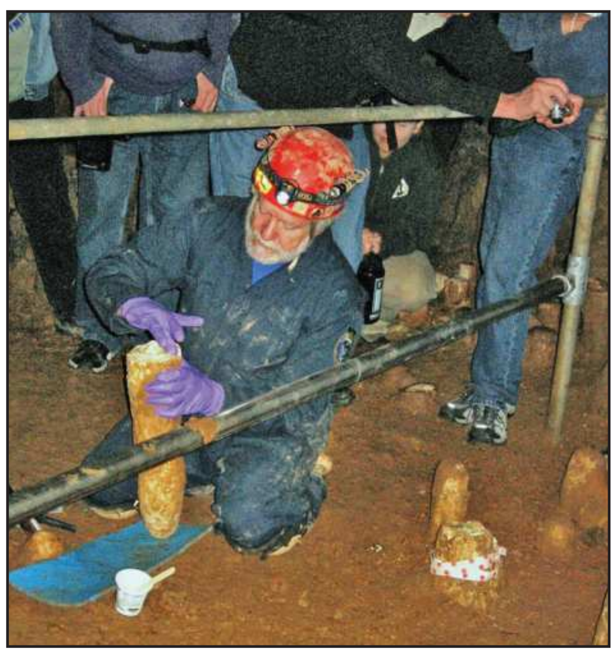
Some brought a little of Mushroom Cave out on their boots and coveralls.

Tom Aley (left) and Jim Baichtal (right), two experts on Alaskan and other karst

The tour of Fisher Cave looks at the old gate, which was removed for a more bat-friendly gate.

Have you ever seen so many cavers in a cave without helmets? But helmets weren't needed in Fisher Cave.

Jonathan Beard explains how he restores speleothems.

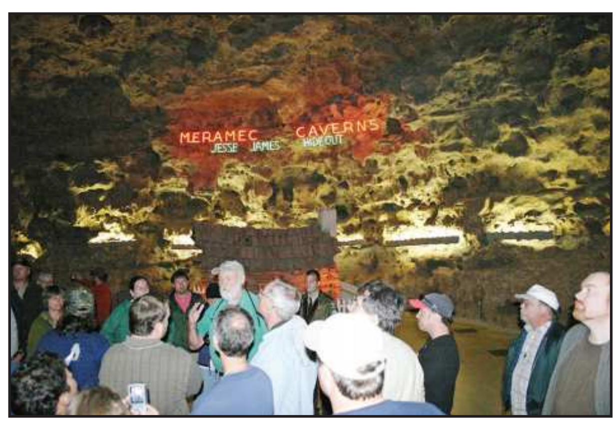


Jonathan Beard restores a broken stalagmite in Fisher Cave. By Bob Currie.

Jonathan Beard and Paul Hummel glue a broken stalagmite back together.

Paul Hummel washes a muddy flowstone area with a backpack sprayer and water in Fisher Cave. By Bob Currie.

Bill Elliott in Fisher Cave. By Bob Currie.



Tom Aley leads a tour of NCKMS 2007 cavers through Meramec Caverns.

The Stage Curtains, Meramec Caverns.

Participants in the Ball Room at Meramec Caverns. By Brian Andrich

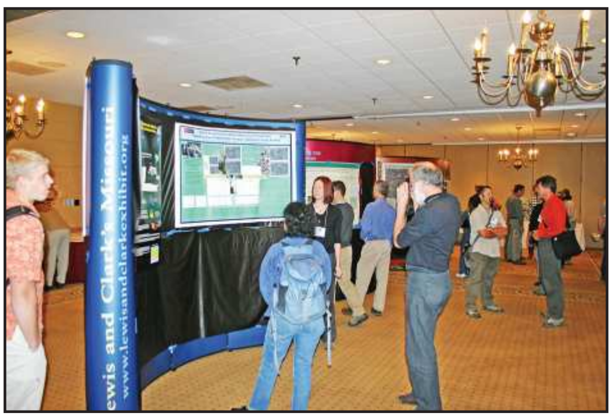
Participants in the Ball Room at Meramec Caverns. By Brian Andrich.

Participants in the Ball Room at Meramec Caverns. By Brian Andrich.

Meramec Caverns cartographer and expert Paul Hauck is at front row center with the white binder. By Brian Andrich

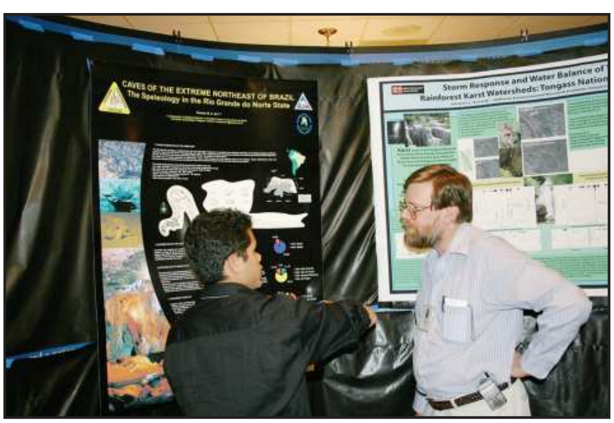
Left to right: Joe and Lois Walsh with our Meramec Caverns hosts, Judy and Les Turilli. By Brian Andrich.

Left to right: Tom Aley, Bill Elliott, Jim Kaufmann, H. Dwight Weaver and Mrs. Weaver at dinner in Meramec Caverns. By Brian Andrich.

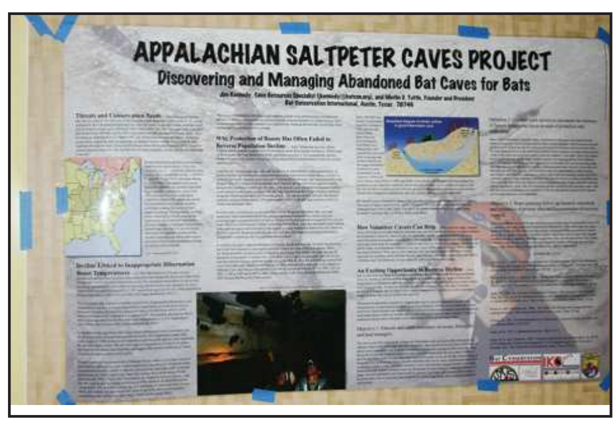


The poster session was spaciously presented and well-attended. We only wish we could include all of the posters in this Proceedings.

Left to right: Meramec State Park staff Eric Otto, Jody Miles, and Brian Wilcox. Julie Healey on the right. By Brian Andrich.

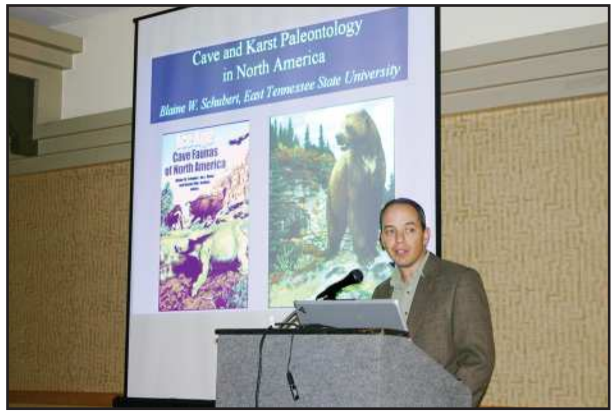


Marcelo Kramer explains his award-winning poster on Brazil to Philip Newell.



A poster by Jim Kennedy and Merlin Tuttle, Bat Conservation International.

A poster by Johanna Kovarik on Alaskan karst.



Blaine Schubert presented a fascinating and humorous banquet speech on Thursday night.

Bob Criss, Washington University (foreground), led us on an Urban Karst field trip Friday afternoon. First stop: The old Rott Springhouse, which has witnessed many groundwater changes since the early 19th Century.

Patricia Beddows ponders how to get into the St. Louis karst via a culvert.

Cliff Cave was a good stop for discussion of how we might improve cave and karst management in St. Louis. A new cave gate may result from the follow-up studies there.

3D DATA COLLECTION FOR CHARACTERIZATION OF BAT HABITAT

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Abstract

Ground-based LIDAR (**Li**ght **D**etection **a**nd **R**anging) units currently are too costly and bulky for effective use in the cave environment. A tripod-mounted Impulse 200 laser rangefinder system allowed us to collect over 1,200 3D data points in just three days of field work. All data points were entered into the WALLS cave survey program and exported to a GIS for creation of a 3D model of the cave environment. The finished product was viewable in both Acrobat 3D PDF format as well as Google's SketchUp software. Future projects include the ability to digitally transfer data while in the cave and incorporation of traditional survey techniques for fine tuning the 3D model.

Key words: cave mapping, cartography, LIDAR, Impulse 200 laser rangefinder, Gruta de Consuelo, Mexico

Introduction

Traditional cave maps often concentrate on floor detail at the expense of other information. This technique often overlooks both existing and potential bat habitat. In early 2007 Bat Conservation International contracted Zara Environmental LLC to investigate and prototype a new laser rangefinder method for data capture and visualization to better understand bat habitat.

LIDAR (**Li**ght **D**etection **a**nd **R**anging) is a technology similar to RADAR that can be used to create high-resolution digital elevation models (DEMs) with vertical accuracy as good as 10 cm. The laser scanner transmits brief laser pulses to the ground surface, from which they are reflected or scattered back to the laser scanner. Detecting the returning pulses, the equipment records the time that it took for them to go from the laser scanner to the ground and back. The distance between the laser scanner and the ground is then calculated based on the speed of light (USGS 2008). Conventional, ground-based LIDAR is used to frame and automatically map a three-dimensional space or object. The unit we used is a simpler, rangefinder LIDAR unit. Unlike the automatic units which "paint" the scene with datapoint, the rangefinder unit must collect each data point individually.

Materials and Methods

Gruta de Consuelo, Coahuila, Mexico, was surveyed in January 2006 using traditional cave mapping techniques (Dasher 1994) and symbols. Survey stations were established and distances were measured between them with a fiberglass tape. Inclinations and azimuths were measured with Suunto clinometer and compass. A sketch of the cave was made in plan and profile views. Baseline survey data were entered into the Walls cave mapping program (free download from Texas Speleological Survey 2008). A line plot was created and sketches aligned around it as a pencil drawing. The completed map was digitized from this pencil draft using the open source drawing program Inkscape (2008) The native file format for Inkscape is Scalable Vector Graphic (SVG), which is directly exportable from Walls.

Field work conducted in January 2007 built upon the map created in 2006. Survey stations were relocated and made permanent by drilling and installing steel anchors. Some additional passages were surveyed and added to the existing cave map, as well as many more cross sections. A tripod-mounted, Impulse 200 laser rangefinder (Figure 1) with distance, azimuth and clinometer capabilities was used to manually measure an additional 1,200 stations on walls, floor and ceiling (Figure 2). The Impulse 200 laser unit was chosen for its small size, waterproof characteristics and overall extreme ruggedness (Figure 3). The laser wavelength is outside of the visible spectrum. We obtained a "point cloud" that represented the shape of the cave passage. These additional stations were added to the survey in Walls. Stations were classified as to whether they represented ceiling, walls or floor, then exported as an ESRI compatible shapefile. We experimented with a number of computer programs for developing the model, including Rhino 3D, ArcGIS, and Blender. Ultimately we used a CAD program (MicroStation) to build the polygon mesh by connecting the survey stations, which form the "skin" of the model. The model was exported from MicroStation's native DGN format to an AutoCad DWG file. Other formats were also exported, such as a 3D PDF file and Google's free SketchUp (2008) software.

Results

Two products have resulted from this project, a standard cave map of Gruta de Consuelo, and a 3D model. The cave map consists of plan, profile and cross section views. The survey stations are included in this map, as they can be used to locate roost areas by future researchers. Since the three main cave passages form a triangle shape, three different profile views were used to best depict these passages. Map files are in SVG, which can be read by a number of programs including Adobe Illustrator, Internet Explorer, Mozilla Firefox and others. However these files are best manipulated in the program which created them, Inkscape. Versions of these cave map files are also provided in PDF (two-dimensional) format.

Figure 1 Lasertech Impulse 200 laser rangefinder. Image courtesy of Lasertech (2008).

The 3D cave model is composed of a collection of joined polygons that form a low-resolution representation of the cave (Figure 4). This model can be rotated, panned and zoomed utilizing the PDF files viewed in version six or newer of Adobe Acrobat, which supports 3D viewing. The model is also provided in DWG format, a common CAD file format. Both the DWG file and Walls three-dimensional, point-cloud shapefiles can be imported to ArcGIS, as well as any

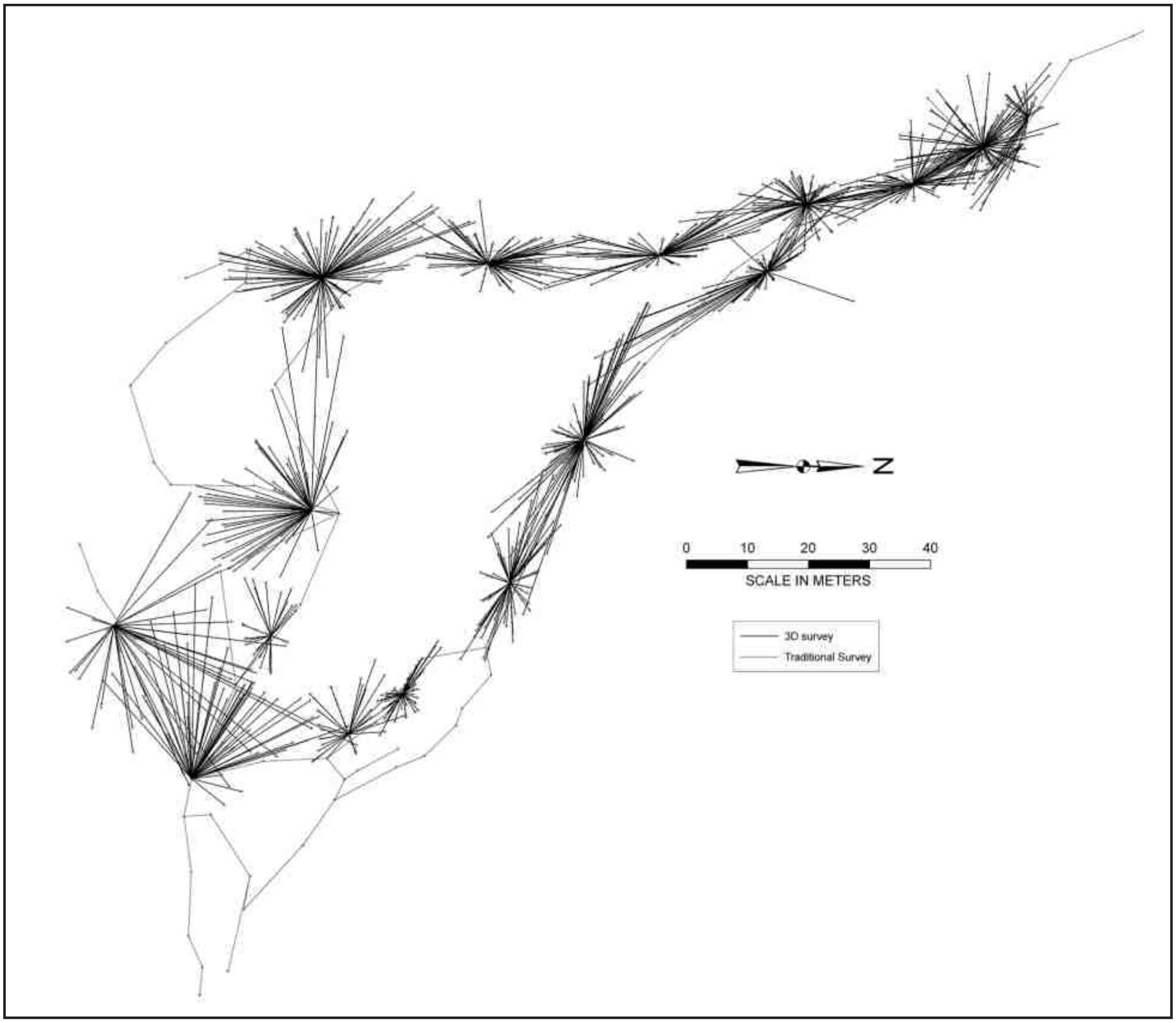

Figure 2 The laser rangefinder took 1,200 survey stations in Gruta de Consuelo, Mexico.

number of other graphics environments. A third format provided here is designed to be used in Google's SketchUp software, a free downloadable program. This user-friendly software can be used to mark bat usage on areas of the model.

Discussion

This project is an experimental one, designed to test methods for delineating bat roosts on irregular surfaces of cave walls. It is likely that the methods used here will be further developed in future projects, in which smoothing techniques could be used to create a more realistic model. While there are other methods currently available for making higher resolution 3D models of caves, such as conventional, ground-based LIDAR, which costs about $100,000, the method used here is quite economical, about $1,000. A model has been created which can now be used to mark bat roosts in an environment such as Google SketchUp.

Acknowledgments

Bat Conservation International provided support for this project.

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Dasher, G. 1994. On Station: a complete handbook for surveying and mapping caves. National Speleological Society, Huntsville. 242 pp.

Figure 3 Aaron Addison configures the Impulse 200 laser unit.

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Lasertech. 2008. http://www.laser-tech.com/Impulse200Spec.pdf

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USGS. 2008. http://vulcan.wr.usgs.gov/Monitoring/LIDAR/description_LIDAR.html

Figure 4 The 3D model of Gruta de Consuelo

CAVE TERRAIN GUIDELINES: A TOOL FOR CAVE RESCUE AND PARK VISITOR MANAGEMENT

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Abstract

Cave rescue callouts are very rare in Canada and even rarer in National Parks of Canada. None the less, Parks Canada public safety rescue leaders in western National Parks need a tool to help them deploy the appropriate resources for the incident.

When a call comes for a cave rescue, Parks Canada depends upon the assistance of volunteer cave rescue groups like British Columbia Cave Rescue and Alberta Cave Rescue Organization. Members of these groups may have response times of one to eight or more hours. Parks Canada can, in certain situations, be able to make an initial response with Park Wardens to assess the incident and stabilize a patient before external resources arrive.

In order for rescue managers to have sufficient knowledge about the specific cave hazards and skills required, a matrix of cave-terrain guidelines has been developed. Each known park cave will be evaluated to provide enough information for the rescue leader to comfortably deploy local (Park Wardens) and remotely located personnel. Some of the factors considered include, map availability, cave length, navigation difficulties, hazards, travel skills and equipment required. The matrix format was adopted from the Parks Canada Avalanche Terrain Exposure Scale (ATES). Although a much different environment, ATES had much to offer from its presentation structure.

There may be application of these guidelines to help park visitors determine if their abilities and experience are compatible with the cave they may wish to visit.

Key words: cave rescue, caving safety, British Columbia, Alberta, Parks Canada

Introduction

The national parks of the western Canadian cordillera (Rocky and Columbia Mountains) have approximately 100 known caves. The potential for more caves to be discovered is considerable. A draft, three-tier classification system (Horne 2005) is proposed to manage the level of public access. Although this classification system addresses general safety concerns, it does not record enough detail to be useful for an actual cave rescue response.

Parks Canada, the agency responsible for the management of Canada's national parks, does not have a formal cave rescue capability. This is because of the extremely rare occasion to carry out this type of rescue. The agency does have extensive technical rescue preparedness in the areas of high angle rock or ice, crevasse, avalanche, swiftwater and helicopter sling rescue. All these technical specialities require dedicated training and equipment. Adding technical cave rescue to the list is not a realistic option.

Parks Canada relies on the volunteer groups British Columbia Cave Rescue and Alberta Cave Rescue Organization to perform major cave rescues. Park Wardens have been sent to their training courses. The purpose of park staff attending the courses is to build contacts, learn skills and understand the volunteer incident command structure. Any cave rescue in a national park will involve logistical support by Parks Canada. The better the understanding and cooperation between volunteers and the land manager, the more likely it will be a safe and successful rescue mission.

Location and Its Complications

Most of the western Canadian national parks developing this strategy (Jasper, Banff, Kootenay, Yoho, Waterton Lakes, Glacier and Mount Revelstoke) are situated away from large urban centers. The cave rescue volunteers, for the most part, live several hours to a full day's drive from a national park. The time to get volunteers to a cave entrance can delay an expedient response. With cave temperatures of the region averaging 2-3° C, hypothermia will always be an urgent concern, even for the most minor injury.

First Response

Is it possible for Park Wardens to perform some basic reconnaissance, patient assessment and stabilization before out-of-park rescue resources arrive? It will depend upon the cave location, its access considerations, difficulty of the cave, equipment available and skills of the wardens. For the rescue leader, especially one not familiar or interested in caves, a summarized description of the terrain difficulties of the cave where a rescue or search is required becomes extremely important.

After listing the factors or conditions in a cave that a rescuer or rescue leader would want to consider, it became clear Parks Canada already had an assessment format that could be adapted to the cave environment. In February 2003, a school group of 17 students and teachers who were backcountry skiing was caught by an avalanche in Glacier National Park, British Columbia. Ten people were saved by another ski party of two who just happened to witness the slide. The ensuing shock waves this incident caused through the avalanche forecasting community, public land managers and backcountry users was significant. One of the positive results of this tragic accident was the Avalanche Terrain Exposure Scale (ATES), a new development from Parks Canada, which offers an avalanche classification system based on the landscape—not the snow (Statham et al. 2006)

ATES is a clearly presented classification or rating system of avalanche terrain for both the land manager and the backcountry user. These ratings are intended to supplement pre-trip planning material.

Table 1. Avalanche Terrain Exposure Scale (ATES) v.1/04, the public communication model developed by Parks Canada.

Description	Class	Terrain Criteria
Simple	1	Exposure to low-angle or primarily forested terrain. Some forest openings may involve the runout zones of infrequent avalanches. Many options to reduce or eliminate exposure. No glacier travel.
Challenging	2	Exposure to well-defined avalanche paths, starting zones or terrain traps; options exist to reduce or eliminate exposure with careful route-finding. Glacier travel is straightforward but crevasse hazards may exist.
Complex	3	Exposure to multiple, overlapping avalanche paths or large expanses of steep, open terrain; multiple, avalanche-starting zones and terrain traps below; minimal options to reduce exposure. Complicated glacier travel with extensive crevasse bands or icefalls.

This means reading guidebook descriptions, studying maps and photos, talking to friends, checking weather and avalanche conditions, and referring to the ATES ratings while planning the trip. Two models of the ATES are available, a public communication model (Table 1) (http://www.pc.gc.ca/pn-np/ab/banff/visit/visit7a1_E.asp, Parks Canada 2005) is designed for communicating general concepts to the public, who is largely unable to comprehend the technical details, and a technical model (Table 2) (http://www.pc.gc.ca/pn-np/ab/banff/visit/visit7a7_E.asp#tech, Parks Canada 2005) designed for users trained and skilled in the subtle nuances of avalanche terrain.

The Cave-terrain Guidelines uses the technical model format of ATES. Public safety Park Wardens are already very familiar and comfortable with ATES. Therefore, to adopt a similar format for the cave environment would mean a higher degree of acceptance and use.

Cave-terrain Factors To Consider

These factors will influence the seriousness of a rescue and/or the complications users may encounter leading to the need for assistance. This list should be considered "a work in progress" with additions or subtractions as the guideline matrix is implemented in the field.

Table 2. Avalanche Terrain Exposure Scale (ATES) v.1/04, the technical model developed by Parks Canada. Using this scale: Any given piece of mountain terrain may have elements that will fit into multiple classes. Applying a terrain exposure rating involves considering all of the variables described above, with some default priorities. Terrain that qualifies under an italicized descriptor automatically defaults into that or a higher terrain class. Nonitalicized descriptors carry less weight and will not trigger a default, but must be considered in combination with the other factors.

	1 - Simple	**2 - Challenging**	**3 - Complex**
Slope angle	Angles generally < 30°	***Mostly low angle, isolated slopes >35°***	***Variable with large %, >35°***
Slope shape	Uniform	Some convexities	Convoluted
Forest density	Primarily treed with some forest openings	Mixed trees and open terrain	Large expanses of open terrain. Isolated tree bands
Terrain traps	Minimal, some creek slopes or cutbanks	Some depressions, gullies and/or overhead avalanche terrain	***Many depressions, gullies, cliffs, hidden slopes above gullies, cornices***
Avalanche frequency (events:years)	1:30 ≥ size 2	1:1 for < size 2 ***1:3 for ≥ size 2***	1:1 < size 3 ***1:1 ≥ size 3***
Start zone density	Limited open terrain	Some open terrain. Isolated avalanche paths leading to valley bottom	Large expanses of open terrain. Multiple avalanche paths leading to valley bottom
Runout zone characteristics	Solitary, well defined areas, smooth transitions, spread deposits	Abrupt transitions or depressions with deep deposits	Multiple converging runout zones, confined deposition area, steep tracks overhead
Interaction with avalanche paths	Runout zones only	Single path or paths with separation	***Numerous and overlapping paths***
Route options	Numerous, terrain allows multiple choices	A selection of choices of varying exposure, options to avoid avalanche paths	***Limited chances to reduce exposure, avoidance not possible***
Exposure time	None, or limited exposure crossing runouts only	***Isolated exposure to start zones and tracks***	***Frequent exposure to start zones and tracks***
Glaciation	None	***Generally smooth with isolated bands of crevasses***	***Broken or steep sections of crevasses, icefalls or serac exposure***

- **Natural Light.** Many of the national park caves are short, in fact short enough that daylight might extend into a significant part of the cave. Obviously, this factor when present, will assist a rescue.
- **Resource Protection.** The more delicate and situated cave resources are in regards to a rescue, the more effort and expertise will be required to minimize impact and carry out protective measures.
- **Air Quality.** Although there are no known national park caves with a deadly air quality environment, it is worthwhile to cover this topic and raise awareness of its importance. Dust concerns due to mineral and/or organic materials are a reasonable hazard to consider in some caves.
- **Map.** A well-drafted cave map will indicate rappel and climb heights or drops. This information can be used to build a tackle list when needed. A complex cave may make a map a necessity for a team unfamiliar with it.
- **Maximum Distance From Entrance.** Greater distances from the nearest accessible entrance will escalate the difficulty of a rescue, human waste management and travel times.
- **Passage complexity.** This factor considers the possibility of navigation errors leading to wasted time, becoming lost or overdue. Additionally, complex caves will require much more time or personnel to adequately search for overdue cavers.
- **Rock Fall—Natural or User-caused.** This factor can be the cause for a rescue or seriously threaten the rescue mission. In a cave with a known high hazard, extra precautions are worth making.
- **Flooding.** The possibility and predictability of flooding may be relevant in regards to overdue parties and/or affect safety of rescuers.
- **Water Travel.** In Canada cave water temperatures are typically cold. Hypothermia is a concern. The inability to keep dry will influence both user and rescuer. Swimming ability and personal floatation may need consideration. The required clothing for safe and comfort travel is covered under a separate terrain factor.
- **Rope Use—In Cave or to Access.** This factor will determine the technical training, experience and equipment required to access the entrance and/or move through the cave. Although ropes may be rigged by the party needing search or rescue assistance, an ability to evaluate their integrity is still needed.
- **Climbing—Unroped in Cave or Access.** This factor will determine the experience and judgement required to access the entrance and/or move through the cave safely. Surface conditions that are less than ideal, altered by rain or snow, may change an easy approach to an entrance into an on-rope event.
- **Stem/Bridge.** Caves can present stemming or bridging terrain with a degree of difficulty, exposure and length that tax users or rescuers both mentally and physically. In a rescue situation, this terrain very likely will result in rope use where it normally was not needed. It may present terrain requiring huge amounts of time, personnel and equipment to safely move an immobile patient.
- **Crawl.** The length and roughness of the cave floor will determine the significance this terrain factor has on travel time. Cave formations, where present, are subject to more accidental damage by this activity.
- **Squeeze.** Squeezes can be a serious barrier to move immobile patients, rescuers not comfortable in the cave environment and size of the rescuer.
- **Technical Equipment.** The more technical equipment required to travel safely, the greater the barrier to hasty searches and reconnaissance situation checks. Level of training and experience become important as the amount and type of gear increases.
- **Clothing.** Easy, simple caves can be visited with little or no special clothing. Or a complex cave may require personally fitted wetsuits and/or other cold/aquatic items. The type of clothing needed, its storage location and availability will influence response times and personnel selection.

Cave-terrain Categories

Each of the previously described cave-terrain factors is described in three categories: Simple, Challenging, and Complex (Table 3). The text descriptors chosen convey the general sense of seriousness, severity or importance of the factor. Minimal speleo-vocabulary was used on purpose to facilitate broad user understanding.

- **Simple Cave.** These caves are friendly, have few surprises and few consequences from poor trip planning or technique. They will typically be short in length, not need special clothing, at the most require only easy handlines and no map. This category of cave would be a reasonable location for Park Wardens trained in mountain rescue to conduct a reconnaissance check with regards to overdue or injured cavers. Potentially, the wardens would be able to complete a rescue without assistance from volunteer rescue organizations.
- **Challenging Cave.** One needs to know what one is doing to safely travel in a challenging cave. There may be the requirement for single-rope technique (SRT), suitable protective clothing for the cave may be needed, multiple factors may have serious injury or deadly consequences and injuries could lead to hypothermia. Park Wardens with extensive mountain-rescue and caving experience may be able to reach a patient to assess and stabilize, but possibly the terrain may be beyond local in-park capabilities. Out-of-park rescue assistance is a high probability unless the situation were very straightforward.
- **Complex Cave.** The seriousness of the terrain factors prevailing in a challenging cave only get more pronounced in a complex cave. Out-of-park rescue assistance, particularly for patient movement, is a near certainty. Screening of public users for this category of cave is crucial for accident prevention.

Cave-terrain Defaults

Cave terrain that qualifies under a **bolded** descriptor in Table 3 automatically defaults into that or a higher terrain category matrix. Non-bolded descriptors carry less weight and will not trigger a default, but must be considered in combination with the other factors. The same principal is used with ATES (Table 2). These defaults are particularly important when most descriptors are rated as Simple terrain, and it would appear the cave's overall evaluation would be a Simple category as well. However, one or more critical descriptors are Challenging or Complex enough that their importance shifts the overall rating to a higher category. Table 4 illustrates as an example how Lost Light Cave primarily scored Challenging factors, yet there is one factor rating complex, stem/bridge. This Complex factor puts the cave's overall rating as Complex. The underlying factor of these bolded descriptors is the potential for significant bodily harm or death if conditions and/or actions go bad. The bolded descriptors are all situations where rescue personnel or public users must know what they are doing—trained and experienced in other words.

Cave Evaluation to Determine Category

The objective is to complete the cave evaluation before it is needed (Table 4 example). Ideally, the evaluator has personal knowledge of the cave. The larger the territory, the more unrealistic this scope of expertise will be. Other first-person knowledge is preferred. One can ask assistance from local cavers and/or by contacting regional speleological groups. Detailed written trip reports, other literature, drawn surveys and second-hand sources can be used if nothing better exists. It is useful to record the source of cave knowledge for each evaluation.

Integration of the cave-terrain evaluation with other information about a specific cave would be an ideal scenario. Then, one-stop shopping could take place when there is an incident. Where the cave is located, how to access it, resources at risk, maps, local knowledge and the cave-terrain category etc. could all be found in one database. However, information security for various reasons may force separation of information. If this is the case, a one-page text summary covering the critical information required by a rescue leader or land manager needs to be attached with a completed evaluation matrix.

Use of the Cave-terrain Guidelines for Pre-Trip Visitor Planning

Although originally developed as an in-house tool to assist staff with cave search and rescue, the cave-terrain guidelines have possible application in public, pre-trip planning. If used to its full potential, the guidelines may prevent a public safety incident from occurring.

Regardless of sport, there is a portion of park users who know the activity they wish to partici-

Table 3. Cave-terrain Guidelines generic matrix (version 5.0, Nov/2007). If any factor scores in the bold cave-terrain categories, then the minimum default rating for the cave will be the same.

Factor \ Category	Simple	Challenging	Complex
natural light	present for significant portion of cave	present for small portion of cave	present for very small portion of cave
resource protection	there are few or no known resources at risk	some resource protection concerns should be addressed during travel	there significant resource protection measures to be taken during travel
air quality	good	good but may have sections with dust concerns	**significant health concerns—dust, dead air or high CO_2**
map	not required	very useful	necessary
maximum distance from entrance	<100m	100–500m	>500m
navigation	none or few junctions or loops	several junctions or loops	many junctions or loops
rockfall - natural or user caused	low potential	some potential	probable unless very careful
flooding	none	predictable and or low consequences	**unpredictable and or serious consequences**
water travel	none or shallow wading	**deep wading, easy swim, and or climbing/rappel in waterfalls**	**lots of wading and or swiftwater, climbing/rappel in waterfalls and or diving**
rope use, in cave or to access	none or easy to rig handlines	**simple rappels <50m, anchors secure**	**rappels >50m, awkward lips, rebelays, deviations, anchors questionable**
climbing, unroped in cave or access	none or less than 3 m	**some, consequences of fall serious**	**some to lots, consequences of fall fatal**
stem/bridge	none or few moves	**longer easy sections or short with moderate fall consequences**	**short to long sections with fall consequences serious to fatal**
crawl	none or short and easy	considerable distances of low and or uncomfortable	very long sections of low and or uncomfortable
squeeze	none or very easy	some moderately tight or awkward places	**many and or some very tight, awkward or unstable**
technical equipment	none	basic SRT equipment,	SRT, aid gear, dive gear
clothing	none special or coveralls	heavy duty coveralls, wet suits, rubber boots/neoprene socks	heavy duty coveralls, dry suits

Table 4. Cave-terrain Guidelines for Lost Light Cave in Jasper National Park (grayed cells). The overall rating of the cave is complex because the stem/bridge factor is a default complex descriptor. If any factor scores in the bold cave-terrain categories, then the minimum default rating for the cave will be the same.

Category / Factor	**Simple**	**Challenging**	**Complex**
natural light	present for significant portion of cave	present for small portion of cave	present for very small portion of cave
resource protection	there are few or no known resources at risk	some resource protection concerns should be addressed during travel	there significant resource protection measures to be taken during travel
air quality	good	good but may have sections with dust concerns	**significant health concern—dust, dead air or high CO_2**
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pate in, but do not really know where they want to go. Another group of users has unrealistic trip goals based on their skills, seasonal conditions and experience. Both of these types of users could benefit from the detail provided by the cave-terrain guidelines evaluation. Also, park staff that are tasked with providing pre-trip planning advice to the public have a very useful tool. This especially is the case for staff who have little or no knowledge of caves.

The ATES builds lists sorted by the three-level categories. Similar style lists of caves held by park staff could quickly help them narrow their recommendations when consulting the public.

How much information, and by which media, that a land manger will provide to the public about caves in their jurisdiction could be a discussion paper in itself.

Conclusion

The cave-terrain guidelines were developed, in part, as a result of a caver fatality on the approach scramble to a national park cave. These guidelines were formatted using the Avalanche Terrain Exposure Scale, also developed as the result of fatalities while travelling in the backcountry. Tragedy can lead to improved safety awareness and accident prevention.

Cave rescue leaders, land managers and speleological groups can use these guidelines to assist with information summary and safety awareness. Homework, consisting of the evaluation of known caves, must be completed and accessible before the rescue call or information request is received.

Acknowledgments

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MAINSTREAMING KARST EDUCATION, OR KARST EDUCATION FOR EVERYONE

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Abstract

I will discuss matching karst education to state educational programs, professional development programs, and regional grant programs. Several success stories are highlighted. Education is a very important part of karst protection and being part of the general education program should be a goal for all karst states.

The Virginia karst education program participates in a strong environmental education network in Virginia and a program called Virginia Naturally. Virginia's statewide education system has several science standards on karst topography and groundwater, required on science tests, which are taught with Project Underground activities. Teachers are awarded continuing education credits towards licensure certifications for attending classes and workshops on karst issues. Funding is provided though NOAA grants for Chesapeake Bay education classes and conferences on karst. Many county school systems across Virginia include karst education in their teaching programs. This presentation will provide ideas other states can use to implement karst education into their general education programs.

Key Words: karst education, Virginia karst education standards

Introduction

Education is an important part of any natural resource protection plan. It is hard for people to protect something they do not understand. Education is especially important to karst protection since karst is an unfamiliar topic to most people. By making karst education available to the students, citizens and agency personnel in karst areas they will gain the knowledge to help protect this valuable and unique resource.

Introducing Karst into Education

There are many ways to introduce karst science into a statewide education system. Instead of just teaching about caves, find ways to match concepts from karst science to the education standards already in place. Virginia does have an earth science standard on karst topography specifically, but there are many other options available for teaching about karst science. Look for standards on groundwater, surface waters, geologic processes, rare or endangered species, habitats, species adaptations and, of course, bats. By using things like cave habitats and karst hydrology to teach general science concepts the students are introduced to karst science. Here is an example of a Virginia Earth Science teaching standard, note the wording and the various topics in this standard that could include karst issues.

Table 1 Virginia Karst Education Standards

ES.9 The student will investigate and understand how freshwater resources are influenced by geologic processes and the activities of humans.	
(a)	processes of soil development
(b)	development of karst topography
(c)	identification of groundwater zones
(d)	identification of other sources of fresh water including rivers, springs, and aquifers
(e)	dependence on freshwater resources and the effects of human usage on water quality
(f)	identification of the major watershed systems in Virginia including the Chesapeake Bay and its tributaries

Using up-to-date teaching methods is also important for working with established education systems. One method, inquiry teaching, works great for teaching science (Moyer 2007). Inquiry teaching methods have the students doing activities first so they can discover the concepts for themselves, then the teacher teaches or explains the lessons and concepts the students needed to learn. Project Underground is a learner-focused, karst-education curriculum that can be used to teach karst science (Zokaites 2006). The activities are hands-on and can fit into the inquiry-teaching methods used in many science classrooms (Zokaites 2007). For more information on the Project Underground program see the web page for Project Underground, Inc. (2008). For information on how Virginia educators use the Project Underground program, including the Project Underground activities correlated to the Virginia Science Standards, see the web page for the Virginia Department of Conservation and Recreation (2008).

Working karst education into existing, educator-training structures is also important. Offering professional development activities for teachers through the Department of Education and local school systems is a good way to provide teaching materials to teachers. One-day workshops can be used to introduce karst science to teachers and provide them with the Project Underground materials. This is a great way to provide teachers with the knowledge needed to teach karst science in their classrooms. Teachers will also receive continuing education credits for attending these workshops. In Virginia, and several other states in the eastern U.S., one focus of education is on protecting and restoring the Chesapeake Bay. This is a good focus to include karst concepts since many of the rivers running into the Chesapeake Bay have headwaters in karst regions. Bay Education grants in Virginia from the National Oceanic and Atmospheric Administration (NOAA) fund several, week-long professional development workshops for teachers. One of these week-long classes is in the mountain headwaters area, and the subjects covered include watersheds, water quality, geology, karst geology and karst hydrology. The teachers also receive the Project Underground materials for their classroom use, along with several other education curricula on watersheds and the environment. The teachers are awarded 45 continuing education credits for this week-long workshop, and they can elect to receive three hours of graduate credit in Life Science. One field trip has the teachers standing in a big sinkhole, experiencing a cave entrance and visiting a karst spring. This field trip really shows the unique groundwater-to-surface water interaction in karst regions and the need to protect karst aquifers.

These same workshops and materials can be provided to agency-outreach personnel such as park interpreters, soil and water conservation district educators, foresters and wildlife managers. These staff members can also facilitate ongoing karst education. Agency staffers are called upon to give talks and programs on natural resources. Given the right materials and resources these folks can easily add karst science to their mix. Providing land planners and local government supervisors with karst information through workshops and seminars is also good for karst education and karst protection. Using karst examples for land planning and natural resources planning will help students and citizens understand the unique development problems in karst.

Project Underground has several lessons and

Figure 1 Teachers on field trip to a sinkhole.

activities on land planning. The Lost River Village activity has the participants planning a town in karst topography. Working together in teams, the participants plan roads, water supplies, sewage disposal, housing developments and community structures including schools, fire stations, stores and restaurants.

The Virginia Naturally Program, a statewide network for environmental education, helps facilitate the training and resources needed by agency-outreach personnel and educators to teach many of the subjects in environmental education, including karst education. This program is a partnership of businesses and organizations offering to help the environment and includes many of the natural-resource agencies and environmental-education programs. Visit the web site for the Virginia Naturally Program (2008).

Summary

Karst education is an important part of general karst protection in any state. There are many ways to involve students and the general public in karst-education programs. Citizens must become aware of the impact that human development can have in karst topography, and understand the need to protect this unique resource. Including karst education as part of the general education program should be a goal for all karst states.

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TEN YEARS OF MONITORING CAVE SITES AT FORT LEONARD WOOD, MISSOURI

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Abstract

In 1997 Fort Leonard Wood was tasked with assessing, monitoring, and developing a management plan for nine clusters of sites deemed potentially eligible for the National Register of Historic Places. These clusters often represent site complexes with both a biological and cultural-resource component that by law had to be protected, monitored, and managed. The Fort's Directorate of Public Works and the Natural Resource Branch's Cultural Resource and Wildlife Management programs combined assets and developed a systematic approach to answer the questions: What are the impacts? Who was making the impacts? When are the impacts occurring? These site clusters contain significant archaeological records, human remains, and endangered bats. Specific guidelines included off-limits/no-entry restrictions during bat hibernation and maternity periods.

The crew did periodic spot checks of sites, utilizing mammal-monitoring protocols (in this case human footprints). All disturbances were recorded as to type of intrusion, what type of boot, time of year, and assessment of immediate and long-term effects. In the beginning of the survey it was assumed that most intrusions were military in nature; after two years of spot survey it was clear that the vast majority of incidents involving cultural resources and endangered species were nonmilitary. Data from the initial survey was used to establish additional monitoring protocols and protective measures, such as light monitors, cameras and cave gates.

Key words: cave monitoring, cave management, archaeology, biology, endangered species, Fort Leonard Wood, Missouri

Introduction

The Maneuver Support Center (MANSCEN) and Fort Leonard Wood (FLW) military installation is 24,852 ha located in southwestern Pulaski County, Missouri, on the Salem Plateau of the Ozark Region. The Mark Twain National Forest borders the installation on three sides. Geologic features border narrow, flat, alluvial floodplains with rock outcrops, karst topography (caves and sinkholes), and sheer bluffs that commonly rise 60 m in elevation. Elevations range from 230 m to >396 m above sea level in the southern portion of the installation. Sixty-three known caves occur within Fort Leonard Wood boundaries. Currently the MANSCEN and FLW military primary missions are to train personnel in basic combat; combat engineering; military policing; and chemical, biological, radiological, and nuclear warfare. Other combined Department of Defense personnel (Army, Air Force, Navy, Marine, and Coast Guard) are trained in heavy equipment instruction and operation.

In 1996 MANSCEN and FLW was tasked in a Biological Opinion (BO) by the U.S. Fish and Wildlife Service (USFWS) and Missouri

Figure 1 *Monitoring included raking fine dirt at the twilight area with a fire rake and checking the sites with footprints.*

Department of Conservation (MDC) to monitor and determine the number and types of entries in several caves with Federal and State Endangered Species. In addition, a negative Environmental Compliance Assessment System (ECAS) finding based on continued Archaeological Resource Protection Act (ARPA) and Native American Grave Protection and Repatriation Act (NAGPRA) violations encouraged the Cultural Resource Program to implement a monitoring program for sites eligible for the National Register of Historic Places (NHRP). The FLW Directorate of Public Works (DPW) Natural Resource Branch (NRB) was tasked to integrate a Biological and Cultural Resource Monitoring Plan. The monitoring plan was to determine who, why, and when caves on FLW were being entered. Since the installation was created in 1940 caves on FLW have had a history of frequent entry and disturbance. Bat caves are sensitive to specific, seasonal disturbances in hibernation and maternity periods. Archeological sites have been looted repeatedly during all seasons. The issues that faced the DPW NRB were to establish a monitoring protocol that would establish the following information: Who were the parties responsible for entering caves located on FLW, military or civilian? Why were the caves on FLW being entered, and what was the purpose of the cave entry? When were the caves being entered, and at what time of the year was the entry?

Materials and Methods

To establish a monitoring protocol that could answer the Who? Why? When? questions, the NRB looked into established military and civilian regulations pertaining to cave entry. The FLW Installation Range and Training Area Reg. 210-14 Chapter 3-17 (e) clearly states "All caves and rock shelters are off limits to military activities." The regulations for civilians were less specific. If the cave did not have a Federal endangered species sign with specific time of year entry prohibition, the cave was subject to entry. The FLW hunting and fishing program as well as the FLW outdoor recreation center had no policy on cave entry. Therefore the NRB had to design a set of monitoring protocols which would track the "type" (military or civilian) of entry into the caves, month of entry and which type of cave restriction entry violation (biological or cultural) and if a violation occurred, which classification of the entry significance (minor or major) had occurred.

In 1997 a cheap, effective monitoring system had to be created in order to satisfy the parameters for the monitoring protocols. The initial site-monitoring protocols that were used to answer our questions were converting a modified Standard Mammal Track Station protocol to record human footprints at stations (Figure 1). This entailed raking fine dirt at the twilight area at the cave entrance with a stiff-tined (metal) fire rake, checking the sites bi-monthly and recording the footprints.

The 109 sites were divided into nine subgroups. The sites were grouped based on geographic proximity to each other, facilitating site survey and personnel resource time and travel. The sites in the initial survey period of two years were visited twice a month and information recorded. The month, type, and severity (temporal and special restriction) of cave access entry was recorded and initial determination, if possible, of Who (military/nonmilitary) was determined. We had worked with military police and installation game wardens to help us use military boot sole patterns to make determinations based on military boot issue. The U.S. military has a very limited boot sole pattern issue (four possible), so determination was relatively easy. Other data collected were frequency of entry since last visit. Evidence was collected for signs, type of disturbance, and the status of the area, whether the area was open or closed for civilian-use hunting or military training. The types of cave-access violations were divided into two categories: biological and cultural. Biological cave violations occurred when people entered posted cave sites (Figure 2) in disregard to the information signs located at the cave entrance point.

Cultural-resource cave violations occurred when people entered posted cave sites in disregard to the information signs located at the cave entrance, and dug for artifacts or disturbed the site looking for artifacts (Figure 3).

Figure 2 *A possible biological disturbance included this dead, juvenile gray bat under a maternity roost.*

Figure 3 *Evidence of a cultural resource disturbance left by looters at NAGPRA Site (bone, pottery and diagnostic points).*

Results

The initial, two-year data summary shows that there were 43 entries, of which eight were major and 35 were minor violations. The violation categories were 37 biological and six cultural. The data analysis and interpretation showed the top months with the most frequent entries were April, November, and December. The top months with the most major entries were December and January. Most entries occurred when the hunting area status was scheduled for public use. Most of the minor violation entries coincide with both spring turkey and fall deer season. Most of the major violation entries coincide with the "Exodus" of personnel (Installation training holiday closure) in December and January. Most of the entry violations are minor and biological (casual, do not go beyond the twilight area). Most of the Cultural Resource violation entries are major and occur over Exodus and are organized (target sites at specific time of the year when military training is limited and post law-enforcement resources reduced). The data suggest that the most entries are civilian in nature, coincide with hunting seasons in the spring and fall when people are in the woods, and that through boredom or a sense of adventure they enter posted cave sites. The fact that most entries do not go beyond the twilight area reveals that the casual entry violations occur because most hunters carry a small flashlight or none at all and will not proceed into a dark zone unprepared. On the other hand the Cultural Resource violations occur at targeted times and sites, and the people who are entering are knowingly violating the posted signs and committing a crime. They are highly organized, prepared to enter caves and do not wish detection. In order to attempt to limit the number of entries into endangered species caves at FLW, the NRB decided to use faux cameras on a trail bases and attempt to see if new signs with electronic camera warning would deter casual entries.

Figure 4 *New electronic warning signs were attached to the bottoms of the existing signs.*

New electronic warning signs were attached to the bottoms of the existing signs (Figure 4) and faux cameras (similar to faux cameras used in convenience stores and homes) (Figure 5) were purchased and installed. The cameras cost approximately US $175.00 to $200.00 and were easy to install in the caves. The concept was to use faux cameras, with Hobo® H06-001-02 light sensors (Figure 6) deep in the cave and the track-count protocol to determine if electronic warning signs and faux cameras would stop the occasional minor entries into the twilight areas of posted, sensitive, endangered-species caves.

After two years of the use of the warning signs, Hobo light sensors, and the track counts, minor entries into the twilight areas of the endangered-

Figure 5 *Faux cameras were installed along with light sensors.*

Figure 6 *Hobo® H06-001-02 light sensor, courtesy of Onset Computer Corporation.*

species sites stopped. There were only two events recorded with Hobo light sensors; both were off-season and correspond to dates that cave survey teams were know to be in the caves doing surveys. The Hobo light sensors had worked and data backed up the fact that the electronic monitoring signs and faux cameras had been effective in deterring occasional cave entries into the twilight zone.

Discussion and Conclusions

Cave with intact cultural-resource deposits (burials, rock art, and paleontology) are gated. These sites are still monitored to check status of the gate. Currently the monitoring protocol for the 109 monitoring sites is to make a visit at least once every six weeks. The only exception is the spring and fall hunting seasons; the sites are checked prior to the start of the season and the week after the season ends. Typically this time frame has been the period with the most public access and past violations. Future actions on FLW dealing with NAGRRA issues at cave sites are to continue cave gating and monitoring at NAGPRA sites, and on-going consultation with tribal governments of the Dhegiha Council (Osage, Kaw, Omaha, Quapaw, and Ponca tribes) on cultural affiliation, repatriation of human remains, and visitation by Tribal Leaders to FLW sites.

The periodic monitoring of caves is an important tool to help protect cave resources, be they biological or cultural-resource sites. Once a routine protocol of site visits, monitoring, and protection measures is established for cave sites by an agency, the word goes out to the public that these areas are scrutinized. The entry violation decreases, damage is minimized and cave resources are conserved. The cost associated with preventive monitoring of sites in the long run will be effective. Taking action at a cave after major problem has occurred is usually expensive and in many cases the damage to the cave resource is not repairable. Therefore an inexpensive protocol of site visits and monitoring can help an agency determine which types of protection measures will be most cost-effective in the long term and best conserve cave resources.

INCORPORATING CAVE AND KARST PROTECTION INTO CONSERVATION EASEMENTS: A TOOL FOR CAVE AND KARST PROTECTION IN VIRGINIA

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Abstract

As economic factors compel landowners to subdivide and sell their lands, caves and other karst resources are at increased risk. According to Virginia Governor, Tim Kaine, if current development trends continue *Virginia will develop more land in the next 40 years than was developed in the last 400 years.* The increased parceling of the countryside leads to suburban sprawl and to a loss of the open spaces that define the rural character of the landscape. *Virginia has instituted a conservation easement program whereby landowners can generate transferable tax credits for donating conservation easements on their land.* Ideally, *conservation easements qualifying for tax credits should principally protect lands possessing legitimate conservation value. Applied appropriately, conservation easements can be a useful tool for preserving the natural environment, including the protection of caves and karst systems.*

Key words: conservation easements, Virginia, karst land management

What Is a Conservation Easement?

A conservation easement is a permanent, legal agreement negotiated between a landowner and a nonprofit conservation organization or a government agency. The deed of easement is a contract that places permanent limits on future development and divisions of the subject property. In Virginia, prospective conservation easements undergo a review to determine what scenic, natural, or historic resources are present.

Who Holds (Owns) Conservation Easements?

A variety of land trusts and several state and federal agencies are qualified to hold conservation easements. An organization must meet certain guidelines before it can legally hold a conservation easement. The Virginia Outdoors Foundation (VOF), a public foundation that also serves as a state agency, holds most conservation easements in the Commonwealth of Virginia. As of 2007, Virginia Outdoors Foundation holds conservation easements on more than 400,000 acres of land in Virginia. For conservation easements held by VOF, the office of the Attorney General of the Commonwealth is empowered to enforce the terms of such easements.

Relatively small organizations, such as cave conservancies, generally lack the considerable financial resources required to defend successfully a conservation easement against a noncompliant landowner–a protracted series of lawsuits could easily cost several hundreds of thousand of dollars. A cave conservancy might nevertheless utilize their own conservation-easement donation as a means of ensuring long-term protection for cave resources under their ownership. A preemptively placed conservation easement would offer some safeguard to owned caves and other karst resources should subsequent misfortunes such as lawsuits, insolvency, or dissolution place a cave conservancy's assets at risk. Placement of wisely crafted conservation easements on appropriate landholdings could enhance protection to conservancy-owned caves, a state or federal agency such as the VOF or USDA Forest Service, or perhaps a large, stable private conservation organization like The Nature Conservancy should logically hold and enforce any such easements.

Tax Incentives for Conservation Easements

Donation of a conservation easement can have tax benefits. There are several ways to deduct a portion of the donated value of a qualified conservation easement from adjusted gross income for federal income tax purposes. Federal tax rules dealing with conservation easements are in a state of flux; a detailed discussion of the Federal Tax Code is beyond the scope of this paper. At present in Virginia, donation of an eligible conservation easement can generate a transferable Virginia State Tax Credit under the terms of the Virginia Land Conservation Incentives Act of 1999. Virginia Tax credits currently are conferred based on 40% of the easement's fair market value; these saleable credits can carry over for up to ten years.

Some other states also offer tax incentives for the donation of conservation easements.

The Landowner's Perspective

Choosing whether to place one's land under a conservation easement is a major decision. Only after carefully considering the benefits as well as potential consequences should a landowner make the informed decision to grant an easement. Except for the rights explicitly given up in the easement document, the landowner continues to own, use, and control his land. Conservation easements, however, are permanent and appurtenant–they pass along with the property to restrict uses of the land by all future owners. A conservation easement typically restricts the ability to subdivide and develop real estate, it prohibits mining and quarrying, and it restricts the size and number of permitted structures. An easement will encumber a property from certain types of land uses, but it does enable a landowner to obligate future owners to continue to protect and conserve the land for future generations. A conservation easement will likely diminish the eventual sales price of the subject property.

Despite these drawbacks, many landowners realize a net economic benefit by donating a conservation easement. Placement of a conservation easement on a property may result in a reduced property tax assessment, and might reduce exposure to estate taxes. As discussed, landowners who donate conservation easements can benefit from federal and state tax incentives, which in some cases (for example Virginia) can be quite significant.

Ensuring That Easements Achieve Conservation

The Virginia Department of Conservation and Recreation (DCR), Natural Heritage Program, performs an environmental assessment on proposed easements to identify what unique plants, animals, or natural communities, including caves and karst features, might be present on the property. In some cases, site visits lead to the discovery of previously undocumented caves and other Natural Heritage resources. After review and, in some cases, site visits, Natural Heritage Program staff generally recommend specific additional protective provisions for incorporation into the easement contract language. The degree to which these recommendations are included in the Final Deed of Gift of Conservation Easement is a matter of negotiation between the landowner and the organization that will hold the easement.

In situations where a donor claims a Virginia Land Preservation Tax Credit of $1 million or more, DCR must review the donation to verify that the donation meets the conservation-value-review criteria adopted by the Virginia Land Conservation Foundation board. In order for the applicant and the Virginia Department of Taxation to receive the required letter of verification of conservation value for tax credits worth $1 million or more from the DCR Director, the final conservation easement or deed of gift must comply with DCR requirements as stated in the comment letter.

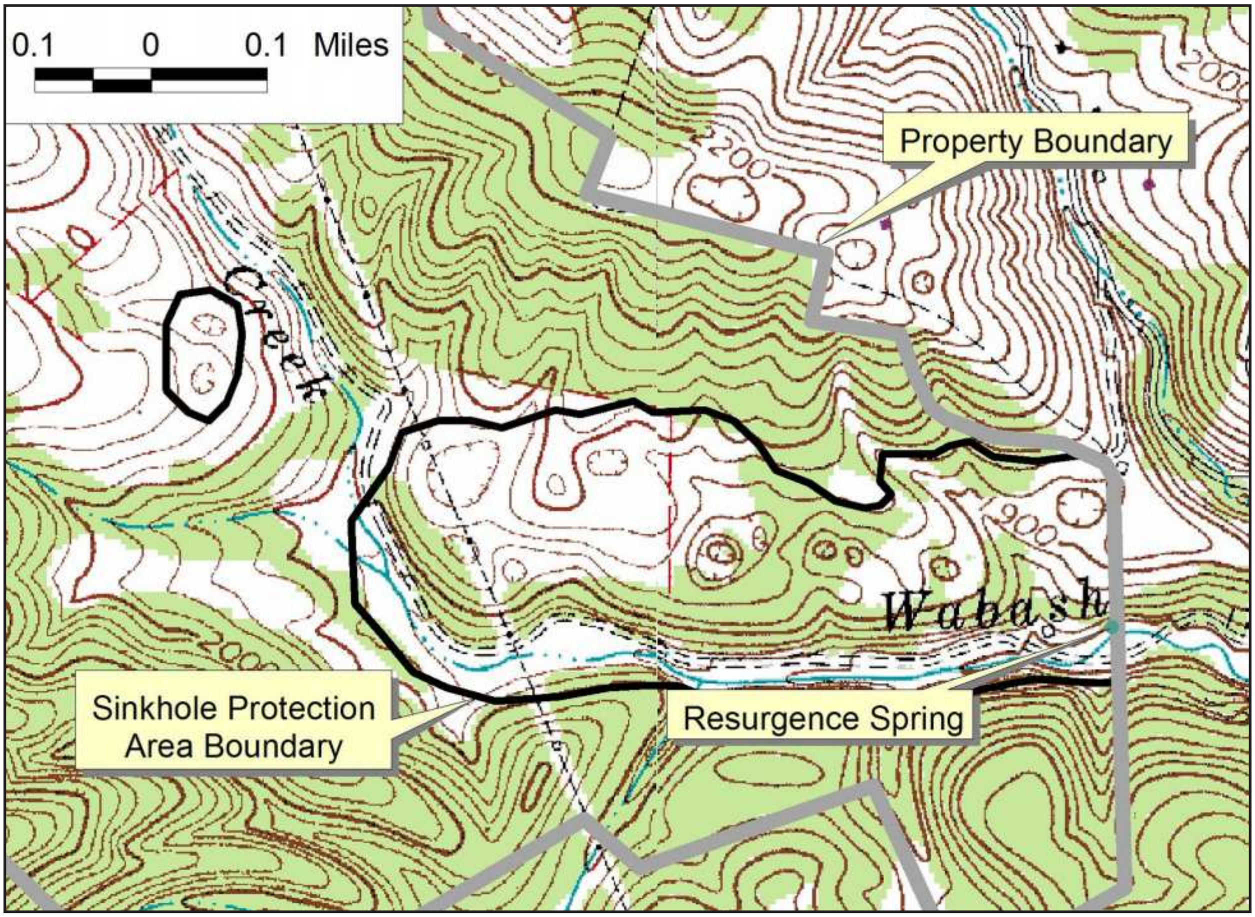

Figure 1 *Buffered sinkhole protection boundaries near Wabash Spring, Poplar Hill Farm, Giles County, Virginia. Map by Wil Orndorff.*

Conservation Practice Requirements

A conservation easement may require use of Best Management Practices (BMPs) in agricultural operations. BMPs such as cleaning out existing sinkhole dumps, installing fencing to exclude livestock from streams and sinkholes, and establishment of riparian buffers along sinking and losing streams helps to protect karst habitats, aquifers, and receiving surface waters. Implementation of such BMPs is frequently a precondition to acceptance of a donated conservation easement by a land trust or government agency. State and federal cost-share programs are commonly available to help landowners install and pay for such conservation practices. Whenever possible, negotiated contract documents should include language to require landowners to adopt and maintain appropriate conservation practices in order to increase the conservation value of the easement and to preserve the environmental integrity of the property.

Examples of Conservation Easements Protecting Karst Resources

The Moss conservation easement in Tazewell County, Virginia, contains four significant caves on 537 ha (1,327 ac.). These caves are home to numerous, globally rare cave invertebrates. The streams in these caves help recharge springs feeding the upper Clinch River, which hosts one of the richest and most imperiled freshwater mussel faunas in the world. Upon recommendation by the DCR Natural Heritage Karst Program, the easement agreement specifies detailed requirements to protect the caves and sinkholes on this working farm.

The Poplar Hill, LLC, conservation easement in Giles County, Virginia protects 256 ha (632 ac) of significant karst and upslope recharge land. The agreement denotes sinkhole protection boundaries on two large areas of the property containing many sinkholes (Figure 1). The sinkholes serve as catchments to recharge the karst aquifer that includes

Figure 2 *Spring entrance to Smokehole Cave, Giles County, Virginia. Photo by Joey Fagan.*

one of Virginia's longer and more biologically significant cave systems, home to at least two extremely rare (G1) cave invertebrate species. The easement specifies steps to protect the sinkholes, including a requirement to exclude livestock from the identified areas.

A conservation easement in Bland County, Virginia protects 104 ha (257 ac) of karst that includes a cave serving as a hibernaculum for several species of bats, including the Virginia big-eared bat (*Corynorhinus townsendii virginianus*), the Eastern small-footed bat (*Myotis leibii*), and, in large numbers, the Little brown bat (*Myotis lucifugus*).

Conservation easements may specify access to private property for monitoring purposes, but typically offer no guarantee of recreational access to the public. The owner of Crossroads Cave in Bath County, Virginia, wanted to make sure recreational cavers could always visit his cave. He placed a conservation easement on the bulk of his land with the Virginia Outdoors Foundation, but reserved a 0.8-ha (two-ac) tract containing the cave entrance, which he donated to the Virginia Speleological Survey, ensuring access to his cave by future generations of responsible cavers. The conservation easement protects a large portion of the recharge area of the cave from development, while the tract donated to the VSS maintains access for the caving community.

The largest easement VOF has accepted to date, a 1,752-ha (4,329-ac) farm in Tazewell County, Virginia covers a landscape underlain almost entirely by karst or land draining to karst (allogenic recharge). Caves on the property are home to a species of cave beetle known only from the property, and to a major colony of a federally protected bats. The easement contract stipulates some provisions to protect caves and karst features on the property and acknowledges an existing agreement to protect and manage the cave housing the bat colony. The recording of this particular easement occurred in 2006, prior to the requirement for DCR to perform a conservation value review. Current DCR criteria would likely require the landowner to install additional BMPs to fence livestock from a sinking creek on the property and develop alternative water supplies for cattle.

The Virginia Outdoors Foundation gives highest priority to easement projects of 40 ha (100 ac) or more. For lands with particularly high conservation value and/or multiple conservation values and strongest protection, this minimum requirement is sometimes relaxed. Presence of a cave or other significant karst features may serve as evidence of such significant conservation value. VOF relaxed these same guidelines when they agreed to accept donation of a conservation easement containing less than 20 ha (50 ac) from the owner of Smokehole Cave in Giles County, Virginia. Smokehole Cave (Figure 2) is one of the resurgence caves of the Clover Hollow karst area, which hosts a globally significant invertebrate fauna, with several species restricted to the Sinking Creek basin. The exceptional conservation value justified for VOF an exception to the 40-ha (100-ac) minimum policy.

The Small Parcel Problem

It is difficult to convince most conservation organizations to agree to hold an easement on tracts less than 30 or so acres. This is at least partly because many land trusts use total acreage placed under easement as their primary measure of success. There are cases, for example, where some relatively small parcels containing biologically significant caves possess considerable conservation value. Even though legal and stewardship expenses to administer conservation easements on small parcels tend to cost more per area, the benefits of protecting certain selected undersized properties should justify the required extra effort. Virginia Natural Heritage program staff continues to work with partners in developing protocols that are more effective to protect small tracts of exceptional conservation value through conservation easements.

Summary

Working partnerships between landowners, VOF and the various land trusts, DCR, and other state and federal agencies help preserve Virginia's natural landscape for both the survival of the natural communities that depend upon it as well as for the enjoyment of future generations. Conservation easements can serve to provide effective protection for caves and other karst resources. Conservation easements already help protect several of Virginia's significant caves. Each specific easement document incorporates wording to address concerns for caves and other karst resources on a particular property. Appendix A offers a list of selected karst protective provisions taken from actual VOF Easement Deeds. May Virginia's successes continue and serve to encourage other states to adopt similar conservation easement programs.

Sources and Acknowledgments

Much of the information presented in this article draws from personal communication with a number of people. The authors offer special thanks to Ruth Babylon, Neal Kilgore, Laura Thurman, Tamara Vance and Bill Wasserman of the Virginia Outdoors Foundation, as well as to Jesse Richardson, Associate Professor of Urban Affairs and Planning at Virginia Tech and member of the Virginia Cave Board. Many thanks for the generous support from Ozark Underground Laboratory and ESRI.

Appendix A
Selected Conservation Easement Provisions for Karst Protection

Poplar Hill (Giles County, Virginia)

1. **Trash.** Accumulation or dumping of trash, refuse, or junk is not permitted on the Property. This restriction shall not prevent generally accepted agricultural or wildlife management practices, such as creation of brush piles, composting, or the storage of farm machinery, organic matter, agricultural products or agricultural byproducts on the Property, as long as such practices are conducted in accordance with applicable laws and regulations and do not damage the karst features on the property.

4b. **Riparian buffer.** A vegetated or forested buffer extending 11 m (35 ft.) from each bank of Wabash Creek shall be maintained on the Property, limited, however, to the property lines, if applicable. This buffer shall be protected from degradation by livestock. Removal of non-native invasive species and minimal harvest of trees is permitted, provided that the function of the buffer to protect water quality both in the surface stream and the surface and subsurface karst features are not impaired. It is hereby acknowledged by both parties to this deed that an existing road traverses the buffer area in some places, and may be maintained by the Grantor.

5. **Karst features.** No sinkholes or cave entrances shall be filled, and no construction shall take place within a sinkhole. All sinkholes on the property shall be maintained as wooded areas, and harvest of trees within sinkhole boundaries shall be limited to minimal selective harvest of trees. Cattle shall not be permitted access to the hydrologically significant sinkholes shown on **Schedule B** attached hereto. Disposal of any material in all sinkholes is prohibited.

6. **Grading, blasting, mining.** Grading, blasting or earth removal shall not materially alter the topography of the Property except for dam construction to create private ponds, or as required in the construction of permitted buildings, structures, connecting private roads, and utilities as described in Paragraph 7. Generally accepted agricultural activities shall not constitute any such material alteration. Best Management Practices, in accordance with the Virginia Erosion and Sediment Control Law, shall be used to control erosion and protect water quality in the construction of permitted buildings and private roads. **Notwithstanding the foregoing, no grading, blasting, or earth removal is permitted on the Property if it will damage the surface or subsurface karst features on the property or materially diminish or impair the Open Space Values of the Property.** Mining on the Property by surface mining or any other method is prohibited.

Smokehole Cave (Giles County, Virginia)

2. **Trash.** Accumulation or dumping of trash, refuse, or junk is not permitted on the Property. This restriction shall not prevent generally accepted agricultural or wildlife management practices, such as creation of brush piles, composting, or the storage of farm machinery, organic matter, agricultural products or agricultural byproducts on the Property, as long as such practices are conducted in accordance with applicable laws and regulations and do not damage the karst features on the property.

5. **Karst features.** No disturbance or alteration of either of the two entrances to Smokehole Cave is permitted. In addition, no sinkholes or cave entrances shall be filled, and no construction shall take place within a sinkhole. Cattle shall not be permitted access to any sinkholes on the Property and disposal of any material in Smokehole Cave and in all sinkholes is prohibited.

Moss Easement (Tazewell County, Virginia)

4. **Management of Forest.** Best Management Practices, as defined by the Virginia Department of Forestry, shall be used to control

erosion and protect water quality when any timber harvest or land-clearing activity is undertaken. All material timber harvest activities on the Property shall be guided by a Forest Stewardship Management Plan approved by VOF or the VA Department of Forestry. A pre-harvest plan consistent with the Forest Stewardship Management Plan shall be submitted to VOF for approval 30 days before beginning any material timber harvest. The objectives of the Forest Stewardship Management Plan may include, but are not limited to, forest health, biodiversity, timber management, wildlife habitat, aesthetics, recreation, water and air quality, carbon or other mitigation banking programs, historic and cultural resource preservation, natural area preservation, or any combination thereof. VOF shall be notified 30 days prior to the clearing of over 4 hectares (10 acres) of forestland for grassland, crop land, or in association with the construction of permitted buildings.

Non-commercial *de minimis* harvest of trees for trail clearing, firewood, or Grantor's domestic use; trees that pose an imminent hazard to human health or safety; or removal of invasive species shall not require a Forest Stewardship Management Plan.

5. **Riparian buffer (pasture/cropland area)**. To protect water quality there shall be no plowing, cultivation, or other earth-disturbing activity in a 11-m (35-ft.) buffer strip along each edge of Liberty Creek, as measured from the top of the bank and there shall be no plowing, cultivation, or other earth-disturbing activity in a 8-m (25-ft.) buffer strip along each edge of the unnamed intermittent tributaries to Liberty Creek, as measured from the tops of the banks (see Schedule B, attached hereto and made a part hereof), except as may be reasonably necessary for (i) wetland or stream bank restoration, or erosion control, pursuant to a government permit, (ii) fencing along or within the buffer area, (iii) construction and maintenance of stream crossings that do not obstruct water flow, (iv) creation and maintenance of foot or horse trails with unimproved surfaces or (v) dam construction to create ponds. Within this buffer strip there shall be (a) no buildings or other substantial structures constructed, (b) no storage of compost, manure, fertilizers, chemicals, machinery or equipment, and (c) no removal of trees except removal of invasive species or removal of dead, diseased or dying trees or trees posing an imminent human health or safety hazard. Mowing within buffer areas is permitted. There shall be no grazing of livestock in the buffer strip, other than periodic or "flash grazing" as defined by the Natural Resources Conservation Service.

6. **Grading, blasting, mining**. Grading, blasting, or earth removal shall not materially alter the topography of the Property except for (i) dam construction to create ponds, (ii) wetlands or stream bank restoration pursuant to a government permit, (iii) erosion and sediment control pursuant to a government-required erosion and sediment control plan, or (iv) as required in the construction of permitted buildings, structures, roads, and utilities. Best Management Practices, in accordance with the Virginia Erosion and Sediment Control Law, shall be used to control erosion and protect water quality in such construction. Grading, blasting or earth removal in excess of 0.4 ha (one ac.) for the purposes set forth in subparagraphs (i) through (iv) above require 30 days' prior notice to VOF. Generally accepted agricultural activities shall not constitute a material alteration. Surface mining, subsurface mining, dredging on or from the Property, or drilling for oil or gas on the Property is prohibited.

7. **Accumulation of trash.** Accumulation or dumping of trash, refuse, junk, or toxic materials is not permitted on the Property. This restriction shall not prevent generally accepted agricultural or wildlife management practices, such as creation of brush piles, composting, or the storage of farm machinery, organic matter, agricultural products or agricultural byproducts on the Property. The Grantor and Grantee hereby acknowledge the existence of a "pre-existing" dump on the property at the time of this deed, which is documented in the permanent files of the Grantees and which is not visible to the traveling public. No additional trash shall be added to the existing dump and no additional dumps shall be permitted on the Property.

9. **Karst features.** To protect water quality and the unique karst features on the Property, **no new building or structure shall be located within 61 m (200 ft.) from the entrance of any cave on the Property.** In addition, no sinkholes or cave entrances shall be filled; no disturbance or alteration of the entrances to the caves is permitted; no fertilizer or other agricultural chemicals shall be applied for a distance of at least 30 m (100 ft.) from any cave opening; no dumping of animal carcasses or other waste is permitted in sinkholes, caves, or other karst features; disposal of any material in the caves and sinkholes is prohibited; cattle shall not be permitted access to any of the three caves on the Property that are already fenced. The Grantor is not required to remediate any condition existing as of the date of this easement.

Notwithstanding the above, the Grantees acknowledge the measures already taken by the Grantor to exclude livestock from three of the four known caves on the Property. Ten (10) years from the date of recordation of this easement, livestock shall be prevented from accessing the remaining known (fourth) cave on the Property.

Unspecified Cave (Bland County, Virginia)

9. **Karst features.** No building, structure, or road shall be located in an area of the Property that would damage the cave system on the property. In addition, no sinkholes or cave entrances shall be filled and no construction shall take place within a sinkhole. Cattle shall not be permitted access to any sinkholes on the Property. Disposal of any material in _________ Cave and in all sinkholes is prohibited. No disturbance or alteration of the entrance to ________ Cave is permitted.

No dumping of animal carcasses or other waste is permitted in sinkholes, cave, or other karst features, provided, however, that Grantor is not required to remediate any condition existing as of the date of this easement.

Cave Protection:
The cave openings on the Property shall be protected from degradation by runoff from agricultural chemicals and livestock waste. If necessary, livestock on the Property shall be fenced out, and no fertilize or other agricultural chemicals shall be applied for a distance of at least 30 m (100 ft.) from the cave opening and no sediment or other debris shall be placed in the cave opening.

Unspecified Cave (Tazewell County, Virginia)

The parties recognize the pre-existing management agreement between ________ and the Nature Conservancy for the management of a cave containing species federally listed as endangered, last renewed on __________ and expiring_________, with provisions for renewal upon agreement of _______ and the Nature Conservancy. Nothing in this easement is intended to supersede this management agreement.

Notwithstanding the above, if the management agreement with the Nature Conservancy terminates for any reason, Grantor agrees to maintain the cave in its current undisturbed state. Grantor agrees to refrain from cutting or uprooting trees or shrubs, dumping trash, digging, or filling cave entrances in the area defined in the current agreement between Grantor and the Nature Conservancy; provide, however, that removal of vegetation that blocks the cave entrances is permitted. No buildings or structures are permitted in the designated area. Specific information about the cave, its location, and species that live in the cave are maintained by the Virginia Department of Conservation and Recreation, Division of Natural Heritage Program.

No disturbance or alteration of the four (4) cave entrances as shown in the Baseline Documentation described in Paragraph 11 is permitted. A vegetated buffer extending a minimum 15-m (50-ft.) radius from the mouth of each cave entrance shall also be maintained on the Property. Cattle shall not be permitted access to said caves and disposal of any material, both man-made or natural, in the caves is prohibited.

Buildings and Structures: Notwithstanding the above, no building or structure shall be located within 91 m (300 ft.) of the cave entrance on the Property.

In the event of subdivision of the Property as provided in Paragraph 3 above, permitted dwellings shall be allocated among the parcels in the instrument creating the subdivision, and private roads and utilities may be constructed on each parcel. **Notwithstanding the above, no building, structure or road shall be located in an area of the Property that would damage the cave system on the Property.**

Sinkhole Buffer. A forested buffer extending a minimum of 11 m (35 ft.) from the edge of any sinkhole shall be maintained on the Property. This buffer shall be protected from degradation by livestock. Removal of non-native invasive species and minimal harvest of trees is permitted, provided that the function of the buffer to protect water quality is not impaired. Waste material of any nature shall not be disposed of in sinkholes.

Disposal of any material in the sinkhole located on the Property is prohibited. Said sinkhole is shown in the Baseline Documentation as described in paragraph 11 herein.

In the event of subdivision of the Property as provided in Paragraph 3 above, permitted dwellings shall be allocated among the parcels in the instrument creating the subdivision, and private roads and utilities may be constructed on each parcel. **Notwithstanding the above, no building, structure or road shall be located in an area of the Property that would damage the cave system on the Property.**

Disposal of any material in the sinkhole located on the Property is prohibited. Said sinkhole is shown in the Baseline Documentation as described in paragraph 11 herein.

Access to _________Cave. Representatives of the Grantee may enter the Property for purposes of scientific investigations and monitoring of __________ Cave, and of other caves and karst features on the Property after permission from or reasonable notice to the owner or the owner's representative. Representatives of the Grantee may investigate the Property for the purpose of documentation and exploration of any additional caves or karst features that may be present.

For a sample VOF Conservation Easement Template see: http://www.virginiaoutdoorsfoundation.org/DOCUMENTS/EASEMENT%20DOCS/20070702_TEMPLATE.doc

SOME "COMMANDMENTS" FOR CONSERVATION IN KARST FAUNAL SECTIONS OF ENVIRONMENTAL IMPACT STATEMENTS

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Abstract

Environmental impact statements as mandated by the National Environmental Policy Act (NEPA) have the mantra of "avoid, minimize and mitigate." Four points are made herein concerning these studies in the case of caves and karst: (1) the cave entrance is not the cave; (2) avoiding the cave does not avoid the subterranean fauna; (3) limiting sampling to project areas produces corridor endemics; and (4) nothing should ever be taken for granted when it comes to karst invertebrates.

Key words: NEPA, EIS, environmental impact statements, karst management, cave biology

Introduction

Federal agencies and others receiving federal funding are required by the National Environmental Policy Act (NEPA) to integrate environmental values into their decision-making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. This requirement is met by the preparation of a detailed document known as the Environmental Impact Statement (EIS). The preparatory work for a major EIS may take years of work by dozens of specialists, with the final product being hundreds of pages in length. With all that is entailed the path remains fraught with obstacles, with the treatment of karst and its unique inhabitants being anything but uniform from project to project.

The mantra of NEPA is to avoid, minimize, or as a last alternative, mitigate, the impacts on the environments being affected by construction (which generally entails destruction). That said, experience shows that compliance with avoidance or minimization can be interpreted in many ways, some of which are better than others. The audience that needs to hear this is seemingly absent from the NCKMS, thus we have the familiar feeling of "preaching to the choir." Following this theme, herein we suggest four "commandments!"

Thou Shalt Not Consider the Entrance to be the Cave.

Although this point has been made previously, the problem continues to re-emerge: during planning caves are considered as dots on maps where the entrances occur. Although the entrance is fundamentally important to the access of organisms and nutrients, the entrance is not the cave. From a functional standpoint the "entrance" denotes a portal for humans. With the exception of blind vertical pits, the cave extends from the point on the map denoting the entrance. Thus, avoiding the entrance does not avoid the cave.

Thou Shalt Not Consider Cave Fauna to Live Only in Caves.

This commandment is essentially an extrapolation from the first. Clearly many of the trogloxenes and troglophiles can and do leave the cave. The role of these animals in the nutrient input into caves needs no further elaboration.

Concerning the obligatory cave inhabitants, cave maps show only passages that are traversable by humans. Invertebrates can easily move around in areas that are not enterable by people. For a pselaphine beetle, linyphiid spider, or springtail, a tube the diameter of a pencil would be equivalent to a subway tunnel to a human. For aquatic animals it is becoming increasingly obvious that the saturated interstices of the epikarst are dispersal corridors for aquatic invertebrates. As an example, we shall examine the case of Jordan's groundwater isopod (*Caecidotea jordani*) (fig. 1). Endemic to southern Indiana, this species was discovered in a seep spring under the building housing the Department of Biology on the Indiana University campus at Bloomington. We have subsequently found it in water dripping from the Indiana epikarst at Chase Cave (Lawrence County), a parafluvial gravel deposit on the bank of the Blue River (Crawford County) and a seep spring on our own property in Burns Hollow (Clark County) (Lewis 1998, Lewis, et al. 2004, Lewis and Lewis 2006). This last site is of particular interest. Of the four known populations, all are in Indiana's south-central upland area, but the Burn's Hollow seep occurs in a nonkarst area at the base of the Knobstone Escarpment. Clearly, this eyeless, unpigmented isopod is not restricted to caves, or even karst.

Figure 1 Jordan's groundwater isopod (Caecidotea jordani).

Thou Shalt Sample Outside of the Project Area.

One of the major concerns of anyone undertaking a construction project is dealing with the presence of animals or plants listed on the U.S. Fish and Wildlife Service endangered species list. The worst case scenario, the object of nightmares and sleepless nights by project managers, is a listed species that is known solely from within the proposed construction corridor.

The potential for finding extremely rare fauna is great when dealing with caves, where even today many species new to science are constantly being found. Many of these are known from single caves. Thus, little did we know that when we collected a water sample from a pool in Stab Cave (in the Highway 80 band for the proposed I-66 corridor in eastern Kentucky), that we had found a species, new to science, of the copepod *Itocyclops*. Until recently this group of groundwater crustaceans had been reported only from Japan and southeastern Alaska, when Reid and Ishida (2000) discovered it in a seep spring in the Great Smoky Mountains, Tennessee.

After finding the unique new species in Stab Cave we began sampling outside of the proposed highway corridor and found it in two caves outside of the project area. Fortuitously, in time *Itocyclops* undescribed species was also found in a cave in north central Tennessee (Lewis and Lewis, 2007). Although still poorly known, this crustacean is relatively widespread. Had sampling been limited to the I-66 project area it would have remained a problematic "corridor endemic" that would have been an artifact of inadequate collecting rather than a true reflection of the range of the species.

Thou Shalt Take Nothing For Granted.

In March of 2007 we were requested by the Hoosier National Forest to evaluate a site that was to be partially inundated by a project on the adjacent surface channel of the Lost River. The river had been channelized resulting in a drop in the water level of several feet. The proposed project would restore the channel and water to their pre-disturbance levels. The concern by the forest service was that the cave would then be flooded as a result.

The site was Holloway Cave, consisting of an entrance large enough to squeeze through into a hole perhaps 10 feet in length. By the standards of the Indiana Cave Survey it was only considered as a karst feature rather than a cave, a veritable hole in the ground.

During our first visit the sinkhole in which the cave entrance was located was completely under water because of the spring flooding of the Lost River. Looking at the water-filled hole it was easy to be dubious that much was going to be found in such a small, inhospitable place.

On the next visit the river had lowered to a more normal stage and the cave was mostly dry, except for a water-filled fissure in the floor. Using a plankton net, a water sample was taken from this small pool. The result was surprising: Holloway Cave contained the only known Indiana population of Hauer's copepod (*Diacyclops haueri*).

This tiny crustacean usually inhabits floodwater pools. It may be that since the Lost River was channelized the copepod has been using the cave as a refugium and will become more common locally when the habitat is restored (Lewis 2007).

The object lesson from the Holloway Cave project was that even the least suitable looking habitat might have some hidden surprises—one should never make any assumptions.

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GRAY AND INDIANA BAT POPULATION TRENDS IN MISSOURI

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Abstract

Since 1975 the Missouri Department of Conservation (MDC) has systematically censused the endangered bats, *Myotis sodalis* (Indiana bat) and *M. grisescens* (Gray bat). A recent statewide reestimate of about 15,812 indicates that Indiana bats declined by 95% since 1979. Pilot Knob Mine, a National Wildlife Refuge, had 80,000-100,000 Indiana bats in 1958, but only 1,678 were found there in February 2008, a 98% decline. At other sites they declined or abandoned one cave for another, seeking protection and more optimal temperatures. Their decline probably was caused by multiple factors, including human disturbance, the partial collapse of Pilot Knob Mine in 1979, warming of hibernacula, and possibly by pesticides and loss of summer habitat in northern Missouri. White Nose Syndrome has not been found in Missouri.

Missouri's Gray bat population declined, but it is now stable or increasing in some protected caves. Many other caves remain abandoned for various reasons. At bottom, Gray bats lost at least 67% of their maximum past population, as measured in 56 important caves, and 53% of the caves were abandoned. The maternity population of Gray bats is currently estimated at approximately 635,000, but it may have been >1,700,000 in the past. The three largest Gray bat hibernacula were censused in 2006 and totalled 773,850. The Gray bat is a key species in Missouri ecosystems, providing nutrient input to cave animal communities and significant control of night-flying insects, some of which are agricultural or health pests. Although there has been a general increase, many maternity colonies are still threatened by intruders and vandals, so further conservation work is needed.

Key words: *Myotis sodalis*, Indiana bat, *Myotis grisescens,* Gray bat, population trends, disturbance of bats, cave temperatures, mine collapse, pesticides, cave gates, White Nose Syndrome, Missouri, Onyx Cave/Crawford County, Bear Cave/Franklin, Copper Hollow Sinkhole, Brooks Cave, Great Spirit Cave, Ryden Cave, Bat Cave/Shannon, Martin Cave, Great Scott Cave, Scotia Hollow Cave, Pilot Knob Mine, Devils Icebox Cave/Boone, Rocheport Cave, Coffin Cave, Mary Lawson Cave, Slaven Cave, Cookstove Cave, Hamilton Cave, Powder Mill Creek Cave, McDowell Cave, Mary Lawson Cave, Toby Cave, Moles Cave, Smittle Cave, Marvel Cave, Mose Prater Cave, Coffin Cave, Bat Cave #1/Franklin, Blackwell Cave, Grandpa Chippley Cave, Lower Burnt Mill Cave, Tumbling Creek Cave

Introduction and Literature Review

In this paper I focus on the status of the endangered bats, *Myotis sodalis* (Indiana bat) and *M. grisescens* (Gray bat) in "Missouri," by which I mean the Missouri region, insofar as we must be censusing some bats migrating to and from neighboring states. We know from previous work that these species migrate fairly long distances seasonally, and among different hibernacula, transient, bachelor, and maternity sites.

Caves provide important habitat to ten Missouri bat species and three other species have been found in caves. Colonies of Grays and Indianas hibernate in "cold air trap" caves, which have descending floors, deep pits, or large entrances that accept large amounts of winter air. Maternity colonies of Grays prefer warm caves with high ceilings to raise their young in spring/summer. Gray bats roost exclusively in various caves in different seasons for maternity, hibernation, bachelor, and transient colonies. Indiana bats primarily hibernate in caves and mines, are transient via other caves, then females leave caves for riparian forests, particularly snags, to raise their young during the summer.

To census these interesting animals is to track a moving target, literally and figuratively. The colonies are dynamic, even fluctuating significantly night to night at some Gray bat caves in late summer.

Richard F. Myers (1964) pioneered the study of myotine bats in Missouri. On February 22, 1958, Myers visited Pilot Knob Mine, Iron County, with three local men to photograph the hibernating Indianas (Figure 1). He visited the abandoned iron mine again on April 11 and December 27, 1958. In December the "Devils Icebox," as the lower mine was called, contained about 80,000 *M. sodalis* by Myers' conservative estimate, based on a density of 2,367 bats/m^2 (220 bats/ft.^{2}). Another photograph appeared to have about 3,229 bats/m^2 (300 bats/ft.^{2}), estimated from the size of a man's hand near the bats and by counting bats inside a frame drawn by Elliott and Kennedy (2008). Myers also estimated at least 35,000 *M. lucifugus* in the mine. Elliott and Kennedy (2008) concurred with the U.S. Fish and Wildlife Service (USFWS) that 100,000 may be a reasonable reestimate for 1958, especially since the upper mine was not visited during Myers' trips, but it is now known to harbor bats. In February, 1958, the interior of the mine appeared to be stable, with old wooden roof supports mostly in place. By December Myers noticed that boulders had shifted, and there had been some rock falls in the entrance area and on the route to the hibernaculum. Myers last visited the mine in March 1960.

In 1975 Richard and Margaret LaVal from the Missouri Department of Conservation (MDC) began harp-trapping estimates of *M. sodalis, M. lucifugus* and *M. septentrionalis* at the lower mine entrance, but they did not enter the mine, owing to its "dangerous" reputation. Richard Clawson

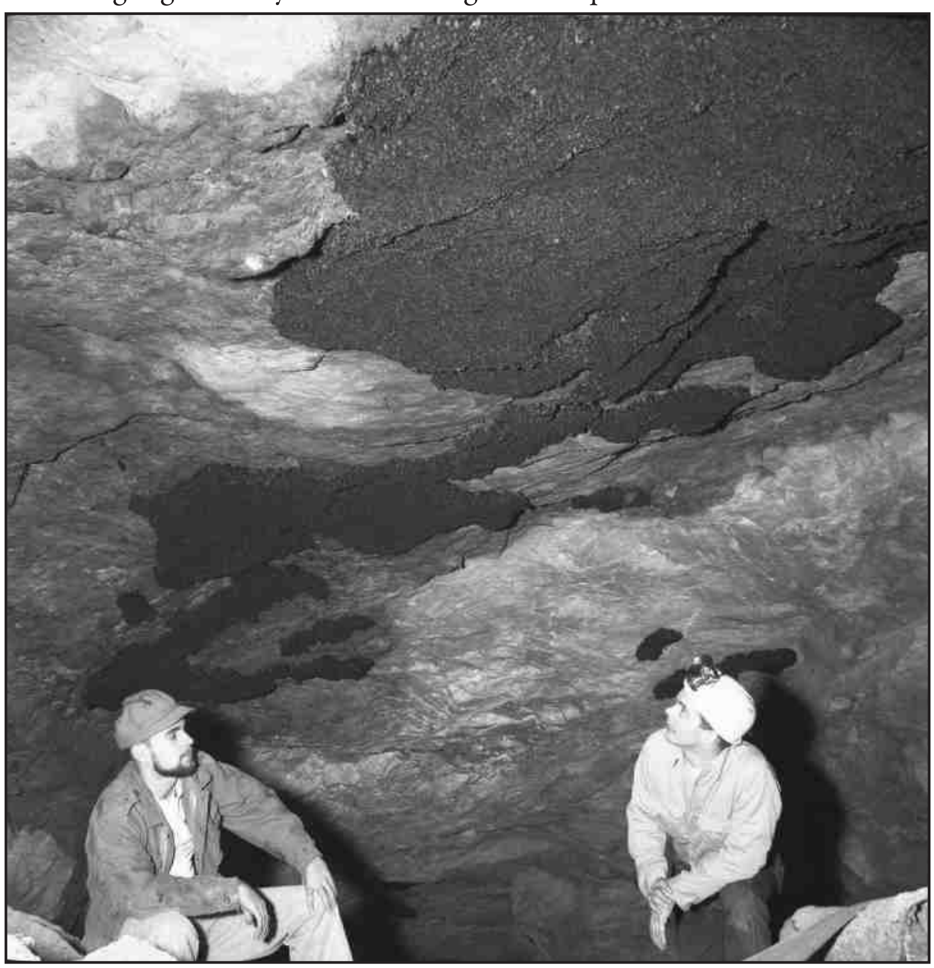

Figure 1 Hibernating Indiana bats in the lower part of Pilot Knob Mine, February 22, 1958. Photo by Richard F. Meyers.

soon joined their project, and they continued the effort until 1978 (Clawson and Titus 1988). Trapping usually was done in late September or early October during the fall mating swarm. The great majority of bats captured and released, usually over a two-hour period in two rounds or "bags," were *M. sodalis*, with some *M. lucifugus* (Little brown bat) and *M. septentrionalis* (Northern bat). They were identified to species, most were sexed, and some were weighed and examined in detail.

MDC continued to census cave bats after 1975 (Clawson and Titus 1988, Clawson et al. 1992, McGimsey and Johnson 1994, Clawson 2002, Clawson, Elliott and Burns 2006, Elliott 2005, Elliott 2007, Sasse et al. 2007). LaVal et al. (1977) completed an evaluation of bat caves in the proposed Meramec Park Lake and Union Lake project areas. Many important caves would have been inundated by the Meramec Lake, but it was not built (Elliott 2007).

On May 25, 1979, at Pilot Knob Mine, LaVal reported that "a colossal collapse has occurred, blocking the two entrances used by bats. Cold air is blowing out of the rocks above the old main exit site, it appears a person could still get in by climbing among newly fallen giant boulders. The higher main entrance that was being used by nearly half the bats earlier this spring appears to be completely blocked. The entire south wall of the 'Devils Icebox' has collapsed, partially filling the icebox ... We suspect foul play, but saw no evidence of same." A federal agent was sent to investigate, but he reported no evidence of violations. After the collapse there were no harp-trapping trips until 1992. Intruders may have affected the bats, but much of the subsequent decline probably was the result of this partial collapse of the lower mine, which may have killed many bats. Furthermore, it probably caused changes in airflow and the availability of habitat (Elliott and Kennedy 2008).

In 1986, a local boy was trapped and injured in the lower mine while exploring with a friend. He was rescued after a two-day ordeal, in which he barely survived and nearly lost his legs. Some called for permanent closure of the mine, but its value as a bat refuge also was publicized. Within a year the U.S. Fish and Wildlife Service received a donation of the mine and 90 acres from the Pilot Knob Ore Co., and the area was fenced (Elliott and Kennedy 2008). In 1992, Clawson and others resumed harp-trapping studies at Pilot Knob Mine, but they did not enter the mine. These studies continued through September 2007.

From 1978 to 1984, Gardner (1986) collected numerous invertebrate specimens from 436 caves and 10 springs, providing important baseline information on subterranean biodiversity. No comprehensive list of Missouri's cave vertebrates has been published, but a 1984 computer printout with a large number of bat observations was contributed by Gardner to the author's Cave Life Database (CLD). The author joined MDC as cave biologist in 1998, and he worked with other researchers to study Missouri's cave life. Bat census and cave protection were important duties of the cave biologist, shared with Clawson. Since 1978 Clawson contributed voluminous census data on bats from 103 caves and three mines in 38 counties, primarily of Grays and Indianas (Elliott 2007). A year-long study of 40 caves was led by MDC and the Missouri Caves and Karst Conservancy, in which common species were recensused 20 years after Gardner recorded them. A possible decline in *Eptesicus fuscus*, Big brown bat, was noted at some caves (Elliott and Ireland 2002).

For spot temperature readings and data logger checks, Clawson and Elliott used digital thermometers, with accuracy ±0.1C°, calibrated in freezing water to measure air and rock temperatures during hibernaculum surveys. In 1998, the author and others installed Hobo® H8 Pro temperature data loggers in seven caves and Pilot Knob Mine for a joint study by Bat Conservation International (BCI) and MDC. The study sites were Great Scott Cave and Scotia Hollow Cave, Washington County, Bat Cave, Shannon County, Pilot Knob Mine, Iron County, Onyx Cave, Crawford County, and Brooks Cave, Great Spirit Cave, and Ryden Cave, Pulaski County (Elliott and Clawson 2001). They obtained weather data from 1975 through 1998 for several Missouri cities from the Department of Soil and Atmospheric Sciences, University of Missouri–Columbia. The data set from Waynesville, Pulaski County, is geographically close to most of the study sites. They examined the secular trend of annual means, extreme lows, and extreme highs.

On February 7, 1999, Jim Kennedy and Sheryl Ducummon of Bat Conservation International (BCI) visited the lower part of Pilot Knob Mine, but found only 303 *M. sodalis.* MDC's harp-trapping results were used to estimate as many as 50,545 Indiana bats in the mine until 2007. This method was not calibrated against a count in the mine, but against catch rates at Great Scott Cave in the 1970s. Concern about the true number of bats in the mine continued, especially as the harp-trapping results decreased. Elliott and Kennedy (2008) found only 1,678 *M. sodalis* there in February 2008.

Missourians have built at least 67 cave gates, 55 of which were for Grays, Indianas or both. MDC built 22 cave gates on Conservation lands, and they assisted ten other landowners with cave gates. Forty-six caves were gated for Grays, 38 for hibernating Indiana bats, significantly helping endangered and other bats. Two gates were destroyed by flash floods and two were removed because they were not helping bats. In the last 30 years the downward trend in Gray bats was reversed at many caves where the landowner was involved or where MDC helped with signs and appropriate cave gates. However, Indiana bats continue to decrease at most sites, despite good protection of the larger colonies since the 1970s and 1980s.

Materials and Methods

General bat activity can be gauged with mist netting and Anabat detectors, but those methods are not used for censusing. In Missouri various methods have been used to census bats, listed below in generally increasing order of accuracy:

- Harp trap with catch rate calibrated against in-cave count,
- Measurements of guano or ceiling stains, with area times density (Figure 2),
- Roost counts: direct counts, measured area times density, counting virtual rows and columns, or counting from photographs (Figure 3),
- Stopwatch visual exit counts with spreadsheet estimate (Elliott et al. 2006),
- Near-infrared (NIR) videography with statistical counts or thermal infrared (TIR) videography with computer count (Sabol and Hudson 1995, Melton et al. 2005, Elliott et al. 2006).

MDC has used most of the above methods, but most of the data on Gray maternity colonies have been from guano estimates until we began using NIR in 2004. Both methods were used until we were satisfied that they were comparable.

Figure 2 MDC biologists measure Gray bat guano in Smittle Cave, Wright County, Missouri.

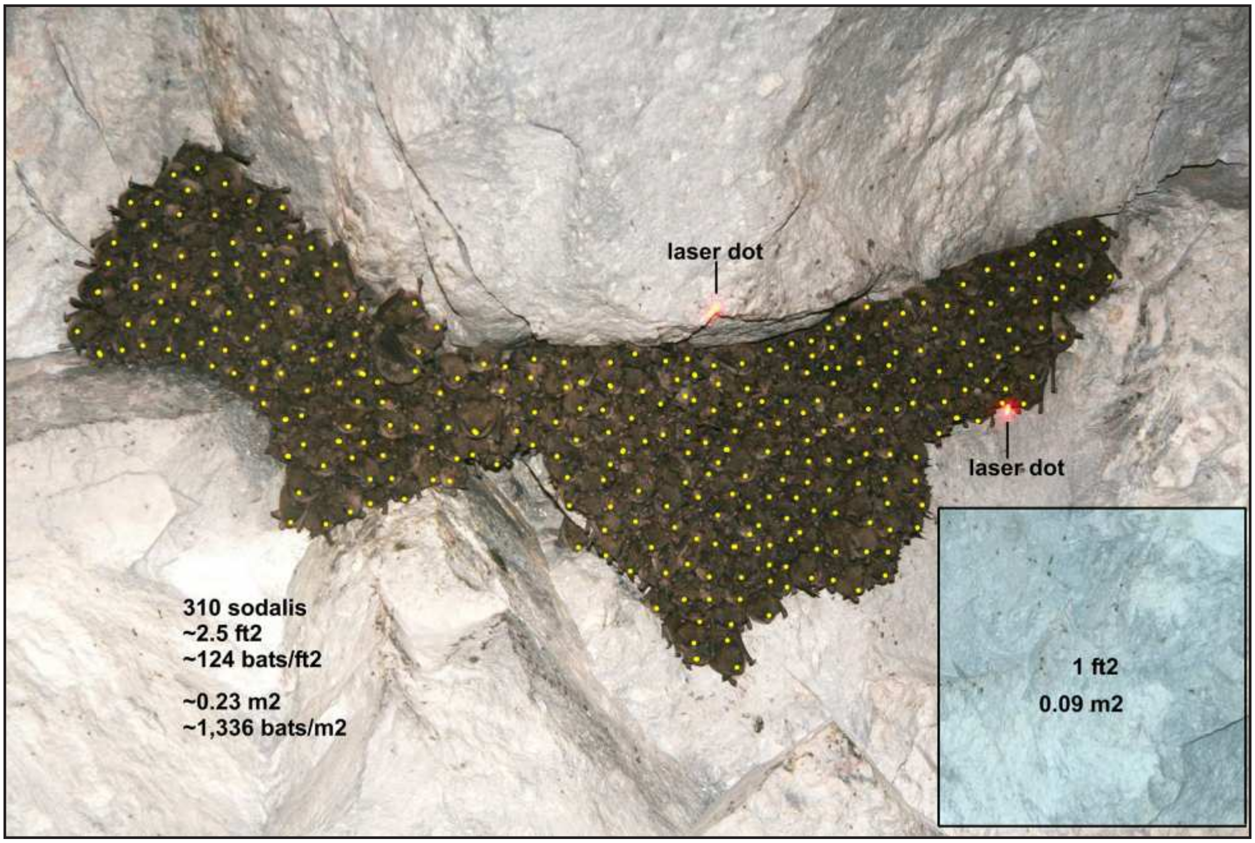

Figure 3 *Pilot Knob Mine, February 25, 2008, view of about 310 Indiana bats. Visual counts were later corrected by adding digital dots on the photos. The two laser dots from a laser caliper are 30.48 cm (1 ft.) apart, yielding about 1,336 bats/m^2 (124 bats/ft.^{2}).*

TIR became available experimentally in 2006, and we used it extensively in the summer of 2008. We may discontinue guano measurements after 2008. Winter visits used roost counts, to which we added high-resolution digital photographs in 2007.

Census data from many sources were entered into the Missouri Natural Heritage Database and the CLD, a Microsoft Access® database. Special queries were made to view and edit the data, export it to Excel® and graph it.

From 1975 to 1977 Indiana bat surveys were done yearly at some sites, but starting in 1979 most were biennial. To examine long-term trends, data from a few dates were moved to the nearest year in the same winter to put all on the same basis, and the 1978 Pilot Knob Mine harp-trap estimate was placed in 1979 for graphing. Five data for Great Spirit in 1981, Scotia Hollow in 1983, Brooks and Ryden in 1989, and Onyx Cave in 2003 were absent, so they were calculated as a mean of the previous two years to fill the cells for graphing. Most of the data for Pilot Knob mine are based on one harp-trap estimate from 1978 and two in-mine counts in 1999 and 2008, the rest were interpolated linearly between these anchor points. However, these estimates do not affect the overall estimate of decline since "1979." Although some hibernaculum surveys began in 1975, I focused on trends since 1979, when more data were available for the 11 major and 8 minor hibernacula. This did not ignore any significant 1975–1979 trends that I could see. I examined the trends for the major and minor sites separately.

Results

Overall results are provided in Table 1, and details are provided in Tables 2-6 and Figures 1-16.

Indiana bats. *M. sodalis* is known from 75 caves and 2 mines, about 1% of the 6,200 known caves in Missouri. Of these, 53 sites are hibernacula and 24 others are used by transients in spring or fall on their way to or from forest habitat, mostly in northern Missouri. The 1979 population was 315,045 as measured at 11 major sites, but it declined to 8,632 at the same 11 sites in 2007, a

Table 1 *Status of Gray bats and Indiana bats in Missouri. MPP is "maximum past population." The recent data are from 2006–2008. The recent hibernating populations were an aggregate of 31 caves.*

	Grays	Indianas
Past population	1,700,000 (MPP)	315,045 (1979)
Maternity caves	49	0
Hibernacula	13	53
Other sites	157	24
Total sites	219	77
Recent maternity colonies	635,000	---
Recent hibernating colonies	784,000	15,812
Percent of past population	37-46%	5%

drop of 97%. Two (18%) of the sites were essentially abandoned. Many additional, minor sites were found in 30 years, so in 2006-2008 there was a total of 15,812 Indianas counted in 31 important sites, but still only 5% of the past, known population.

The overall trend for 11 major Indiana bat hibernacula is shown in Table 2 and Figure 4. All of the major sites lost a large number, whether or not they also had large numbers of Gray bats hibernating nearby. The decline in Pilot Knob Mine, which contained 36-44% of the state population in 1979, was 98% depending on which estimate used.

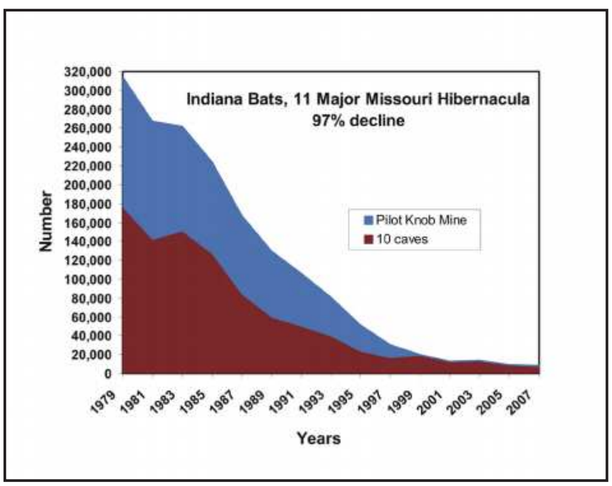

Figure 4 *Population trends at 11 major Indiana bat hibernacula, 1979-2007. The Pilot Knob data are stacked on the data for 10 caves.*

The trends for eight minor *M. sodalis* hibernacula are more difficult to assess numerically because all have not been followed completely for many years. Table 3 shows that four have been

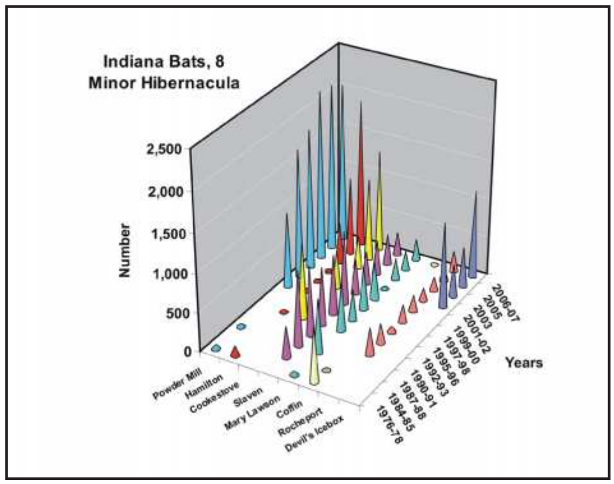

Figure 5 *Population trends at eight minor Indiana bat hibernacula, 1976–2007.*

censused since the 1970s, and most of the others since 1990-1991. Four of the colonies were up by 2006-2007, two were stable, and two were down (Figure 5). The largest increase was at Powder Mill Creek Cave, which was gated in 1995, after which the colony increased to >2,000 despite temperatures >10°C in the late 1990s. These bats may have moved from Bat Cave, Shannon County, about 28 km away, which essentially was abandoned, perhaps because of extremely variable temperatures, often below freezing (Elliott and Clawson 2001), and an increase in Gray bats there, but the true cause is uncertain (Figure 6). At Bat Cave the Grays usually moved up to the 10-meter-high ceiling where it is warmer, but the Indianas stayed under ledges and domes close to the floor where it was colder.

Gray bats are present at some of the sites that

Table 2 *Indiana bats in 11 major Missouri hibernacula, 1975–2007. Trends were examined and graphed from 1979-2007. Missing data (bold) were inserted from means of the previous two years (caves), or from a linear function between anchor points at Pilot Knob Mine. The 1979 estimate for Pilot Knob Mine was actually from October 1978, and the 2007 count was from February 2008. Since 1979 there was a 97% decline in the bats at the major hibernacula, and all lost a large number, whether they also had large numbers of Gray bats hibernating nearby or not.*

Year	Onyx Cave, Crawford	Bear Cave, Franklin	Copper Holow Sinkhole	Brooks Cave	Great Spirit Cave	Ryden Cave	Bat Cave, Shannon	Martin Cave	Great Scott Cave	Scotia Hollow Cave	10 caves	Pilot Knob Mine	Totals
1975	10,800	3,000	15,550						38,860	5,480	73,690	59,695	
1976	21,625	2,100	12,600				46,000		46,600	93	129,018	100,357	
1977	12,700	1,800	9,050				20,670		59,500	3,450	107,170	85,361	
1979	11,100	3,250	8,850	19,375	549	10,550	42,821	8,100	68,700	2,750	176,045	139,000	315,045
1981	5,325	1,750	5,200	11,850	1,792	5,800	32,800	2,425	72,350	3,100	142,392	125,130	267,522
1983	3,267	1,100	3,150	11,150	1,171	4,950	30,750	5,350	85,700	4,550	151,138	111,261	262,398
1985	2,250	650	1,050	5,500	500	2,000	30,450	3,550	77,950	3,400	127,300	97,391	224,691
1987	2,050	525	600	4,900	40	700	4,150	4,900	60,650	5,300	83,815	83,521	167,336
1989	1,575	400	250	5,200	35	1,350	4,275	2,600	38,875	5,150	59,710	69,652	129,362
1991	1,275	300	160	2,700	8	160	4,275	2,975	32,125	6,225	50,203	55,782	105,985
1993	700	225	125	1,550	625	80	6,175	2,250	22,750	4,550	39,030	41,912	80,942
1995	325	190	140	750	450	40	941	2,125	14,850	3,600	23,411	28,042	51,453
1997	260	95	175	600	195	14	450	1,500	11,875	1,615	16,779	14,173	30,952
1999	155	80	155	400	175	14	6,175	1,000	9,100	2,375	19,629	303	19,932
2001	265	105	185	235	285	10	89	2,460	8,250	450	12,334	647	12,981
2003	210	90	250	130	160	13	1,020	2,100	8,875	290	13,138	991	14,129
2005	180	100	250	70	40	10	0	1,300	6,450	150	8,550	1,334	9,884
2007	180	110	380	65	60	3	16	950	5,100	90	6,954	1,678	8,632

Table 3 *Indiana bats in eight minor Missouri hibernacula, 1975–2007.*

Year	Devils Icebox Cave	Rocheport Cave	Coffin Cave	Mary Lawson Cave	Slaven Cave	Cookstove Cave	Hamilton Cave	Powder Mill Creek Cave	Totals
1976–78			714	60			119	60	893
1984–85			0		405				405
1987–88				700	975			50	1,675
1990–91		350			900				1,250
1992–93		250		625	750	1,000	6		2,631
1995–96		80		400	775				1,255
1997–98		220		570	950		44	975	1,784
1999–00		215		500	450	500	1	1,660	3,326
2001–02	1,100	170		5	425			1,800	1,700
2003–04	420	180		280	440	430	530	2,175	2,280
2005–06	520	180		240	400	1,062	1,000	2,150	3,402
2007	1,140	259	17	275	290	1,300	1,900	2,050	5,181

had declines, but not all. Grays are absent at Pilot Knob Mine, which had the worst decline, so if crowding from Gray bats is a factor in the decline of Indianas, it is not the most important factor. New, minor hibernacula of Indiana bats have been found, most notably at Devils Icebox Cave, Boone County, in 2002, but they do not make up the large decline in the major hibernacula. Small colonies of transients are found in additional caves from time to time, they are not represented here, but their conservation also is important.

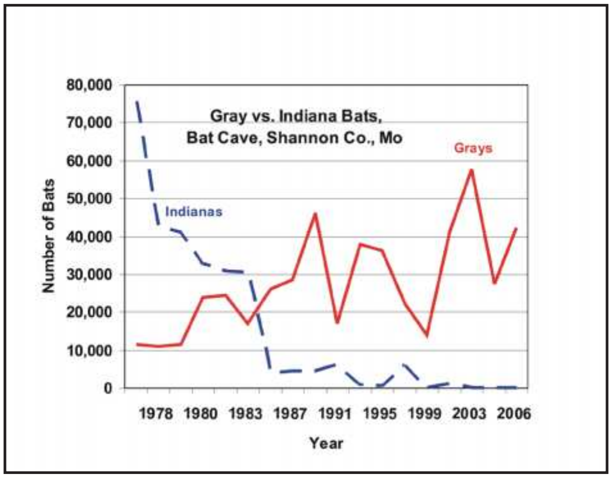

Figure 6 *Gray bats increased in Bat Cave, Shannon County, while Indiana bats declined since 1978. The trends are inversely correlated, but the true cause is uncertain.*

Gray bats. *M. grisescens* has been recorded from at least 219 caves, about 3.5% of Missouri caves (Table 1). Of these 49 are maternity caves, 13 are hibernacula (three with >30,000), 125 are transient and/or bachelor sites and 32 (15%) are abandoned. Additional sites likely exist, especially transient and minor maternity caves.

Table 4 and Figure 7 depict the trends at nine, priority 1, Gray bat maternity caves with a long census record: Devils Icebox, Great Spirit, McDowell, Mary Lawson, Toby (formerly confused with Mauss Cave), Moles, Rocheport, and Smittle caves. Data were placed in five-year bins for analysis. Overall, these colonies increased by 21% from about 1980 to 2005, and were at roughly 37% of their MPP (maximum past populations). Gray bats bottomed out between 1970 and 1985, but increased at many protected caves since then.

Table 5 and Figure 8 illustrate the trends at four, major, Gray bat hibernacula: Marvel, Mose Prater, Coffin, and Bat/Shannon caves. Marvel Cave, a show cave, lost most of its hibernating Grays because of warming trends in the cave caused by man-made alterations at the entrance, which decreased the influx of winter air. The other three hibernacula, which are protected without artificial alterations of airflow, have had increases in Gray bats.

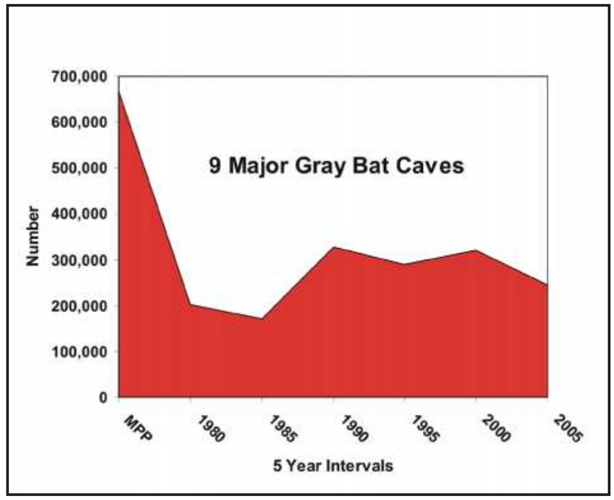

Figure 7 *Trends at nine, priority 1, Gray bat maternity caves with a long census record. See Table 4. Overall, these colonies increased by 21% about 1980 to 2005, and were at roughly 37% of their MPP (maximum past populations).*

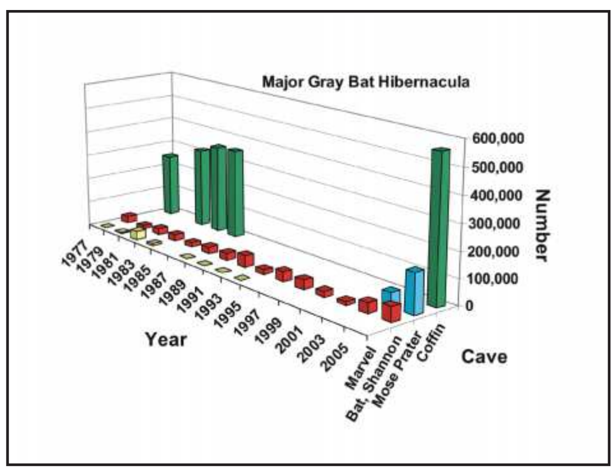

Figure 8 *Trends at four major, Gray bat hibernacula, 1977-2006. Some data have been shifted a year for graphing.*

Table 4 *Trends at nine, priority 1, Gray bat maternity caves with a long census record. Data were placed in five-year bins, bold numbers had no data so numbers were inserted from adjacent cells from the same cave. Overall, these colonies increased by 21% about 1980 to 2005, and were at roughly 37% of their MPP (maximum past populations). Toby was up to 97,000 and Smittle was currently down to 12,800 in the 2008 TIR census.*

	Devils Icebox, Boone	Great Spirit, Pulaski	Mc-Dowell, Miller	Mary Lawson, Laclede	Toby, Camden	Moles, Camden	Roche-port, Boone	Smittle, Wright	Totals
MPP	5,000	250,000	11,000	97,000	54,000	100,000	100,000	50,000	667,000
1980	5,000	10,000	12,000	21,500	42,800	40,000	25,000	46,000	202,300
1985	2,300	11,600	12,000	19,000	54,500	49,000	385	22,200	170,985
1990	9,350	10,200	10,200	36,700	71,400	67,320	16,320	105,500	326,990
1995	9,200	24,000	10,200	36,550	73,450	73,450	26,000	33,650	290,188
2000	13,050	22,000	7,800	34,300	76,700	93,840	41,000	33,650	320,815
2005	12,150	10,900	13,898	71,000	17,000	43,500	50,000	24,500	243,848

Table 5 *Trends at four major Gray bat hibernacula, 1977–2006. Some data have been shifted by one year for graphing. See Figure 8.*

	Marvel	Bat, Shannon	Mose Prater	Coffin
1977	86	27,299		250,000
1979	3,380	11,000		
1981	34,200	23,850		316,300
1983	8,850	24,400		349,500
1985		17,150		355,450
1987	2,425	26,050		
1989	1,286	28,725		
1991	1,300	46,300		
1993	900	17,030		
1995		37,945		
1997		36,400		
1999		22,400		
2001		14,100		
2003		41,100	52,000	
2005		57,850	155,000	561,000

Discussion and Conclusions

Indiana bats. Indiana bats have declined drastically in the Missouri region. The recent, statewide reestimate of about 15,812 indicates that Indiana bats declined by 95% since 1979. Some probably abandoned one cave for another, such as Powder Mill Creek Cave, seeking protection and more optimal temperatures. Pilot Knob Mine, a National Wildlife Refuge since 1987, had 80,000-100,000 Indiana bats in 1958, but only 1,678 were found there in February 2008, a 98% decline.

Tuttle and Kennedy (1999) analyzed 15 cave systems and found a strong correlation between increasing cave temperatures and declining populations of *M. sodalis*. Elliott and Clawson (2001) analyzed temperature data from Missouri caves and surface weather. From 1975 to 1999 the mean annual temperature (calculated from daily highs and lows) at Waynesville, Missouri, was 12.9°C (55.3°F). The standard deviation was 1.4°C and the range was 11.7 to 14.4°C (53 to 58°F). There appeared to be no significant change in mean annual temperature between 1975 and 1999. However, in examining extreme lows in January, they found a possible warming trend since 1975 from about -21 to -18°C (-7 to 0°F). The author believes that extremely low temperatures from severe cold fronts could influence hibernaculum temperatures all year, probably more than mean annual temperatures. Severe cold fronts are usually associated with strong winds and barometric pressure drops, which cause more cold air invasion into caves than weaker fronts. It is possible that the loss of extreme winter lows magnifies the warming at some cold-air traps in Missouri.

We have no continuous temperature records in the hibernacula for 30 years, but we do have spot readings taken with a digital thermometer on every winter trip. Figures 9–13 are selected graphs depicting trends in Indiana bat populations with the simultaneous air and rock spot temperatures. The data were not controlled for exact date, so there may be some hidden variance related to January vs. February visits, generally, and a few December and March dates. However, the rock temperature changes slowly. These graphs illustrate that temperatures were generally above the optimal 5°C for hibernation of *M. sodalis,* found by Dzurick (2007). However, the populations began plummeting generally without much change in hibernaculum temperature. Brooks Cave (Figure 9) is interesting in that it is located on Fort Leonard Wood with only a little disturbance, lacks Gray bats, was never gated, had little temperature change, and yet the bats declined. Ryden Cave (Figure 10) was gated, lacks Gray bats, had little warming and a recent cooling, and the Indianas declined. Great Scott Cave (Figure 11) warmed up mostly because its second entrance was blocked off, but it cooled again after a second cave gate was installed in 1999. Indianas increased there until 1983, then they declined despite the later cooling. Bat Cave, Shannon County (Figure 12), is extremely variable in temperature, and it has had a cooling trend since 1995. Yet Grays increased there while Indianas essentially abandoned the cave (Figure 6). Indianas may have moved from the latter cave to Powder Mill Creek Cave (Figure 13). In the author's opinion, these five examples indicate that the decline in Missouri's Indiana bats has not been caused by temperature changes alone.

Disturbance during hibernation was one of the important, early factors in the decline of Indiana bats, and it still is a threat at unprotected sites. Improperly designed cave gates have been implicated in some population declines, but all such gates have been removed or replaced at Missouri Indiana bat caves. Loss or reduction of roosting or foraging habitat during the warm season also has been suspected.

Pesticide residues were detected in Indianas, Grays, and other bats in Missouri (Clark et al. 1978, 1980, 1983, Clawson et al. 1983, 1989, 1991, McFarland 1998, O'Shea and Clark 2002, Schmidt and Glueck 2002). O'Shea and Clark (2002) provided a review and examined temporal and spatial patterns of agricultural pesticide use in Missouri and Indiana. Some Grays and Indianas died from organochlorine (OC) insecticides prior to their discontinuance in the 1980s. Dieldrin in carcasses of Indiana bats from Missouri in the 1970s was one to two orders of magnitude higher than the norm and reached lethal concentrations in brains of

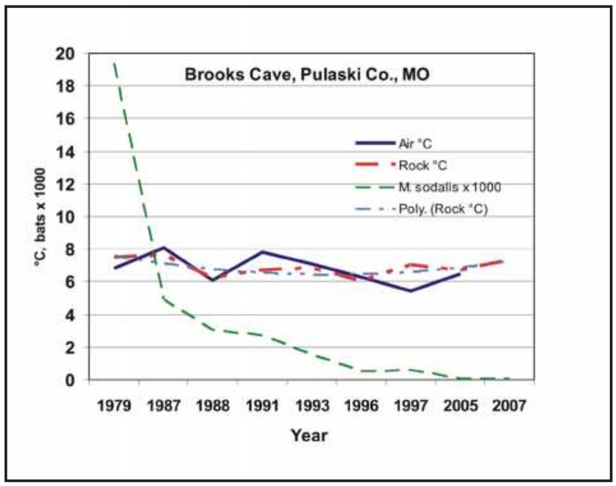

Figure 9 Indiana bat population trend in Brooks Cave, Pulaski County, combined with concomitant air and rock temperature readings. A polynomial trend line (dot-dash line) has been fitted to the rock temperatures in this and Figures 10–13.

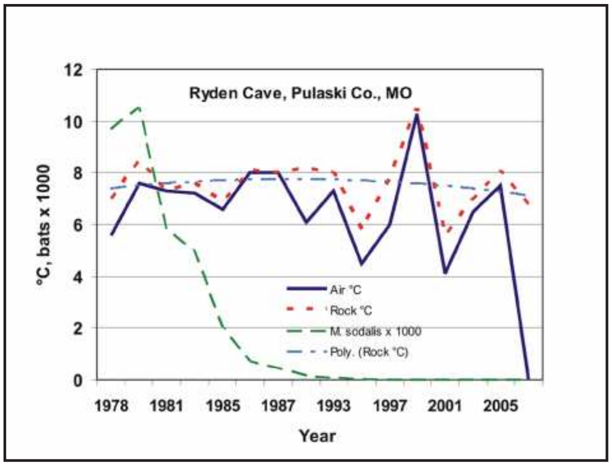

Figure 10 Indiana bat population trend in Ryden Cave, Pulaski County, combined with concomitant air and rock temperature readings.

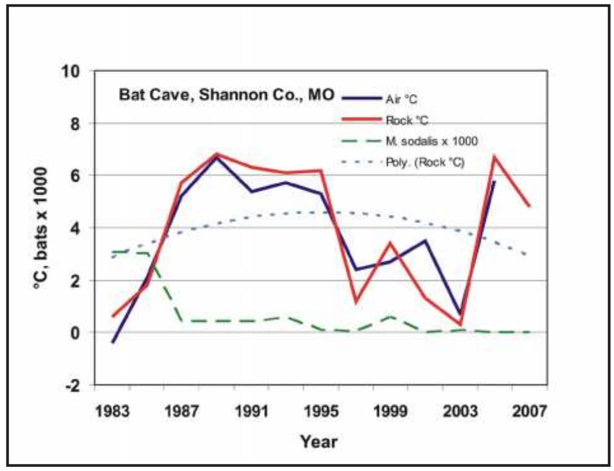

Figure 12 Indiana bat population trend in Bat Cave, Shannon County, combined with concomitant air and rock temperature readings. This cave has extremely variable winter temperatures.

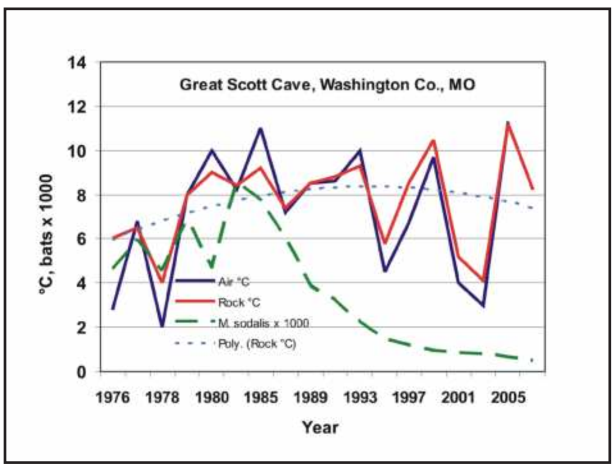

Figure 11 Indiana bat population trend in Great Scott Cave, Washington County, combined with concomitant air and rock temperature readings. A blocked, secondary cave entrance was regated in 1999, which cooled the cave to somewhat normal temperatures.

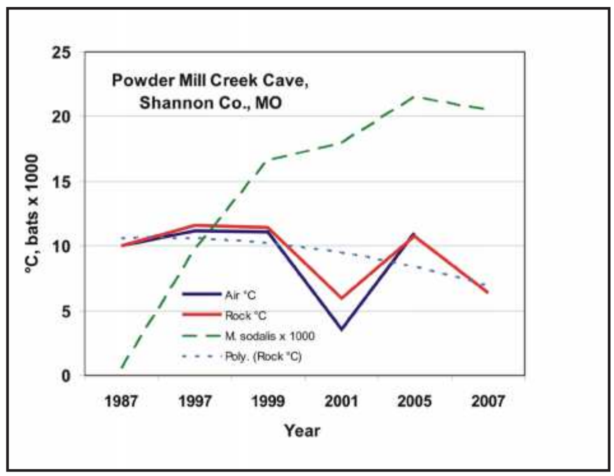

Figure 13 Indiana bat population trend in Powder Mill Creek Cave, Shannon County, combined with concomitant air and rock temperature readings. Although temperatures were >10°C in the late 1990s, the population increased, possibly because they abandoned Bat Cave, Shannon.

some individuals. Chronic mortality was suggested in these two endangered species even in the 1980s. McFarland (1998) found persistent OC residues in Little brown bats and Northern bats, long after OCs were discontinued.

Some studies found organophosphates (OP) and carbamates in Missouri bats. These insecticides are not as persistent as OCs, but they may cause acute toxicity, death, or sublethal intoxication leading to inability to fly, which is certain death in flying mammals. Other sublethal effects on thermoregulation, food consumption, and reproduction could lead to population declines. Pyrethroid use increased later in Missouri, and would also be toxic to bats.

No systematic surveys are currently being done in Missouri that would find pesticides in Indiana and Gray bats, or other suitable surrogate species. O'Shea and Clark's (2002) suggestion that Indianas may forage over cotton fields in southeastern Missouri, heavily treated with insecticides, is an unlikely scenario because cotton is >100 km from the nearest, known hibernaculum. A more realistic hypothesis of a cause of Indiana bat decline would be pesticide contamination of prey insects in northern Missouri, where there is much more pesticide use in row-crop agriculture than within the range of foraging Indiana bats in most of southern Missouri. Circumstantial evidence in favor of this hypothesis is the continued increase of Gray bats, which range more in the southern part of the state, in forest, pasture, and hay areas with little pesticide use. The Missouri Natural Heritage Database has no current records of Indiana or Gray bats in the row-crop areas of southeastern Missouri, such as Perry County, which has many caves, but is also farmed for corn and soybeans. No caves occur in the cotton-growing areas of the Missouri Bootheel, comprising Dunklin, Pemiscot, New Madrid, Stoaddard, and Scott counties (Elliott 2007).

Another hypothesis would be crowding by increasing Gray bats, but I do not believe that to be an important factor based on two observations (1) Indiana bats declined at most sites, even without Gray bats present, and (2) I have not observed agonistic behavior between Grays and Indianas, although I have photographed Grays crawling on the edges of Indiana bat clusters several times, and even on top of Indiana bats (Figure 14). Grays do this in their own clusters, but I have not observed Indiana bats leaving as a result of such behavior, although our visits are brief.

Disease is another hypothesis of decline that has not been eliminated. White Nose Syndrome, which had a recent outbreak in bats in the north-

Figure 14 *A cluster of 43* Myotis sodalis *with five* M. grisescens *on the edge, indicated by white dots. Onyx Cave, Crawford County, Missouri, January 19, 2007.*

eastern U.S., has not been found in Missouri to date, and it probably was not involved in declines 30 years ago. Several Missouri bat caves were checked in the winter of 2007–2008 and, although some bats were seen with mold on their skin, they did not fly outside during the day or appear to be starving, which are characteristic of this syndrome.

I suggest that Indiana bats in Missouri have been adversely affected by several factors: disturbance by humans (especially 30 years ago, but at some sites even today), the partial collapse of Pilot Knob Mine in 1979, some effect from global warming at some hibernacula, (especially from the loss of extreme winter lows), and possibly pesticides and loss of summer habitat in northern Missouri.

Gray bats. Missouri's Gray bat population declined, but is now stable or increasing in some protected caves. Many other caves remain abandoned for various reasons. At bottom, Gray bats had lost at least 67% of their maximum past population, as measured in 56 important caves, and 53% of the caves were abandoned. The maternity population of Gray bats in Missouri is currently estimated at approximately 635,000. This is compared to evidence (guano and ceiling stains) suggesting that historic populations in the same set of caves once numbered over 1,700,000 (Table 1).

Thirty-one Gray bat hibernacula totaled 784,000 in recent years. The three major hibernacula were censused in 2006 and totaled 773,850. While Marvel Cave declined, Bat Cave, Shannon, was at 337% in 20 years, and Coffin Cave was at 157% (Tables 1 and 5).

Although there has been a general increase in Gray bats, many maternity colonies are still threatened by intruders and vandals. Table 6 summarizes events and population trends at 13 selected caves. These examples illustrate the typical problems that MDC has seen in managing these caves, and there are a few extreme examples as well. Figures 15 and 16 illustrate the vagaries of management at Blackwell and McDowell caves, whose bat populations have fluctuated with archaeological looting and breaches of the otherwise effective gates built in 2001.

The conclusion that I draw from ten years of bat cave management in Missouri, is that it requires a major effort by many people to keep Gray bat colonies stable or increasing, and to keep the few remaining Indiana bat colonies from being disturbed by intruders. One cannot gate a cave and consider it safe for long. Each cave gate must be checked and maintained periodically. It is common to find a breach in even the strongest cave gate within a few years. The more cave gates that are built, whether on state or private land, the more long-term commitment we have to maintain the gates. The gates may have an expected lifetime of 30 to 50 years in a relatively dry entrance, but at caves that are prone to flash flooding the gate may only last two to four years. Many lessons have been learned by wildlife agencies who build cave gates. Having lost three cave gates to floods in the last 11 years persuades the author to be cautious about building any more, unless they are built to higher engineering standards at greater cost.

Obtaining accurate census data also is a large task, now involving several experienced biologists, weeks of field time every year, high-quality digital cameras, flash units, infrared video gear, specialized software, and many hours for analysis. As pointed out by Martin (2007) and Sasse et al. (2007), more accurate and standardized census data are needed across the range of Gray bats before one could downlist or delist them from the U.S. Endangered Species List.

The Gray bat is a key species in Missouri cave ecosystems, providing nutrient input to animal communities. Conservation work has returned Gray bats in Missouri to about 46% (784,000) of the state population decades ago. I have calculated that the average colony of 10,000 Gray bats consumes about 45 kg (100 pounds) of insects each night between March and October, based on eating half their weight each night, or up to their weight each night for pregnant or nursing mothers. That translates to about 10 metric tons per year, about 4.3 billion insects. They eat a variety of species, such as aquatic insects—especially mayflies, caddisflies, and stoneflies—but also beetles and moths, some of which are agricultural pests. Statewide, Gray bats are eating 490 metric tons (223 billion) of insects per year. This is a major economic and environmental benefit to humans. We should also consider how much insect control we have lost by losing 300,000 Indiana bats in 30 years.

We have found that Grays and Indianas are unlikely to return to long-abandoned roosts, but this does not mean that restoration of caves and cave gating should not be tried where the potential payoff may be great. For Grays and Indianas, cave gates

Table 6 Examples of management problems and population trends at selected Gray bat maternity caves.

Cave, County	History	Population Trend
Bat Cave #1, Franklin	Upper entrance bulldozed 1970s, lower entrance full gate1989, airflow reduced, cave cooled, pigeons infested lower entrance. MDC opened upper entrance and gated 2005, temperatures more natural. Upper gate breached and repaired 2007.	MPP 91,800 in 1976. Abandoned before 1990. Colony in nearby suboptimal cave might recolonize. MDC monitors for bats yearly.
Blackwell, Hickory	Difficult to monitor. Full rebar gate in 1979 hindered bats, modified to flyover in 1980. Break-ins by looters and abandonment 2000. New flyover gate 2001. Intrusions and break-in in 2004–2005, bats dropped to 700 in 2005.	Varies with intrusions.
Devils Icebox, Boone	No gate, intruders are infrequent because of strict park management, scheduled caving trips and long, cold water passage.	Stable since 1995.
Grandpa Chipley, Camden	MDC aquired 1997. Some intrusions, flyover gate 2004. Gate fell down April 2008 because of flooding and too few pins to walls.	Probably stable. Guano washes out, difficult to census until NIR and TIR.
Great Spirit, Pulaski	Show cave 1950s, MDC acquired 1981 and installed inadequate chain-link fence. Intense looting and bat disturbance. Large flyover gate 2002 for multiple resources.	Nearly abandoned. Struggling maternity colony.
Lower Burnt Mill, Camden	Frequent intruders from river recreators until April 2008 when MDC built chute gate and acquired land. Bats absent summer 2008, may be at Toby 5 km away.	Struggling maternity colony varied 0–30,600 since 1978 with intrusions.
Mary Lawson, Laclede	Good private protection for many years, MDC acquired and gated with flyover, 2004.	Up since gating
McDowell, Miller	Isolated area of park, frequent looting and visitors disturbed bats despite signs, chute gate 2001, breached 2003 or 2004, breached 2006 or 2007. More maintenance needed.	Varies with intrusions. Censused most summers since 2001.
Moles, Camden	In remote area, full constricted gate 1978, removed 1979 when it hindered bats.	Stable for long time, down in 2005, colony exchanges with Toby Cave.
Rocheport, Boone	Show cave 1965, owner tried to smoke out bats. MDC acquired 1995, flyover gate 1996, washed out 1997. New, very large flyover gate 2002, washed out 2004-2007. Second gate too heavy for structure, inadequately anchored, flood debris clean out a problem. Perimeter fence installed 2008.	Varies with flash floods, intrusions.
Smittle, Wright	Show cave 1950s. Acquired by MDC and fenced 1988. Flyover gate 1997. Some intrusions and two breaches. Open to permit caving in May and September. Key may have been copied by some permittees. Guano difficult to measure in cave stream.	Peaked at 105,500 in 1985 (guano). Down to 12,800 in 2008 (TIR).
Toby (Mauss), Camden	Large cave in remote area, protected well by private owner. Some caving allowed during appropriate times.	17,000–81,600 in 1977–2003, 97,000 in 2008.
Tumbling Creek, Taney	Intrusions led to constricted internal barrel gates 1966. Gates removed and large chute gate built 2004.	Declined 36,450–12,400 from 1976–2004. Up to 36,000 since regating.

are still important, and they must be checked and maintained periodically (Elliott 2006).

Acknowledgments

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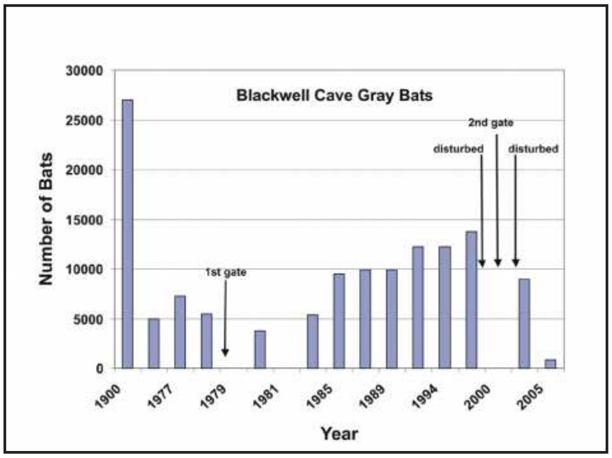

Figure 15 *Blackwell Cave's Gray bats have been repeatedly disturbed by archaeological looters and vandals. The flyover gate, built in 2001, was breached and a ladder was used to gain entry. Only 98 bats were seen in July 2008.*

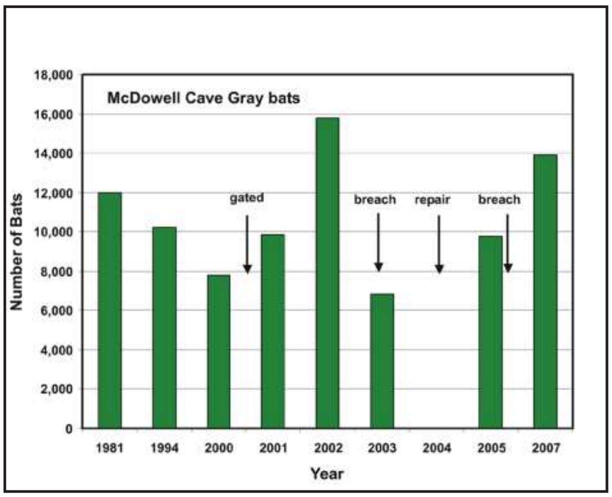

Figure 16 *A chute gate was built on McDowell Cave in 2001. No census was done in 2004. Small breaches of the chute were repaired, but the Gray bat colony was affected sometimes.*

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OZARK CAVEFISH (*AMBLYOPSIS ROSAE*) CONSERVATION IN MISSOURI: A PROACTIVE APPROACH TO RECOVERY

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Abstract

Missouri Department of Conservation personnel are conducting a three-year project using recharge area delineations for known Ozark cavefish (*Amblyopsis rosae*) sites to reach landowners and implement groundwater protection efforts in Southwest Missouri. A U.S. Fish and Wildlife Service Landowner Incentive Program grant is being used to support these efforts and to protect and recover this species of special concern.

The recharge areas encompassed by this project are variable in both size and degree of development and human disturbance. Various methods are being used to reach people living in these recharge areas. Targeted mailings, special-invitation meetings, telephone contacts, and on-site visits are among the approaches used. Outreach and education efforts are designed to reach highly urbanized populations in some recharge areas and include informational meetings, booths and displays at special events, cooperation with local watershed groups, distribution of promotional materials, newsletter articles, and information distributed through local media outlets.

This project differs from most Missouri Department of Conservation incentive programs in that selected landowners are actively contacted, rather than waiting for landowners to initiate contact. With a unique environment and an unusual and often-misunderstood fish as the focus, the best information and management practices available are used to match the characteristics, problems and limitations at each site.

Landowners in seven recharge areas have received mailings, efforts are underway to secure easements, and Missouri Department of Conservation staff is working closely with partners to promote non-traditional "best management practices" at selected locations. Summaries, examples and case histories are discussed.

Key words: *Amblyopsis rosae*, cavefish, Ozarks, karst land management, Missouri

Introduction

The Ozark cavefish, *Amblyopsis rosae* (Figure 1), is a stygobite, an aquatic, subterranean organism. Its range is exclusively in the Springfield Plateau region of the Ozarks, which includes parts of southwestern Missouri (Figure 2), northeastern Oklahoma, and northwestern Arkansas (Pflieger 1975). The small size of the Ozark cavefish, which is not known to exceed 56 mm (2.2 in.), allows it to move about in small cracks in limestone bedrock. *A. rosae* is observed in solution cave streams, springs and wells within karst groundwater of its range. It

Figure 1 **Ozark cavefish, *Amblyopsis rosae*. Photo by Jim Rathert, Missouri Department of Conservation.**

is well-adapted to life in total darkness with no body pigment or eyes, but with sensory papillae located throughout its body that aid in finding food. It is inferred that as few as 20% of females breed and have mature ova in a given year (Poulson 1961, 1963).

The Ozark cavefish is listed as a federally threatened species by the U.S. Department of the Interior (Willis and Stewart 1984), and the Missouri Department of Conservation (Missouri Department of Conservation) lists *A. rosae* as endangered in the state of Missouri (1999). Southwest Missouri contains the majority of the documented active sites for the Ozark cavefish. A site is considered active, not historic, if it is currently accessible and Ozark cavefish have been documented at the location after 1970 (Missouri Department of Conservation 1999).

Missouri Department of Conservation has taken a leadership role in recovery of this species in southwest Missouri. In 1999, Missouri Department of Conservation created "An Action Plan for the Ozark Cavefish (*Amblyopsis rosae*)." This plan set up a long-range strategy for protecting *A. rosae* in Missouri that centered on identifying and minimizing threats to current populations. The major threats to Ozark cavefish outlined in the Missouri action plan were declining water quality related to groundwater pollution in karst environments, habitat disturbance of cave ecosystems, and loss of stream flows by declining groundwater levels. Since establishment of this action plan, Missouri Department of Conservation has started a water-quality and population-monitoring program, constructed protective structures around active sites, and contracted recharge delineation studies in known, active-site geographies of Ozark cavefish to identify sensitive areas for groundwater and Ozark cavefish protection.

Because of growing threats to these sensitive karst ecosystems in southwest Missouri, Missouri Department of Conservation applied for and received a three-year Landowner Incentive Program (Landowner Incentive Program) Tier 2 Grant from the U.S. Fish and Wildlife Service. The purpose of the grant is to work specifically with private land-

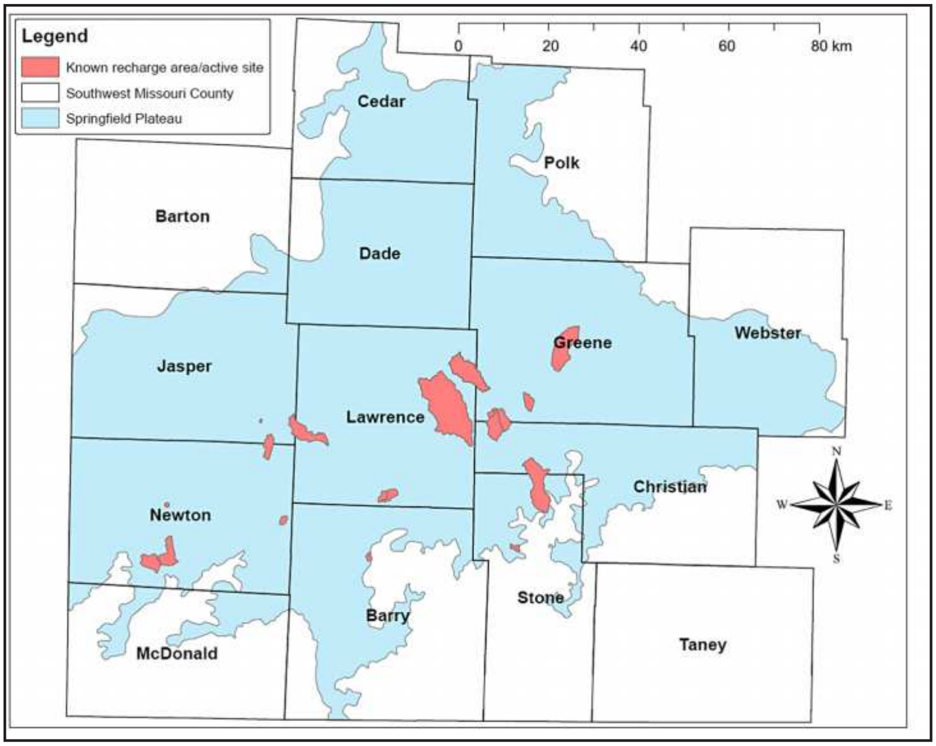

Figure 2 **Range of the Ozark cavefish in Missouri, 2008.**

owners within these Ozark cavefish recharge areas to protect the karst groundwater they inhabit from degradation. The federal share of this Landowner Incentive Program grant is $240,900. This grant allows a unique opportunity for Missouri Department of Conservation to take a more proactive approach to contacting and educating landowners and implementing conservation. As of the start of this Landowner Incentive Program grant, Ozark cavefish were known from 15 specific cave or well locations in southwest Missouri. Thirteen recharge areas have been delineated for known active sites (one recharge area contains two active sites).

Materials and Methods

As a conservation agency, Missouri Department of Conservation has consistently worked to provide genuine assistance to public and private land managers to preserve fish, forest and wildlife resources for the state of Missouri. One of the most important means by which Missouri Department of Conservation has done this is by offering technical assistance and cost sharing with landowners on conservation-friendly land practices. Most of the day-to-day, private-landowner work that Missouri Department of Conservation coordinates is reactive in nature. A landowner requests assistance, and Missouri Department of Conservation responds promptly and courteously. Even in endangered-species management and recovery, generally an interested or concerned landowner initiates first contact.

Since the Ozark cavefish is unknown and unseen by most of the general public, this reactive approach is not the preferred method. An effective outreach to specific landowners in recharge areas is essential to make these landowners aware of technical, and cost-share assistance available to them. A more proactive approach is needed to ensure better results. The strategy implemented through the Landowner Incentive Program grant utilizes this proactive strategy.

The 13 targeted recharge areas vary in size, shape and land use, but the determining factor deemed most important to planning appropriate landowner outreach to these recharge areas was degree of development. Nine of the recharge areas are rural with the majority of these areas located outside any municipality. The land use in these areas is currently dominated by agricultural practices. The other four recharge areas are considered urban with most of these recharge areas encompassed within the city limits of a growing community. Different outreach strategies were used for rural and urban recharge areas.

The main method used to accomplish initial outreach in rural recharge areas was sending targeted, direct mailings to area landowners. Names and addresses of property owners within the delineated recharge areas were collected from county courthouse records and used to address postcards sent to the landowners. These postcards invited the landowners to an evening meeting in their community explaining special technical and financial assistance made available through the grant for practices that protect groundwater quality. At the meetings, landowners learned about the relationship between Ozark cavefish and groundwater quality and how specific conservation practices benefit groundwater for both cavefish and people. If landowners were interested, individual site visits/appointments were set up to address groundwater quality protection on their land and develop an individualized plan of action using available cost-share options. A follow-up mailing was sent to those unable to attend within two weeks after the landowner meeting. This was done to ensure that all landowners within the recharge area had ample opportunity to learn about the cost share available. Interested landowners could then contact Missouri Department of Conservation via telephone or e-mail.

This direct mailing approach was not plausible or cost-effective in reaching landowners in the urban recharge areas. Also, since the property owners associated with these urban recharge areas generally owned lots smaller than 2 ha (5 ac.) in size, it was less likely that these urban landowners would require a detailed, cost-shared conservation agreement. As a result, general education on groundwater quality protection practices, not establishment of larger, cost-shared conservation practices, was the main outreach goal to these urban landowners.

To accomplish this education, Missouri Department of Conservation cooperated with local urban watershed committees, and utilized such outreach opportunities as fair booths, youth programs, and newspaper/newsletter articles. A new Ozark cavefish brochure was created that outlined the importance of protecting Ozark cavefish, and promotional items such as magnets, stickers, rain gauges, and coffee mugs are routinely given away at community events. Also, a variation of the special invitation meeting has been planned for the public at a local nature center.

One other method employed to reach these urban landowners was the creation of an Ozark cavefish placemat as an outreach tool. The placemat highlights drinking water quality and contains pictures, kids' activities, trivia and useful facts on groundwater protection. It will be made available to restaurants within the urban recharge areas.

Results

To date there have been targeted landowner meetings for seven of the 13 delineated recharge areas in Missouri, with three remaining meetings projected. A total of 43 landowner contacts were made at these meetings. Fifteen people attended the public meeting on Ozark cavefish intended for urban landowners at the Springfield Conservation Nature Center. Follow-up landowner visits have been made to 27 different, individual landowners, and currently seven landowner contracts are pending payment/completion in three Ozark cavefish recharge areas. Nearly 500 targeted landowners have been contacted about the Landowner Incentive Program grant through initial and follow-up mailings. Also, over 7,800 landowners received information on Landowner Incentive Program grant opportunities through published articles in local Soil & Water Conservation District and Farm Service Agency (SWCD/FSA) newsletters. The Ozark cavefish placemat intended for area restaurants is currently under development.

This grant is currently providing opportunities for landowner assistance through a number of nontraditional best management practicess including assistance on installation of an advanced septic system, removal of trash from a sinkhole, establishment of two light equipment crossings, and installation of lockable lids for viewable well openings.

Other accomplishments include discovery of two new Ozark cavefish locations. Landowner Incentive Program funding is paying for a recharge delineation of one of these new sites, while alternative funding is currently being sought for the other new site. Landowner Incentive Program is also currently funding a recharge delineation study on a once-historic, newly-active Ozark cavefish site. This site was classified as historic until an old well cap was removed and Ozark cavefish were seen there in May 2006. The current number of active sites in Missouri is now 18.

Two grant proposals for additional funding were drafted during the first year and a half of this Landowner Incentive Program grant. A recovery land acquisition grant proposal was sent to the U.S. Fish and Wildlife Service for acquisition of an Ozark cavefish site currently on the open market. This grant proposal was unsuccessful. A grant proposal also was drafted for a karst-conservation-easement project through the U.S. Fish and Wildlife Service, which did receive funding of $400,000. Additional efforts to secure easements are pending.

Discussion

A major benefit realized from working with a proactive, flexible project is the opportunity for Missouri Department of Conservation to cooperate with landowners on projects that are not normally available for cost-share assistance. Federal government programs offered through the United States Department of Agriculture, such as the Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program, Environmental Quality Incentives Program, and Wildlife Habitat Incentives Program, already provide important cost-share assistance to landowners on a variety of conservation practices. The Landowner Incentive Program grant has ultimately been used to fill in the gaps where these other land management assistance programs have no program available to assist landowners. Conventional best management practices have been utilized and promoted through the Landowner Incentive Program grant and will continue to be, but other specific, alternative groundwater protection projects are being funded through this grant as well. Two examples follow of how this grant has assisted landowners with management goals when other programs cannot.

Mary Turton Project

Mary Turton was first invited, by mail, to a landowner meeting in her area. Miss Turton attended the meeting, and made plans for a future site visit on her property in eastern Lawrence County with an Missouri Department of Conservation biologist. At the meeting, plans were agreed upon between Miss Turton and Missouri Department of Conservation to partner with Landowner Incentive Program funds to restrict livestock access from five sinkholes on her property. One of the sinkholes has been used as a place to dump trash, including scrap metal and old tires, by the previous landowner. Part of Miss Turton's project plan with Missouri Department of Conservation is to remove the trash from the sinkhole and properly dispose of it in an effort to protect groundwater quality.

Charles Johnson Project

Prior to receiving funding through the Landowner Incentive Program grant, Missouri Department of Conservation initiated direct contact with Mr. Charles Johnson after determining that an historic Ozark cavefish site was located on his property. Efforts were successful in confirming the presence of *A. rosae* and constructing a viewable entrance to the site, while maintaining protection from direct disturbance. As dye tracing was being done to determine the recharge delineation for the new active site in southern Lawrence County, Missouri, a dye-trace from Mr. Johnson's toilet proved that his nearby failing septic system is hydrologically linked to the Ozark cavefish site. Landowner Incentive Program funds are currently being used to remove the old system and install a new, advanced, waste-treatment system to eliminate direct groundwater contamination caused by the old system. The efficiency of the new system will be quantified through additional dye-tracing analyses.

These unconventional practices for groundwater protection in Ozark cavefish recharge areas would not be eligible for cost-share assistance under any other program, but the benefits of these practices should not be overlooked. Cleaning and protecting a sinkhole which provides a direct conduit to karst groundwater and fixing a failing septic system directly minimize pollution into the karst environment associated with these recharge areas. In the case of the advanced septic system installation, the pre- and post-project dye tracing analyses provide a rare opportunity to measure the amount of contamination that is being prevented from entering the Ozark cavefish active site. The installation of this advanced septic system is the first of its kind to be installed within the county and it will serve to demonstrate the effectiveness of advanced septic treatment within sensitive karst areas. These projects, along with implementation of more conventional conservation practices, should have a direct, positive impact on Ozark cavefish and other karst fauna.

One challenge to installing a major septic-system renovation is the cost. Cost sharing on projects like this takes up a substantial percentage of the Landowner Incentive Program money available for other cost share projects. One question is, "Should money be used on these larger projects?" Smaller projects allow for a larger volume of projects to be implemented in many different recharge areas, allowing a larger number of individuals to participate in a cost-share conservation practice. Conversely, large projects have the capacity to provide solutions to large groundwater pollution problems. Large projects that help fulfill the goals of the grant should not be overlooked simply because they require more funds than smaller projects. With this Landowner Incentive Program grant, if a significant groundwater threat could be neutralized, funds were utilized to minimize the threat. This is another benefit of administering a flexible Landowner Incentive Program grant.

As noted in the results, two new Ozark cavefish locations have been discovered since the start of the grant. This has been an unexpected, positive benefit of the proactive outreach approach. To find a new site location, first a cave, spring or well opening to the groundwater must be found within the Ozark cavefish's range. Not knowing the location of caves, springs and wells containing adequate habitat on private property makes an already state-endangered species even harder to find. Actively contacting and communicating with area landowners has opened lines of communication between Missouri Department of Conservation personnel and landowners who own or have knowledge of features with direct access to the groundwater. Through investigation of leads from informed landowners, not only have new active sites been documented, but successful landowner partnerships have been forged.

Progress will continue with this grant, utilizing this proactive outreach approach until the grant's scheduled end date of March 31, 2009. Grant objectives and goals are currently being met and a complete final report will detail all accomplishments mentioned in this paper and those yet to be attained.

Acknowledgments

The authors thank Jim Rathert for his photo of the Ozark cavefish.

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WATER QUALITY MONITORING IN THE PERRY COUNTY KARST, MISSOURI

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Abstract

The Perry County Karst of eastern Missouri has more than 670 known caves, the most of any county in Missouri. The caves are large, complex, flood-prone systems, which make contamination of groundwater and possibly drinking water a growing problem in this area. The diverse aquatic cave fauna that includes a unique cave-dwelling fish called the grotto sculpin, *Cottus* sp. cf. *carolinae*, is susceptible to water contamination. This project focuses on water quality on the surface and in the caves, and identifying nonpoint sources of water contamination. Components of the project include: (1) continuous water-quality monitoring with moored water-quality multi-probe sondes, (2) monthly grab samples of water for chemical, nutrient, coliform, and sediment analysis, (3) rainwater-runoff sampling of sinkholes unmodified or modified with vertical drains for chemical, nutrient, and sediment analysis, (4) SPMD and POCIS sampling for analysis of chemicals that are below detectable limits of traditional analytical methods, and (5) dye tracing and recharge delineation of the major cave systems. The data collected will provide managers needed information to protect groundwater and the populations of the grotto sculpin.

Key words: water-quality monitoring, groundwater contaminants, Grotto sculpin, *Cottus* sp. cf. *carolinae*, Perry County, Missouri

Introduction

Missouri contains over 6,200 caves in several karst zoogeographic regions. These regions include the Springfield and Salem plateaus, the Boone, Hannibal, St. Louis, Jefferson-Ste. Genevieve, and Perryville karsts, and an isolated Caney Mountain area (Elliott 2007). The Perryville Karst encompasses most of the eastern portion of Perry County, Missouri. Perry County leads the state in the number of known caves at more than 670, and it also boasts some of the longest caves, e.g. Crevice Cave (45 km), Moore Cave System (29 km), Mystery Cave (25.5 km), and Rimstone River Cave (22.8 km). The study area for this project is located within the Perryville Karst about 120 km (75 mi.) south of St. Louis, Missouri. The study area will be referred to as the Perry County Karst and totals approximately 59,000 ha (46,000 ac.). This area contains thousands of sinkholes ranging from a few meters to several hundred meters in diameter and can be from one to 30 meters deep. These sinkhole plains filter surface-water runoff into the cave systems below.

In addition to several caves of considerable length, the Perry County caves have a fairly species rich cave fauna. The diversity of cave life in Missouri was ranked by the Missouri Department of Conservation using the Cave Biodiversity Ranking system (Elliott 2007). Several caves within the Perry County karst are ranked in the top 50 for biodiversity, e.g. Mystery (#3), Berome Moore (#4), Tom Moore (#8), Running Bull (#36), and Crevice Cave (#48). Five major cave systems in Perry County contain an endemic cave-dwelling fish called the grotto sculpin, *Cottus* sp. cf. *carolinae*. The undescribed but distinct grotto sculpin (Burr et al. 2001) was listed as a federal candidate species in 2002 and assigned a priority number of 2, indicating an imminent threat to the existence of the species.

The cave fauna is potentially threated by human impact because cave systems are potentially affected by the influx of surface waters. Water from the surface enters the groundwater supply via caves and natural percolation through the ground. Changes in land use bring new and almost certainly more serious threats to groundwater quality, and possibly to water quality in aquifers that supply drinking water. Aquifers in karst terrains are exceptionally sensitive to pollution and have higher potential for contamination than nonkarst aquifers. Previous limited surveys of karst groundwater in the study area indicated that ammonia, nitrite, nitrate, chloride, and potassium were detected within caves at levels high enough to be detrimental to aquatic life (Taylor, Webb, and Panno 2000, Vandike 1985). These compounds result primarily from cultivation. These same surveys also revealed that fecal contamination at 27 springs and caves was a serious problem (Taylor, Webb, and Panno 2000). The increase in contaminants is associated with population increase in the region. The largest population center and the focus of business and industry in the area is the town of Perryville. The region traditionally and still is dominated by agriculture, but now urbanization in the form of subdivisions is spreading out around Perryville. Continued population expansion, both suburban and rural, increases the potential for contaminated groundwater sources, however, little research has been conducted to see what the impacts of sedimentation and agricultural chemicals have on the karst system.

Another concern in the study area is the use of vertical drains to control erosion in sinkholes. A vertical drain is defined as "a well, pipe, pit, or bore in porous, underground strata into which drainage water can be discharged" (Natural Resources Conservation Service 2006) (Figure 1). These vertical drains could allow contaminated water to directly enter caves and aquifers without the benefit of natural filtration via percolation through the ground. Although the impact of vertical drains on water quality is poorly known, the installation of vertical drains into sinkholes is promoted by state and federal cost share practices in Perry, Ste. Genevieve, and Cape Girardeau counties, through the County Soil and Water Conservation Districts and the Natural Resources Conservation Service. In these counties, landowners are eligible to receive up to seventy-five percent cost-share to install vertical drains to stop erosion.

Figure 1 *Vertical drains installed in two sinkholes in a crop field.*

Very little water quality data has been collected from the study area. This project will be the initial phase to gather the required data to make informed decisions on the recharge areas of the cave systems, to determine water quality issues, to develop appropriate techniques to manage sinkholes, to develop educational tools that will inform citizens of the unique features that they live on, to help prevent the streams and springs in the study area from being listed on the 303(d) list, and to help prevent the grotto sculpin from being elevated from a candidate species to an endangered species. The data generated from this project will also be used to develop a Perry County Karst Watershed Management Plan which can be used, we hope, to guide future water-quality initiatives.

Materials and Methods

This project is divided into five subprograms. Each subprogram is designed to contribute to the overall assessment of water quality in the Perry County Karst, and to support ongoing and future scientific research. Figure 2 illustrates the station locations of each subprogram within the study area.

Continuous Deployment of Water-Quality Probes (Sondes). The first subprogram will be the continuation of preliminary water-quality research started in January 2006. Hydrolab and YSI multiprobe sondes were permanently moored at six cave and/or resurgence locations (Figure 2) in January, 2006, and will continue through August, 2010. These sites will allow for the determination of sea-

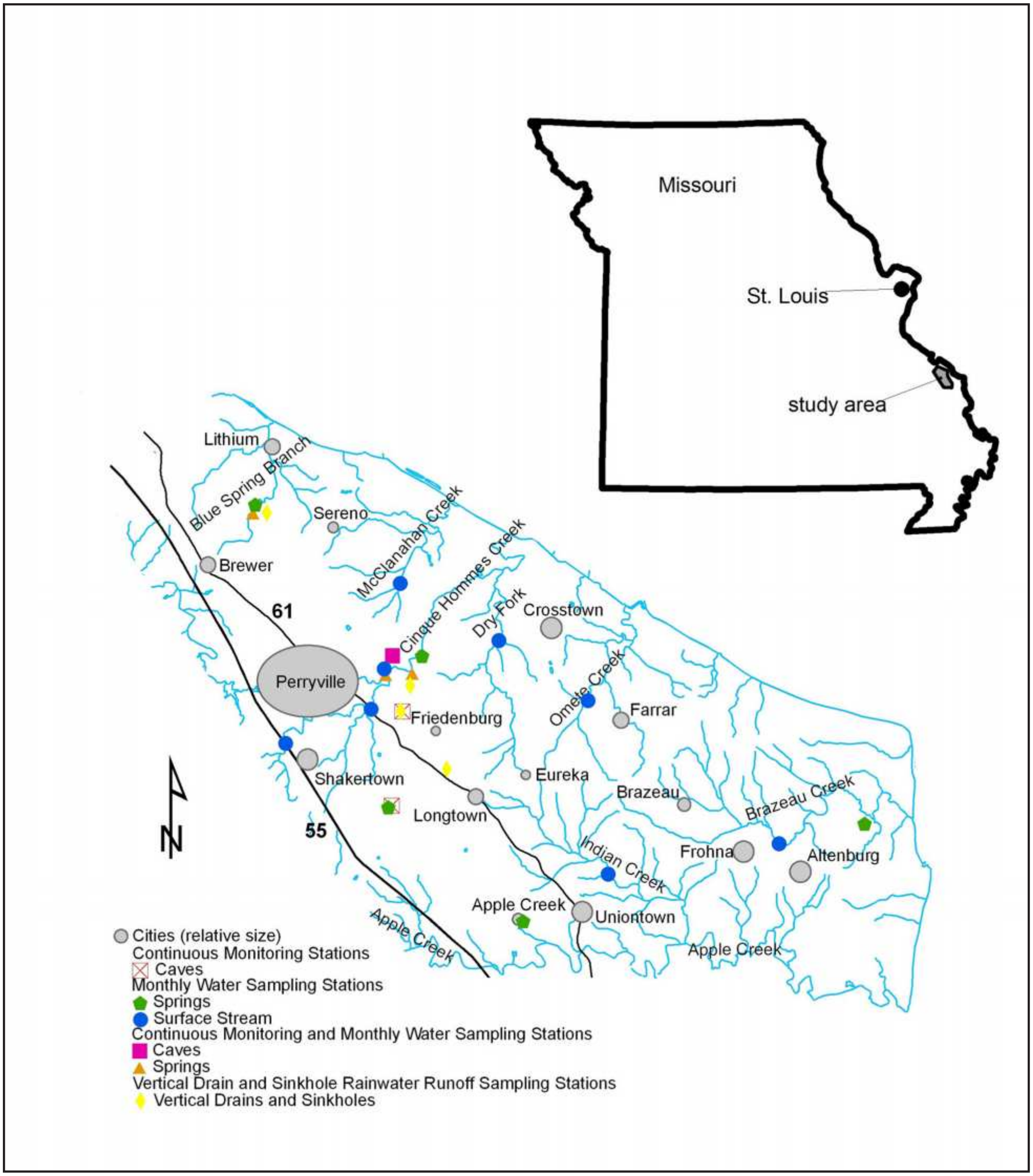

Figure 2. Study area showing continuous, monthly and vertical-drain, water-quality stations.

sonal fluctuations in urban and agricultural runoff, livestock waste, and septic runoff in the study area. Four of the six sites correspond with monthly water-grab-sample sites. Sonde data will be compared to data collected in the monthly water-grab-sampling subprogram.

Continuous deployment of water-quality probes will be placed in the same location of the thalweg of the resurgence and/or subsurface stream. Physical parameters are measured every 30 minutes and consist of: temperature, pH, specific conductivity, ammonium (NH_4^+-N), total ammonium nitrogen, turbidity and dissolved oxygen. Self-cleaning turbidity sensors are equipped with central wiper units to prevent fouling of other sensors with biological growth or debris. The sondes will be switched out monthly and the data will be downloaded and checked for accuracy. Sondes will then be post-calibrated, cleaned, internal batteries exchanged, and pre-calibrated for re-deployment the following month. *In-situ* field measurements of temperature, pH, specific conductivity, dissolved oxygen and turbidity will be recorded when the sondes are switched. Water velocity (m/sec) will be measured seasonally at each site in the thalweg of the resurgence and/or subsurface stream using a Marsh McBirney Model 201D Portable Water Current Meter with a 122-cm (4-ft.), top-setting wading rod.

Monthly Water Grab Samples. The second subprogram involves collecting water-grab samples from resurgences, springs, surface and/or subsurface streams at 17 sites (Figure 2) during each month from March 2007 to February 2009. The Cedar Spring site will be sampled seasonally (four grab samples per year) because of difficult access. Selection of sampling sites was based on past water-quality sampling data (Kraemer 2006 and MDC continuous monitoring). Sampling sites will allow for the determination of urban and agricultural runoff, septic runoff, and livestock waste in the study area. Water-grab samples will be collected according to U.S. EPA WAS Field Operations Manual (2004). Only flowing water will be sampled, thus, some sites will not be sampled during dry seasons of the year. Stagnant water will not be sampled to prevent biased water quality data that may be caused by evaporative concentration. Flow regime, e.g. runoff, base flow, or both, will be recorded. All samples will be analyzed for nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), chloride (Cl^-), ortho-phosphate (PO_4^{3-}), total phosphorus (P_{total}), *Escherichia coli* (*E. coli*), total coliforms, total suspended solids, and the agri-chemicals in the atrazine family (only April through June). Selection of analytes was based on a review of the scientific literature dealing with karst water quality (Boyer and Alloush 2001, Graening and Brown 2000, Panno et al 2003, Taylor, Webb and Panno 2000). Atrazine will only be analyzed from April through June during the application period of the herbicide. A Hydrolab Quanta Water Quality Monitoring System will be used to measure temperature, pH, specific conductivity, turbidity and dissolved oxygen at each site. A ThermoOrion AQ4500 Turbidimeter will be used to measure turbidity at each site. Water velocity (m/sec) will be measured as noted above.

Sinkhole and Vertical-Drain, Rainwater-Runoff Sampling. The third subprogram involves sampling rainwater runoff at sinkholes and vertical drains at five to six sites for at least one rain event each month from March 2008 to July 2009. The sites have both unmodified and modified sinkholes with vertical drains (Figure 2). The sites will allow for the determination of seasonal fluctuations in agricultural runoff and sedimentation in the study area. Rainwater runoff samples will be collected using ISCO portable water samplers according to U.S. EPA NPDES Storm Water Sampling Guidance Document (1992). These samplers will be programmed to collect water during the first thirty minutes of a runoff event. A combination of monitoring local weather forecasts and notification by partnering agency personnel (NRCS, University Extension Service, Perry County Soil and Water Conservation District and MDC Field Offices) will be utilized to coordinate sampling during rain events. All samples will be analyzed for nitrate (NO_3^--N), nitrite (NO_2^--N), ammonia (NH_3-N), chloride (Cl^-), ortho-phosphate (PO_4^{3-}-P), total phosphorus (P_{total}), total suspended solids and atrazine. Atrazine will only be analyzed from April through June during the application period of the herbicide.

SPMD and POCIS. The fourth subprogram involves deployment of moored SPMD (semi-permeable membrane device) and POCIS (polar organic chemical integrative sampler) devices in resurgences, springs, surface and/or subsurface streams at five or six sites. Stations will correspond with continuously deployed, water-quality sonde stations and/or monthly water-grab- sample stations. Samplers will be deployed for 30 days and then retrieved for analysis. These samplers will sequester trace levels of chemicals that cannot be detected by typical analyses of water grab samples. *In situ* field measurements of temperature, pH, specific conductivity, dissolved oxygen and turbidity will be recorded when the samplers are deployed and retrieved. Target analytes and procedures are currently in development.

Dye Tracing. The primary focus of the fifth subprogram is to conduct 36 water traces in the Perryville karst plain. These traces will help determine the full extent of the recharge area for Mystery, Crevice, Running Bull, Moore, and Rimstone cave systems. These traces are planned over a three-year time frame with an average of 12 traces each year. Scheduling and prioritization of water traces, as well as the selection of proposed dye types, have been planned based on review of existing water-trace data, proposed injection and monitoring locations, current cave mapping data, available dye types and analysis technologies and logistics required for injection. Schedule flexibility will be required to accommodate uncontrollable logistical circumstances such as weather conditions, property access and water availability. Dye monitoring receptors (packets of activated charcoal) will be used to absorb dyes from solution to determine if the dye was present within the water column at a particular location. For the traces proposed here, the receptor-monitoring points chosen are hydrologically significant groundwater resurgence points, cave streams and surface streams. The general water-tracing methodology established by Ozark Underground Laboratory (Aley 2007) will be used to conduct this work.

Results and Discussion

We are beginning the second year of this four-year study of water quality. Preliminary results after a few months of samples indicate that *E. coli*, chloride, atrazine, and turbidity could be some of the water-quality issues that may be impacting the Perry County Karst. Vulnerability mapping by Ozark Underground Laboratory indicates that most of the study area is vulnerable to groundwater contamination (Aley and Moss 2007). Within the sinkhole plain, only parts of the riparian corridors of the surface streams have moderate vulnerability. The rest of the landscape is high vulnerability because most of the runoff enters sinkholes with little to no filtration.

We hope that continuation of the water-sampling and dye-tracing studies will provide us with the data and watershed boundaries needed to assist with the drafting of the Perry County Karst Watershed Management Plan in three key ways: (1) long-term data sets will allow for interpretation of water-quality trends throughout the karst regions, (2) water-quality data will provide the needed information to develop or improve best management practices (BMPs) and cost-share practices, and (3) the dye-tracing study will delineate groundwater-recharge areas for five major cave systems to provide a better understanding of the relationships between surface-water and groundwater hydrology and biology.

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HABITAT USE BY GROTTO SCULPIN (*COTTUS CAROLINAE*), A TROGLOMORPHIC FISH IN PERRY COUNTY, MISSOURI

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Abstract

Habitat studies in caves have been limited to qualitative studies providing general descriptions of the habitat utilized by fish populations. The lack of quantitative habitat use data for troglobitic species makes it difficult to examine important ecological traits such as the effects of habitat change or evidence of habitat specialization. This study quantitatively examined the habitat use of two grotto sculpin (*Cottus carolinae*) populations and corresponding resurgence populations in Perry County, Missouri. Study sites were divided into 10-meter sections and in-stream physical habitat was quantified for each section seasonally. Sculpin were captured using a variety of capture techniques (seining, dipnets, and electroshocking) from each section every 4-6 weeks. Weight, standard length, and eye length were recorded before individuals were released. Regression trees were constructed for analysis of our habitat data. Analyses showed that grotto sculpin on the surface disproportionately used shallower areas with high abundances of prey items. Grotto sculpin habitat use in the caves was best explained by depth, with sculpin favoring deeper habitats. Possible effects of altering land use in the porous Perry County karst region are discussed. The results from this study will help conservation officials make critical decisions regarding land use practices within the recharge area and provide baseline data on the habitat use of a benthic cave fish species.

Key words: *Cottus carolinae*, grotto sculpin, habitat use, troglomorphic, cavefish, silt, Missouri

Introduction

Cave environments are distinctive in many ways that make them fascinating settings for scientific studies (Poulson and White 1969). However, while the cave environment offers many unique research opportunities, the scarcity of organisms, the need for specialized gear, and the often treacherous surroundings associated with caves have historically limited research in this field (Trajano 2001). As a result, the knowledge of cave ecosystems is limited and most species have only been studied descriptively, if at all.

While the amount of cave research in general is limited, studies of habitat use for cave dwelling fishes are relatively non-existent. Habitat research in caves has been limited to qualitative studies providing general descriptions of the habitat utilized by fish populations. The lack of quantitative habitat use data for troglobitic species makes it difficult to examine important ecological traits such as the effects of habitat change or evidence of habitat specialization.

This study quantitatively examined the habitat use of two grotto sculpin (*Cottus carolinae*) populations and corresponding resurgence populations in Perry County, Missouri. Grotto sculpin (Figure 1) provide a unique opportunity to study

Figure 1 *The Grotto sculpin* (Cottus carolinae) *is a small fish from six caves in Perry County, Missouri. Photo by A.J. Hendershott.*

a troglomorphic fish population that utilizes both epigean and hypogean ecosystems. Additionally, grotto sculpin are endemic to Perry County and their limited distribution elevates the possibility of a catastrophic event extirpating their entire population. As a result of this increased risk, the grotto sculpin is listed as an S2, G1-G2 "species of concern" in Missouri and as a candidate species under the Federal Endangered Species Act.

Methods

We quantitatively examined grotto sculpin habitat use in two caves, Mystery Cave and Running Bull Cave, and two corresponding resurgence sites, Cinque Hommes Creek and Thunder Hole Resurgence, respectively, in Perry County, Missouri. Study sites were divided into 10-meter sections and in-stream physical habitat was quantified for each section seasonally. Habitat measurements included stream width, water depth, maximum depth, substrate, silt cover and in-stream habitat. In addition, the porous karst landscape associated with Perry County karst may allow large amounts of runoff to enter directly into the caves. In order to quantify these effects, the presence and depth of silt was recorded at each of our locations.

Sculpin were captured every 4-6 weeks at each of our sites using a variety of capture techniques (seining, dipnets, and electroshocking). Weight, standard length, and eye length were recorded for each sculpin before individuals were released. A total of 3,815 grotto sculpin were captured over 14 sampling periods from March 2006 until October 2007.

Overall grotto sculpin population densities from our study (0.04-0.06 sculpin/m^2) were similar to those of other cave fish populations (Trajano 2001). Among the grotto sculpin captured at each of our sites, 66% were juveniles (less than 60 mm) and 34% were adults. This age class disparity was largely explained by site location with adults forming a higher percentage of the overall grotto sculpin abundances at both cave sites while juveniles tended to account for a higher percentage of overall abundance on the surface.

Regression trees were constructed for analysis of our habitat data. Regression trees use the available data to determine a split for each node that best explains the variability of the dependent variable as it relates to the independent variable (Breiman et al. 1984, Andersen et al. 2000, De'ath and Fabricius 2000, Dzeroski and Drumm 2003). This splitting procedure continues for each group until an overlarge tree is grown. Overgrown trees will have higher error and attempt to explain differences that, in fact, may not be true (De'ath and Fabricius 2000, Usio et al. 2006). Trees of optimal size (measured as the sums of squares about the means) provide the most information. We used V-fold cross-validation to determine the optimal size of our regression trees.

Results

Analyses showed that grotto sculpin habitat use was influenced by a variety of factors. On the surface, grotto sculpin favored areas with shallower habitats and high abundances of amphipods and isopods (Figure 2). Within these shallower habitats, grotto sculpin utilized areas where more than 23% of the substrate was clay. In the caves,

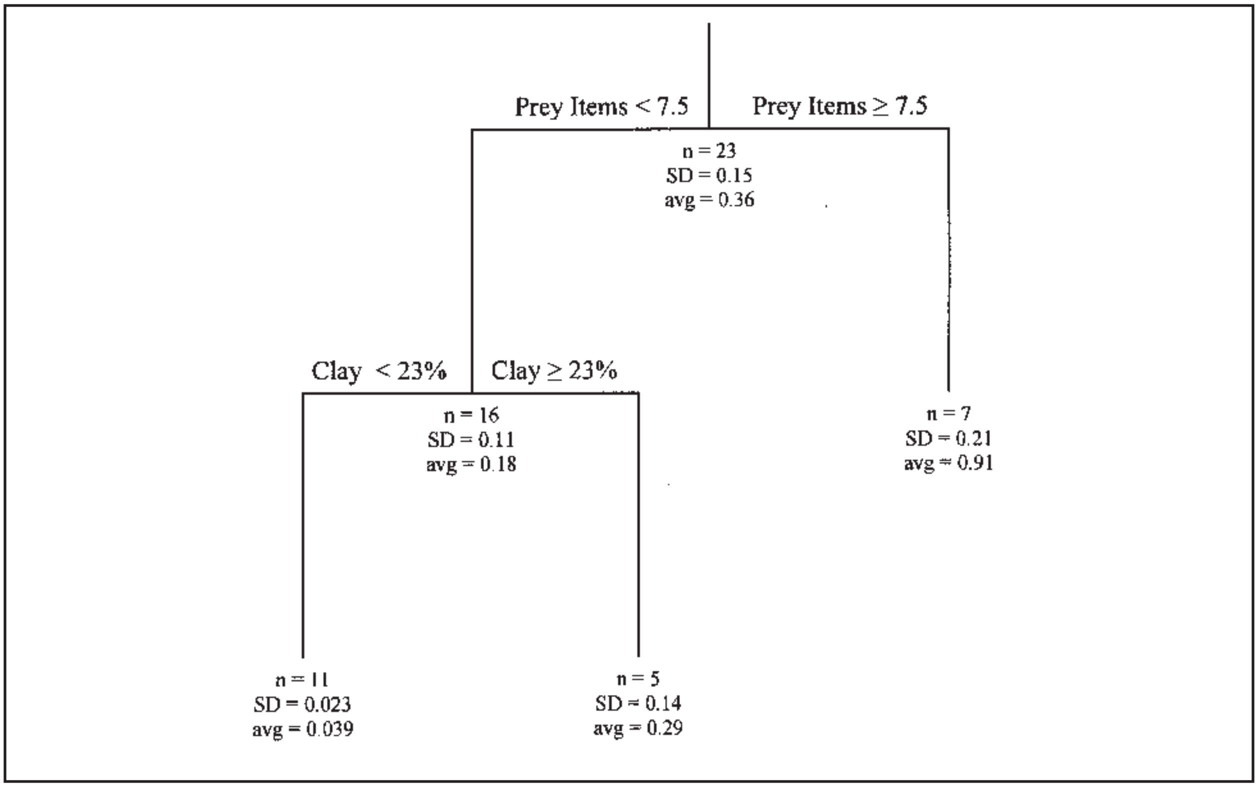

Figure 2 *Regression tree analysis for the habitat use of all grotto sculpin of both surface populations. Sample size (n), standard deviation (SD), and mean densities per node (avg) are given for each node. V-fold cross validation error was 0.43.*

grotto sculpin were found at highest abundances in deeper (greater than 16.3cm) habitats (Figure 3). Within deeper habitats, grotto sculpin disproportionately utilized areas where cobble represented at least 10% of the substrate. When grotto sculpin utilized shallower habitat (less than 16.3 cm), they were found in highest abundances in areas where silt was deeper than 1.9 cm.

The amount and composition of silt varied greatly among our sites. The substrate at both of our cave sites was covered by a significantly higher percentage of silt compared to the surface locations ($F_{3,156} = 121.2$, $p < 0.01$). The depth of the silt, when present, was also significantly higher at the cave sites compared to the surface (Table 1). While the average depth of silt on the surface was less than 0.1 cm, both cave sites had an average depth of >1 cm.

Discussion

Our results indicate that a wide variety of habitats are utilized and important to grotto sculpin populations. Because an overriding habitat variable was not found for the habitat use of all grotto sculpin, it is imperative that we preserve an assortment of habitat types for grotto sculpin populations to use. One of the biggest threats to the availability and quality of grotto sculpin habitat may be the increased siltation found throughout our study sites. Many of the habitats available to grotto sculpin have been covered in large amounts of silt indicating that ongoing siltation in the porous Perry County karst may limit the amount of desirable habitat available to the grotto sculpin. Silt has been shown to negatively impact the habitat use of many species and has been listed as the primary reason for decline in many surface-dwelling fish species (Judy et al. 1984, Berkman and Rabeni 1987, Wood and Armitage 1997, Rowe and Taumoepeau 2004). Because of their relatively small population sizes, this risk may be increased, and it is imperative that we protect the delicate environments they are found in. As such, efforts should be undertaken to limit and reduce the amount of silt and runoff entering the cave systems. The potential for negative impacts related to increased siltation are alarming and should be considered by conservation officials

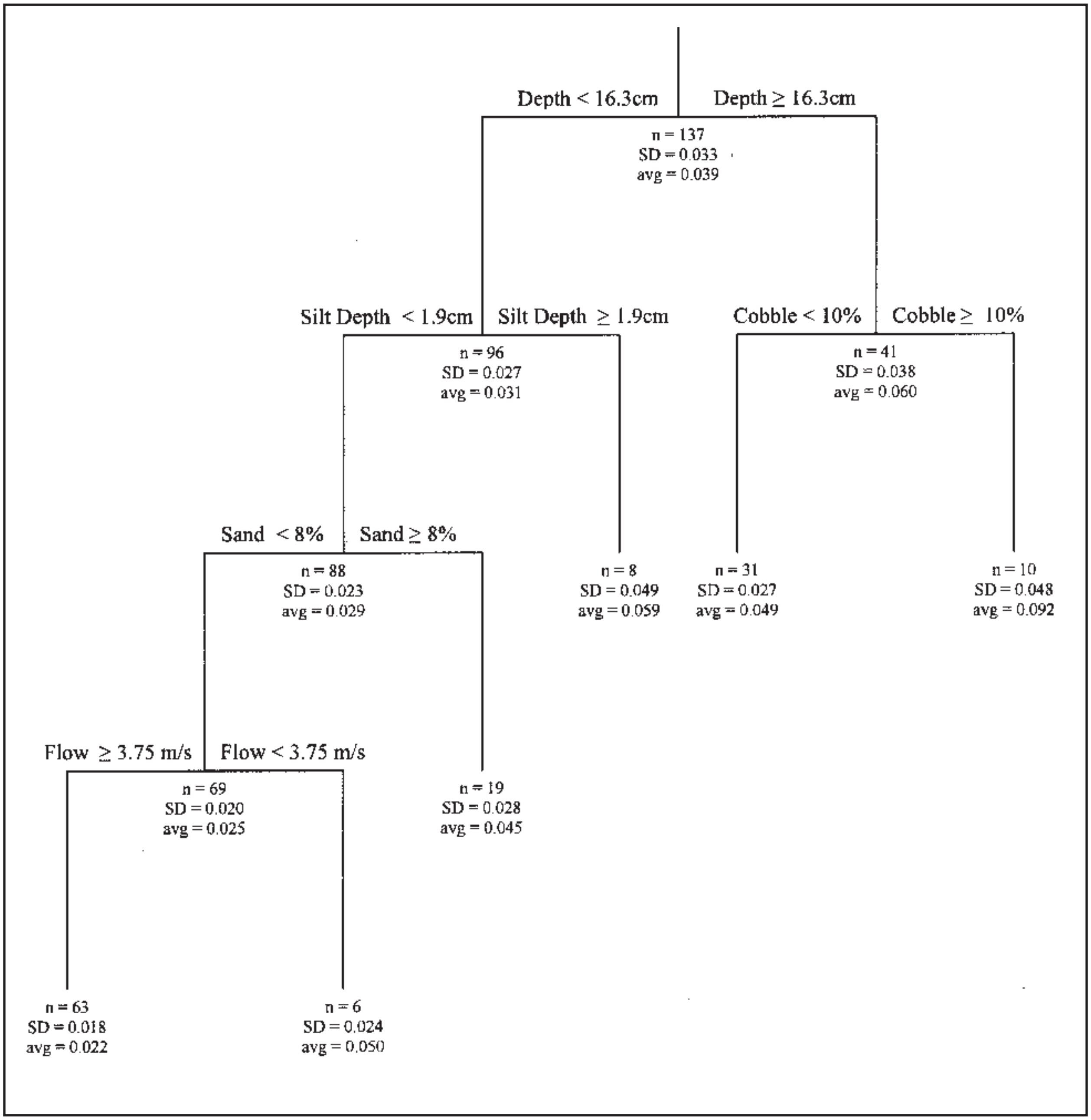

Figure 3 *Regression tree analysis for the habitat use of all grotto sculpin in both cave populations. Sample size (n), standard deviation (SD), and mean densities per node (avg) are given for each node. V-fold cross validation error was 0.69*

when making critical decisions regarding land use practices within the recharge area.

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Table 1. Mean values and standard error for silt cover and depth for Mystery Cave (n = 108), Running Bull Cave (n = 29), Thunder Hole Resurgence (n = 10), and Mystery Cave Resurgence (n = 13).

Variables	Mystery Cave	Running Bull Cave	Mystery Cave Resurgence	Thunder Hole Resurgence
Silt Presence	93.06%	62.26%	14.20%	0%
Percent Silt Cover*	65.76% ± 1.6%	28.30% ± 2.8%	6.12% ± 2.8%	0%
Silt Depth*	1.03 ± 0.06	1.20 ± 0.31	0.09 ± 1.44	0.00

* Indicates significant difference between cave and surface sites ($p < 0.01$)

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PHYLOGENETICS OF THE SOUTHERN CAVEFISH (*TYPHLICHTHYS SUBTERRANEUS*): IMPLICATIONS FOR CONSERVATION AND MANAGEMENT

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Abstract

Like other cave organisms, amblyopsid cavefishes have been a subject of continued debate regarding "regressive" evolution of characters in the adaptation from epigean to subterranean habitats. With six described species, the eastern North American endemic Amblyopsidae exhibit morphologies that range from epigean to troglomorphic. The clade also includes the most widespread stygobitic fish in North America, the Southern cavefish (*Typhlichthys subterraneus*). The widespread distribution and limited genetic work hinted that the Southern cavefish is comprised of several genetically distinct species obfuscated by convergent morphology. However, the phylogenetic relationships within *T. subterraneus* and within the family remain poorly understood. We investigated the intraspecific phylogenetic and biogeographic relationships of the Southern cavefish throughout its range in the Interior Low Plateau using DNA sequence data from a mitochondrial and nuclear gene. Our sampling includes populations both east and west of the Mississippi River. Our results support a monophyletic Amblyopsidae dating to the early Miocene with substantial divergence among the described forms. Considerable cryptic variation was observed within a monophyletic *T. subterraneus* with genetic variation structured within watersheds. Divergence times up to 11 Mya were estimated between certain drainages, indicating that some populations have been on separate evolutionary trajectories since the mid- to late Miocene. These findings suggest greater diversity within *Typhlichthys* than previously recognized, and support the idea that convergent evolutionary patterns associated with subterranean life make it difficult to infer the biogeographic history of subterranean lineages. While more extensive population-level data are needed to designate taxonomic groups or ESUs, it is clear that southern cavefish inhabiting different watersheds are demographically inconnected and possess unique genetic attributes.

Key words: *Typhlichthys subterraneus*, southern cavefish, amblyopsidae, evolution, phylogenetics, Alabama, Georgia, Tennessee, Kentucky, Missouri, Arkansas, Oklahoma

Introduction

Groundwater is an essential component of the global hydrological cycle and is fundamental to human development and survival (Danielopol et al. 2003, Boulton 2005). Groundwater organisms serve as ecological indicators of groundwater pollution and habitat degradation (Malard 1996, Elliott 2000, Culver et al. 2000) and perform vital ecosystem services, such as nutrient cycling and transformation and biological filtration (Hancock 2002, Danielopol et al. 2003, Boulton 2005). Subterranean ecosystems harbor significant biodiversity, nearly 1,800 subterranean species occur in North America alone, 25–30% of which are aquatic (Elliott 2000). However, recent molecular studies suggest that there is an underestimate of groundwater biodiversity, as considerable genetic variation has been observed among morphologically similar populations that are widely distributed (Buhay and Crandall 2005, Lefebure et al. 2006, Finkston et al. 2007). Discovery and protection of this evolutionary diversity is a conservation goal that requires significant input from molecular phylogenetics and population genetics.

Many aquatic, subterranean species (stygobites) are confined to distinct karstic hydrological systems (Finston et al. 2007, Zaksek et al. 2007), often endemic to a single aquifer. Their distributions are defined by both geologic structure and hydrological processes (Finston et al. 2007). The discontinuous distributions of many subterranean species resulting from presumed, limited dispersal ability and habitat fragmentation has led many to treat subterranean habitats as underground "islands" (Culver *et al.* 1995), even though the barriers between isolated habitats are unclear. Molecular analyses of many groundwater fauna have revealed highly subdivided population structure consistent with island-like habitat fragmentation, and genetic differentiation is often associated with hydrological patterns (Verovnik et al. 2004, Finston et al. 2007). Further, several instances of cryptic speciation have been revealed (e.g. amphipods, Finkston et al. 2007, crayfish, Buhay and Crandall 2005).

Just as distinct evolutionarily significant units (ESUs) of salmonids inhabiting different drainages merit individual management attention (Waples 1991, 1995), groups of cavefish in different hydrological systems may be genetically isolated and each represent an important component of the evolutionary legacy of the group, i.e., they should be recognized as ESUs or full taxonomic species. The presence of genetic diagnosable lineages that are morphologically indistinguishable or contradict patterns predicted by morphology suggest that defining subterranean species solely on the basis of morphology may be misleading and underestimate subterranean diversity. It is estimated that fewer than half of the obligate subterranean fauna of the United States have been described (Elliott 2000). Cryptic diversity obscured by convergent morphologies resulting from similar responses

Figure 1 *An adult southern cavefish, Typhlichthys subterraneus, from Marion County, Tennessee.*

to selection likely accounts for a large proportion of undescribed species. Molecular genetic data may be particularly appropriate for identifying cryptic species or ESUs with similar phenotypes (Allendorf and Luikart 2007). Given the potential decoupling of morphological and molecular evolution in subterranean environments resulting in gross underestimates of biodiversity based on morphological taxonomy alone, examining cryptic diversity in widely distributed groundwater taxa should be a priority for subterranean biologists and management agencies. Determining the genetic distinctiveness of subterranean populations, particularly those that are morphologically conservative, is critical to the conservation and management of subterranean biodiversity.

The amblyopsid cavefishes have intrigued students of ichthyology and evolutionary biology since the 1840s. The southern cavefish, *Typhlichthys subterraneus* (Figure 1), is an obligate cave-dwelling fish within the Amblyopsidae, a small family endemic to the unglaciated regions of the eastern United States. The family includes surface, stygophilic (facultative cave-inhabiting), and stygobitic (obligate cave-inhabiting) species that represent a graded series from surface to subterranean inhabitation, and are viewed as an excellent system to investigate evolutionary trends and speciation in subterranean environments (Eigenmann 1909, Poulson 1963, 1985). Although the family has been known to science since the early 1840s, the systematic relationships among and within species remain poorly understood. The southern cavefish has one of the largest distributions of any North American aquatic, cave-dwelling vertebrate with two major centers of distribution: the Ozark Plateau of central and southeastern Missouri, northeastern Oklahoma and northwestern Arkansas, and the Cumberland and Interior Low Plateau of northern Alabama, northwest Georgia, central Tennessee and Kentucky. Because of its large distribution and presumed limited dispersal, the potential is high for both subsurface and surface hydrologic patterns to contribute to the genetic structuring of populations and potentially facilitate cryptic speciation within southern cavefish. Electrophoretic analyses by Swofford (1982) showed considerable differentiation among populations of *Typhlichthys*, and suggested that the group may represent multiple, independent invasions of subterranean waters. However, owing to small sample size, Swofford's study was limited in its ability to distinguish modular or hierarchical subdivision from a continuous relationship between genetic and geographic distance.

This study examines the genetic structure of populations of *Typhlichthys* testing for an association of genetic divergence with hydrological patterns. If hydrological boundaries, either surface or subsurface, are barriers to dispersal and gene flow, genetic structure is expected to be associated with hydrological structure. Specifically, we examine sequence variation in both mitochondrial and nuclear markers to: 1) examine genetic diversity and structure, 2) determine the relationships among species within the Amblyopsidae, 3) examine the potential for cryptic diversity, and (iv) identify ESUs for management and conservation agencies. For the purposes of this paper, we focus on preliminary data obtained for populations of *Typhlichthys* in Tennessee, Alabama, and Georgia, but we also address interspecific relationships within the family.

Materials and Methods

Tissue samples (fin clips) or voucher specimens were collected from 66 southern cavefish from 32 localities throughout the range of the species in Tennessee, Alabama, Georgia, and from Arkansas (Figure 2). Tissue samples or DNA for the other amblyopsid species (except *S. poulsoni*) and eight *T. subterraneus* localities were provided by T. Near (Yale University), D. Neely and B. Kuhajda (University of Alabama), and Aldemaro Romero and Ron Johnson (Arkansas State University). Voucher specimens will be deposited into the University of Tennessee Ichthyological Collection.

DNA was extracted using standard methods and polymerase chain reaction (PCR) was used to amplify portions of one mitochondrial gene, ~1218bp of NADH dehydrogenase subunit 2 (ND2) including the entire coding region and portions of flanking tRNAs, and one nuclear gene, 820bp of ribosomal protein S7. Sequencing reactions were performed using original PCR primers and run on an ABI Prism 3730 at the Molecular Biology Resource Facility at the University of Tennessee. The trout-perches (*Percopsis omiscomaycus* and *P. transmontana*) and pirate perch (*Aphredoderus sayanus*) served as outgroups because of their alliance with the amblyopsids within the order

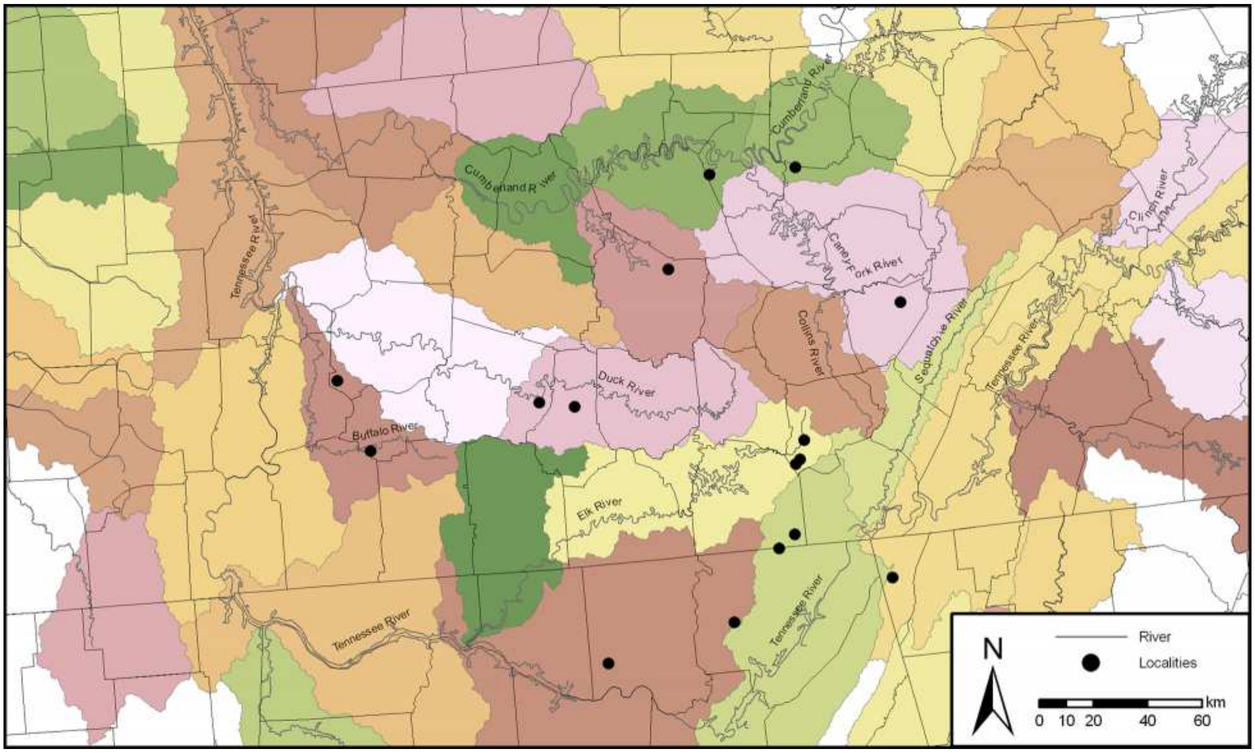

Figure 2 *Sampling localities and distribution of the southern cavefish,* Typhlichthys subterraneus. *Localities are color-coded to match clades in ND2 phylogeny. Present-day drainages are also highlighted. Sampling localities from Arkansas are not shown.*

Percopsiformes (Nelson 2006). Sequences were aligned to each other and to outgroup sequences for each locus.

Gene trees were constructed using Bayesian analyses with the ND2 and S7 datasets analyzed separately. The optimal model of sequence evolution for each dataset was determined using Akaike's information criterion (AIC) implemented in Modeltest 3.7 (Posada and Crandall 1998). Bayesian posterior probabilities were estimated in MrBayes 3.1 (Ronquist and Huelsenbeck 2003). Two independent runs using four Markov chains and temperature profiles at the default setting of 0.2 were conducted for 8 million generations, sampling every 100th generation. Modeltest selected different models of sequence evolution for first, second, and third position codons of ND2. Therefore, the ND2 dataset was partitioned accordingly and unlinked allowing values for transition/transversion ratio, proportion of invariable sites and among-site rate heterogeneity to vary across codon positions during analysis. Random trees were used to begin each Markov chain and a molecular clock was not enforced. The first 1.5 million generations were discarded as "burn-in" to ensure stationarity after examination of the posterior probability. Samples from the stationary distribution of trees were used to generate 50% majority-rule consensus trees for each locus. Divergence times for uncalibrated nodes in the ND2 dataset were derived by using the program r8s (M.J. Sanderson). Two fossils were used to date key nodes representing the most recent common ancestor (MRCA) of all percopsids and the MRCA of the Aphredoderidae and Amblyopsidae (Rosen 1962, Rosen and Patterson 1969, Murray and Wilson 1996). Fossil dates were treated as a fixed minimal age.

To test whether genetic population structure is best described as isolation by distance or as hierarchical subdivision, distance-based redundancy analysis (dbRDA, Legendre and Anderson 1999, McArdle and Anderson 2001, Geffen et al. 2004) was used to investigate the joint effects of distance and watershed boundaries on genetic structure in *T. subterraneus*. Understanding geographic population structure can yield important information regarding whether gene flow is sufficiently restricted across a species range to allow substantial differences to accumulate via genetic drift, and if so, whether the genetic population structure is best described as isolation by distance or as hierarchical subdivision. The program DISTLM (Anderson 2004) was used to perform dbRDA using a second-order polynomial function of latitude and longitude as our distance variable set (Borcard et al. 1992). First, the relationship between the DNA distance matrices and the distance variable set was analyzed alone using dbRDA with p-values estimated from 9999 permutations of the distance matrix. Then a set of dummy variables indicating the watershed containing each site was analyzed as a predictor variable set with the distance variable set fitted as covariates. We used 9999 permutations of the residual distance matrix to estimate p-values.

Results

Phylogenetic analyses. Bayesian analyses of both the mitochondrial ND2 and nuclear S7 datasets support the monophyly of *T. subterraneus*. Likewise, the Amblyopsidae was monophyletic with *C. cornuta* most basal, however, monophyly of the genus *Amblyopsis* was not supported by both the ND2 and S7 datasets. Solutions to this problem in classification include lumping all four troglomorphic species into the oldest genus, *Amblyopsis*, or splitting the existing *Amblyopsis* into *A. spelaea* and *Troglichthys rosae* (Eigenmann 1899).

Within *Typhlichthys*, 41 haplotypes were recovered for the ND2 dataset. There was a clear pattern of correspondence between mtDNA lineages and surface hydrological boundaries (Figure 2) with sequence divergence up to 11.6% among lineages. Almost all haplotypes from a given hydrological unit grouped within the same lineage (Figures 2 and 3). Exceptions included haplotype TsubAE from Marion County, Tennessee, that grouped with haplotypes from northwest Geor-

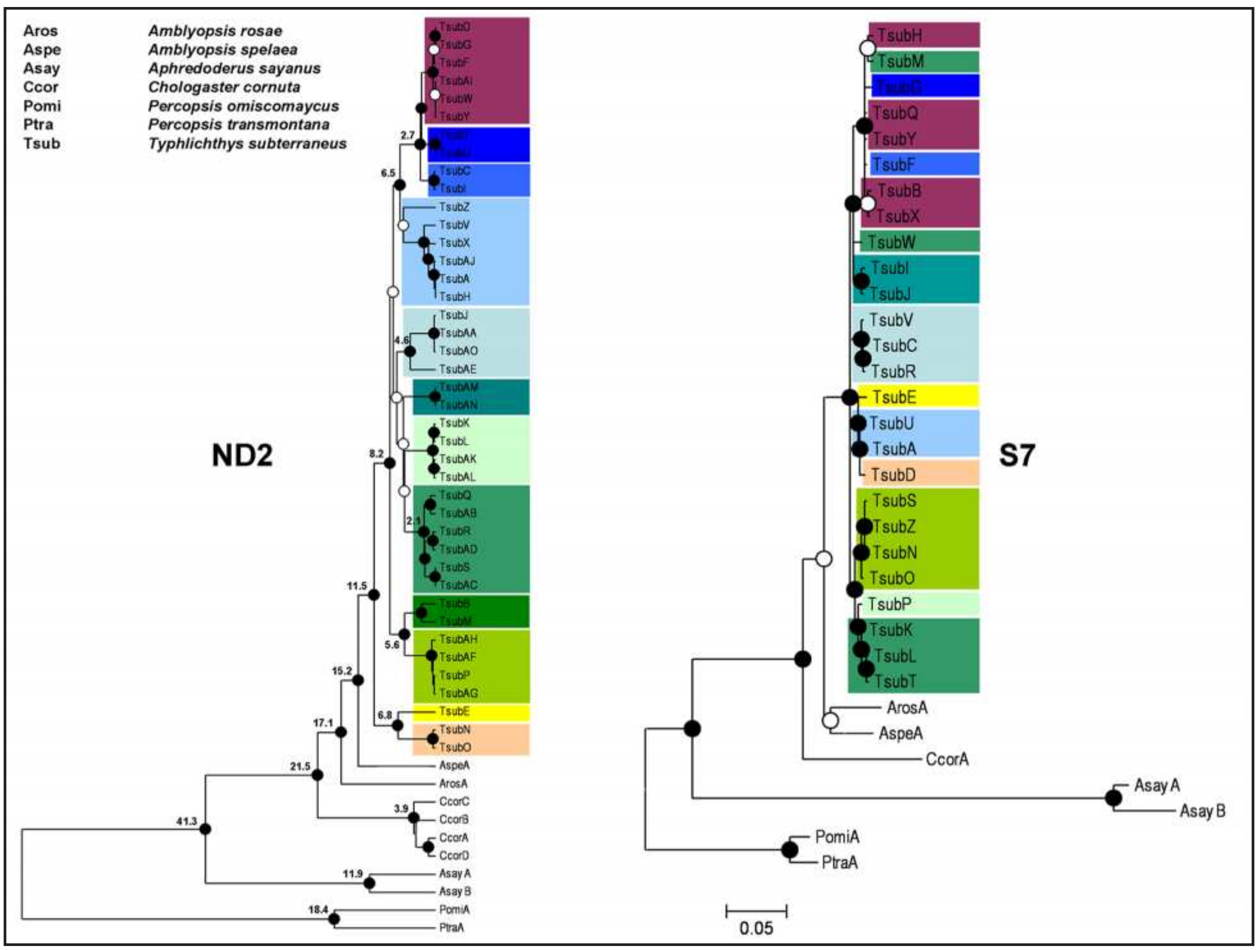

Figure 3 Bayesian chronogram of ND2 (left) and phylogram of S7 (right) datasets. Solid circles at nodes indicate posterior probabilities > 0.95. Numbers above nodes indicate divergence time estimates in Mya. Outgroups used were Asay, Pomi, and Ptra.

gia and haplotypes from caves in Overton and Putnam counties in the Upper Cumberland River drainage of Tennessee that grouped with haplotypes from the Upper Caney Fork River drainage in Van Buren County rather than other Cumberland River haplotypes downstream. Little evidence of contemporary gene flow was found, particularly among drainages. Only two localities located in Franklin County, Tennessee, and separated by 2.5 km shared ND2 haplotypes. The S7 dataset also supported a monophyletic *Typhlichthys* but relationships among drainages were not nearly as resolved (Figure 2). Twenty-six S7 haplotypes were recovered with uncorrected sequence divergence up to 2.6% observed among drainages.

Divergence time estimates. Fossil-calibrated divergence estimates place the MRCA of *Typhlichthys* at 11.5 Mya with the MRCA of all amblyopsids dating to 21.5 Mya. Divergence estimates among some eastern lineages dated to 8.2 Mya. Interestingly, the population sampled from the Red River drainage in the Highland Rim in Robertson County, Tennessee, grouped more closely with western populations in Arkansas than other eastern populations. This split is estimated to have occurred around 6.8 Mya suggesting that the biogeographic history of populations east and west of the Mississippi River is more complex than a single vicariant event.

Distance-based redundancy analyses. Distance-based redundancy analyses further emphasized the hierarchical genetic subdivision of populations (Table 1). Significant association between genetic variation and geographic distance was detected for both datasets. Moreover, conditional tests revealed a significant association between genetic variation and drainages for both the ND2 and S7 datasets accounting for 42.6 and 47.6% of the variation above and beyond geographic distance alone.

Discussion

Cryptic diversity and conservation. The identification of cryptic species and ESUs has important implications for conservation and management. The occurrence of cryptic species in endangered nominal species requires special consideration in conservation planning (Bickford et al. 2007). First, species already having a conservation listing might be comprised of multiple species that may be more rare than previously thought. Second, these species might require different conservation strategies (Schonrogge et al. 2002). Here we examined genetic variation and structure in the widely-distributed southern cavefish, *T. subterraneus*, a species of conservation concern in all states throughout its distribution. Our analyses reveal a diversity of deeply divergent lineages within *Typhlichthys* and support provisional recognition of ESUs and even new species with more restricted geographic distributions than *T. subterraneus sensu lato*.

A definite pattern of correspondence existed between mitochondrial lineages and surface hydrological drainages within *Typhlichthys*. This pattern also has been observed for several other stygobitic species (Verovnik *et al.* 2004, Finston *et al.* 2007). No haplotypes were shared among drainages and pairwise sequence divergence between some drainages was as high as 11.6%. Lower levels of sequence divergence between some surface drainages east of the Mississippi River indicate a more recent connection. However, we found little evidence

Table 1 *Tests for the relationships between DNA variation of* Typhlichthys *populations and the predictor variables distance and hydrologic drainage using dbRDA. On the left are the results of marginal tests of the distance variable set where a second-order polynomial function of latitude and longitude was fitted. On the right are the results of conditional tests evaluating drainage connections as predictors of DNA variation with the distance variable set included as covariables. All P-values were <0.05.*

Dataset	Distance			Drainage		
	F	*P*	%var	F	*P*	%var
ND2	5.770	0.0001	54.59	21.234	0.0001	42.60
S7	2.347	0.0027	38.18	3.726	0.0035	47.62

of contemporary gene flow among drainages and among populations within drainages. In addition to lack of haplotype sharing, distance-based redundancy analyses further emphasized the hierarchical genetic structure of mtDNA and S7 haplotypes according to surface hydrological drainages. Haplotype sharing was observed only between two caves separated by 2.5 km in southern Franklin County, Tennessee. However, sampling for this preliminary dataset is sparse within localities and within some drainages. Therefore, more thorough collections are needed to elucidate contemporary gene flow among *Typhlichthys* populations.

It is important not to employ a single source of data, even molecular, when identifying units for conservation and management. Some sources, such as morphology for many wide-ranging cave organisms like *T. subterraneus*, may not offer much valuable information when discerning taxonomic or conservation units. Therefore, multiple sources of data, if available, should be utilized when identifying units for conservation and management. For many cave organisms, sources may be limited to geography, geology, morphology and a few molecular markers. The monophyly of several lineages within *Typhlichthys* that correspond to distinct drainages provides evidence that these lineages have evolved independently for considerable amounts of time. Some lineages have been separated since the late Miocene (longer, for example, than humans and chimpanzees Kumar et al. 2005). Relying on genetic evidence alone, many of these lineages would be considered distinct species despite lack of morphological differences. Many of these lineages also inhabit different geological units and physiographic regions. However, can we demonstrate that genetic variation among lineages corresponds to speciation? Life history and behavioral evidence for reproductive isolation among lineages are lacking and remain to be domonstrated. However, several lineages can be defined as "genealogical species" under the genealogical species concept (Avise and Ball 1990, Baum and Shaw 1995) based on concordance of genetic, geographic, and geologic datasets. Likewise, these lineages can be considered "diagnosable species" under the criteria of the phylogenetic species concept (de Queiroz and Donoghue 1990) and as ESUs (*sensu* Moritz 1994) for conservation and management.

At this time, we offer three provisional recommendations. First, the *Typhlichthys* found on the Ozark Plateau west of the Mississippi are geographically and genetically distinct and should be designated an ESU or potentially a separate species. Second, *Typhlichthys* north of Tennessee must be studied further, as our single sample from the Red River drainage appears to be sister to the Ozark group and deeply divergent from all other eastern samples. Third, each of the other watersheds in Tennessee and Alabama should be considered ESUs or at least as demographically separate management units (Palsboll et al. 2007) because the lack of haplotype sharing and deep divergences among haplotypes suggest that each drainage harbors a unique and historically significant portion of the evolutionary diversity of *Typhlichthys* and dispersal among drainages is insignificant.

Systematic relationships in the Amblyopsidae. Although amblyopsid fishes have been known to science since the early 1840s, the systematic relationships among species within the family remain poorly understood. Previous systematic investigations are limited to the morphological study of Eigenmann (1909) and Woods and Inger (1957) and genetic studies by Swofford (1982), Swofford *et al.* (1980), Bergstrom *et al.* (1995) and Bergstrom (1997). Woods and Inger (1957) synonymized all four species of *Typhlichthys* recognized prior to their study on the basis of lack of any clear geographic pattern in morphological variation. Likewise, *Troglichthys rosae* was synonymized under *Amblyopsis* and *Forbesichthys* was synonymized under *Chologaster* (Woods and Inger 1957). Electrophoretic analyses by Swofford (1982) showed considerable differentiation among populations of *Typhlichthys* suggestive of multiple, independent invasions of subterranean waters. Likewise, substantial differentiation was detected between the synonymized species of *Chologaster*, warranting resurrection of the genus *Forbesichthys*. However, the relationships among amblyopsid species were equivocal. More recently, Figg and Bessken (1995) have questioned the monophyly of *Amblyopsis*. Likewise, Bergstrom et al. (1995) and Bergstrom (1997) examined variation at the mitochondrial ND2 locus and resolved *Amblyopsis* as polyphyletic and *Typhlichthys* as paraphyletic. Regrettably, incomplete sampling and inadequate sample sizes limited past studies.

Our study also resolved *Amblyopsis* as non-monophyletic but supported the monophyly of *T. subterraneus* despite several, highly genetically-differentiated lineages. *Amblyopsis rosae* is the sister lineage to *T. subterraneus* and *A. spelaea*. The MRCA of these two lineages is estimated at 15.2 Mya based on the ND2 phylogeny. *Amblyopsis* also is unsupported in the S7 phylogeny, however, the branching order of *A. rosae*, *A. spelaea*, and *T. subterraneus* are equivocal. Although preliminary, our results support the nonmonophyly of *Amblyopsis*. If other genetic markers reveal a similar topology, the genus *Troglichthys* (Eigenmann 1898) may need to be resurrected for *A. rosae*.

Summary

The deep genetic divergence in Southern cavefish highlights discordance between molecular and morphological evolution, a finding that is becoming more prevalent in studies investigating genetic divergence in cave organisms. These results demonstrate that current morphological taxonomy may greatly underestimate genetic diversity, and, in turn, biodiversity in subterranean ichthyofauna. Future studies of subterranean fauna should incorporate multiple datasets, including morphological, genetic, geographic and geological, when identifying cryptic species or ESUs with similar phenotypes for conservation and management.

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IS A MINE A TERRIBLE THING TO WASTE? ADDITIONAL SUBTERRANEAN HABITATS FOR TROGLOBITIC FAUNA AND OTHER CAVERNICOLES IN THE OZARKS

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Abstract

Multiple studies have shown the importance of abandoned mines as surrogate habitat for bat species, but little information exists for other species that may use these habitats. Fifteen abandoned mines located on the Buffalo National River, Arkansas, near the historic mining town of Rush were inventoried from summer 2001 to summer 2005 for the presence of cavernicoles. Over 80 taxa were observed in these abandoned mines, including nine troglobites. The troglobites observed were: a terrestrial isopod (*Brackenridgia* sp.), two families of springtails (Arrhopalitidae, Entomobryiidae), two families of diplurans (Campodeidae, Japygidae), the grotto salamander (*Eurycea spelaea*), a millipede (*Causeyella* sp.), a harvestman (*Crosbyella* sp.), and an amphipod (*Stygobromus* sp.). Since these mines were driven into carbonate hillsides as discrete tunnels, a reasonable explanation for the presence of troglobites is colonization of mine passageways following the intersection of naturally occurring voids. This study suggests that abandoned mine habitats may be important to a suite of rare and interesting species, in addition to bats.

Key words: mines, cave biology, biodiversity, Buffalo National River, Arkansas, Ozarks

Introduction

While studies have shown the importance of abandoned mines as habitat for bat species (Raesly and Gates 1987, Whitaker and Rissler 1992), little information exists for other species that may use these habitats. Cavernicoles, or cave-dwelling species, are known to occur in abandoned mines (McDaniel and Gardner 1977, Dorris and Saugey 1983, Heath et al. 1986, Peck 1988, Kjaerandsen 1993, McAllister et al. 1995, Nielsen and Andreasen 1998). Relatively few cavernicoles from these studies could be considered troglobites (or cave-limited species), and a majority of species were classified as accidentals, trogloxenes, or troglophiles. Accidental species are species that wander into a cave but can't live there. Trogloxenes are species that complete part of their life cycle in caves and part outside. Troglophiles are species that may complete their entire life cycle in caves, but can also complete life cycles outside caves.

The occurrence of a troglobitic beetle in a Kentucky coal mine (Barr 1986) and the successful transplant of a rare harvestman (Opiliones) to an abandoned mine in California (Elliott 2000) suggests that mine habitats may also contain troglobites or have environmental conditions that could support troglobites. The purpose of this study was to examine abandoned mines for the presence of troglobites and characterize some of the environmental conditions associated with the mines.

Materials and Methods

From April 2001 to September 2005, we conducted biological inventories in 15 abandoned mines along the Buffalo National River, near the historic town of Rush, Arkansas (Figure 1). Mining activity in this area involved the extraction of zinc ore from carbonate rock sequences and occurred from 1900 to 1945 (Howard 1989). Fourteen of the mines were quarried into hillsides as horizontal tunnels, while one had an initial vertical drop before continuing as horizontal passage. Several mines had more than one entrance. Average mine length was 86.8 m (SE ± 24.6 m), with a range of 10 to 300 m.

In all 15 sites, visual searches and hand collections were used to record or collect organisms. During summer 2004, additional collections were made using baited pitfall traps in six mines (Toney Bend Mine #2, #3, Morning Star Mine #5, #6, #7, Long Ear Mine). Traps consisted of 30-ml, straight-sided, wide-mouth Nalgene® jars, filled with 5 ml of propylene glycol. The traps were baited with 5 ml

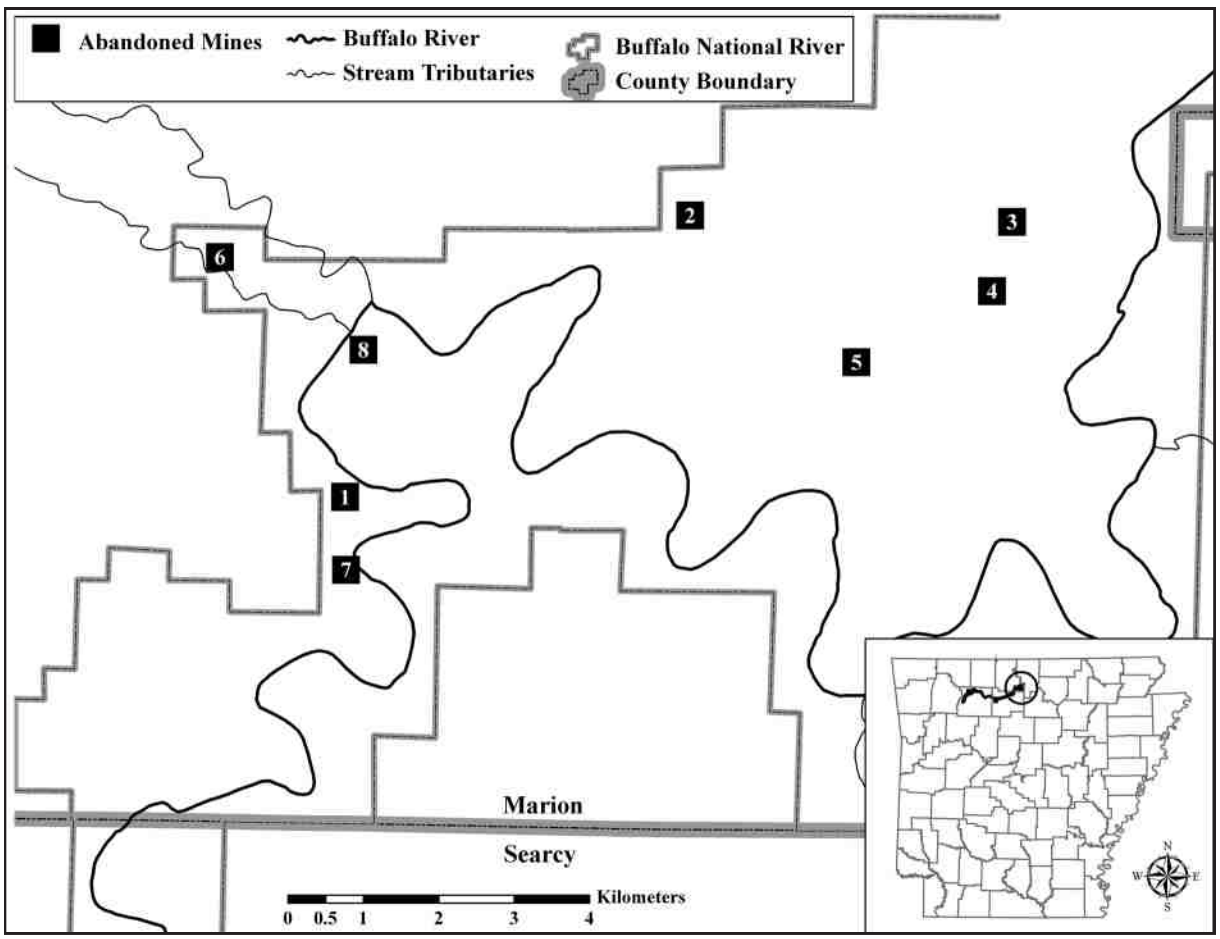

Figure 1 *Study area near Rush, Arkansas, Buffalo National River. Inset map shows counties of Arkansas, Buffalo National River (black polygon), and location of study area (black circle). Abandoned mines are shown as filled squares (▪), and the numbers correspond with specific sites: 1) Bice Mine, 2) Boat Creek Mine, 3) Bonanza Mine, 4) Fox Den Mine, 5) Long Ear Mine, Mary Agnes Mine, Prospect Cave, Sixteen Mine, 6) Morning Star Mines #5, #6, #7, #15, 7) Toney Bend Mines #2, #3, and 8) Red Cloud Mine.*

of slightly rancid limburger cheese spread smeared around the inner lip of the jars. For each trap, a hole was dug in the substrate deep enough to allow placement with the lip of the jar just at or below the floor level. Considerable care was taken to ensure that the substrate into which the trap was placed, usually clay, covered the lip of the jar, so that the top of the jar did not serve as a barrier for smaller fauna from entering the trap. A 10 cm x 10 cm x 5 cm box, constructed of 6.3-mm mesh hardware cloth, was placed over each trap to reduce the potential for trap disturbance by vertebrates such as *Peromyscus* spp., *Neotoma floridana*, and *Procyon lotor* (mice, eastern wood rat, and raccoon). Traps remained in place for approximately 72 hours.

Each observed or collected taxon was given an ecological classification of accidental (AC), trogloxene (TX), troglophile (TP), or troglobite (TB). Collected invertebrates were identified to the lowest possible taxon, and invertebrates that were not identifiable to specific level were classified as morphospecies. Specimens were preserved in 70% ethanol and deposited in the Arthropod Museum at the University of Arkansas, however, these specimens remain the property of the National Park Service. The collection of invertebrates was conducted under the following permits: Arkansas Game and Fish Commission Scientific Collection Permit #020920042 and Buffalo National River, National Park Service Scientific Research and Collecting Permit #BUFF-2004-SCI-0008.

Additionally, temperature (2-cm soil depth, 2-cm air, 1-m air) and relative humidity were measured in the six sites where pitfall traps were placed. Temperature and humidity measurements were taken at the surface, entrance, twilight, and dark zones.

Results

Overall, a total of 4,620 individuals representing 82 taxa in 40 families, 26 orders, and 13 classes were observed or collected. Several taxa were not previously documented from Arkansas. A centipede, *Buethobius* prob. *oabitus* (Henicopidae), found in Long Ear Mine was the first record for this family in the state. Another state record was a terrestrial isopod, *Brackenridgia* sp., found in Morning Star Mine #6 and Toney Bend Mine #3. Additionally, two undescribed species were discovered. A new species of *Rhagidia* (Rhagidiidae: Acari) was observed in Morning Star Mine #5 and Toney Bend Mine #3, while a new genus of Japygidae (Diplura) was collected from Toney Bend Mine #2.

The most common arthropods were cave crickets, four families of flies, and tomocerid springtails (Table 1). The most common vertebrates were: Eastern pipistrelle (*Pipistrellus subflavus*), Western Slimy salamander (*Plethodon albagula*), Northern bat (*Myotis septentrionalis*), Cave salamander (*Eurycea lucifuga*), and Ozark Zigzag salamander (*Plethodon angusticlavius*). The average number of taxa per site was 19.69 (SE ± 4.67), with a maximum of 54 in Toney Bend Mine #3 and a minimum of 2 in Mary Agnes Mine (Table 2). Average number of total individuals was 291.43 (SE ± 104.87), with a range of 2-1137.

The majority (79%) of fauna were categorized as trogloxenes (N=34) and troglophiles (N=31), while accidentals made up 10% (N=8). Interestingly, troglobitic taxa (N=9) made up 11% of the fauna and occurred in two-thirds of mines (10 of 15). The nine troglobites were: an isopod (*Brackenridgia* sp.), two families of springtails (Arrhopalitidae, Entomobryiidae), two families of diplurans (Campodeidae, Japygidae), the Grotto salamander (*Eurycea spelaea*), a millipede (*Causeyella* sp.), a harvestman (*Crosbyella* sp.), and an amphipod (*Stygobromus* sp.). Average troglobitic taxa per site was 2.06 (SE ± 0.52), with a maximum of six (Toney Bend Mine #3) and a minimum of 0. For the 10 sites where troglobites occurred, average troglobitic taxa per site were three (SE ± 1.84). Total troglobitic abundance was highest in Long Ear Mine (80 individuals), with an average of 12.63 (SE ± 5.52). For the 10 sites where troglobites occurred, average troglobitic abundance was 18.36 (SE ± 24.83). The most abundant troglobite was the springtail family Arrhopalitidae (N=133). Less than 20 individuals per taxa were observed for the other troglobites.

In summer 2004, temperature decreased and relative humidity increased from surface zones to dark zones (Figure 2). The average surface temperature ranged from 21.55°C (SE ± 1.31°C) to 26.43°C (SE ± 0.95°C) across the three levels of temperature measurement, and surface relative humidity averaged 73.47% (SE ± 2.53%). Average entrance zone temperature ranged from 17.6°C (SE ± 1.14°C) to 20.91°C (SE ± 1.29°C), and entrance relative humidity averaged 88.04% (SE ± 1.27%).

Table 1 The 15 most abundant fauna documented in the abandoned mines. Taxa were identified as morphospecies and ordered by total number of individuals.

Class or Order	Family	Scientific name	Individuals
Orthoptera	Rhaphidophoridae	*Ceuthophilus gracilipes gracilipes*	964
	Phoridae	....	632
Diptera	Heleomyzidae	....	457
Chiroptera	Vespertilionidae	*Pipistrellus subflavus*	400
Diptera	Tipulidae	....	273
Diptera	Mycetophilidae	....	269
Collembola	Tomoceridae	*Tomocerus* sp.	246
Araneae	....	....	173
Diptera	Sphaeroceridae	....	134
Collembola	Arrhopalitidae	....	133
Gastropoda	....	....	123
Diptera	....	....	103
Hymenoptera	Formicidae	*Camponotus* sp.	64
Opiliones	....	....	64
Caudata	Plethodontidae	*Plethodon albagula*	41

Average twilight zone temperature ranged from 15.8°C (SE ± 0.62°C) to 18.71°C (SE ± 0.87°C), and twilight relative humidity averaged 90.58% (SE ± 0.77%). Average dark zone temperature ranged from 13.84°C (SE ± 1.18°C) to 15.66°C (SE ± 1.72°C), and dark relative humidity averaged 91.65% (SE ± 0.66%).

Discussion

Abandoned mines are definitely not things to waste. It is well documented that mines are important habitat for over half of the 43 bat species found in the United States (Tuttle and Taylor, 1994). In addition to being important for bats, abandoned mines provide habitat for other cavernicolous species, such as 74 taxa (excluding eight accidental taxa) observed during this study. Based on the nine troglobites observed in this study, abandoned mines are also habitat for troglobitic species.

Since mines in the current study were driven into carbonate hillsides as tunnels, there is a reasonable explanation for the presence of troglobites. Many of these mines intersect naturally occurring bedrock voids, and troglobites may have colonized mine passageways from these voids. Nearly all the troglobites in this study were also reported from surrounding caves (Graening et al. 2004, Graening et al. 2006). Lack of troglobites in previous mine studies may stem from sampling mines that were quarried in noncarbonate bedrock (Dorris and Saugey 1983, Heath et al. 1986, Saugey et al. 1985) or sampling mines in geographic locations where caves in general have few troglobites (Peck 1998).

An interesting comparison can be made between the number of troglobites documented in the more intensively sampled mines in this study and 50 biologically diverse Missouri caves (Elliott 2007). For each 50 Missouri caves, at least two troglobitic species were reported. In this study, there were eight mines with at least 2 troglobites. The average number of troglobites in the 50 Missouri caves was 5.3 (SE ± 0.3), with a range of 2-12. The average number of troglobites in the eight abandoned mines was 3.8 (SE ± 0.56), with a range of 2-6. Because of the difference in sample size, average number of troglobites was compared using a non-parametric test. No significant difference was detected for mean number of troglobites between the eight mines and 50 Missouri caves (Wilcoxon

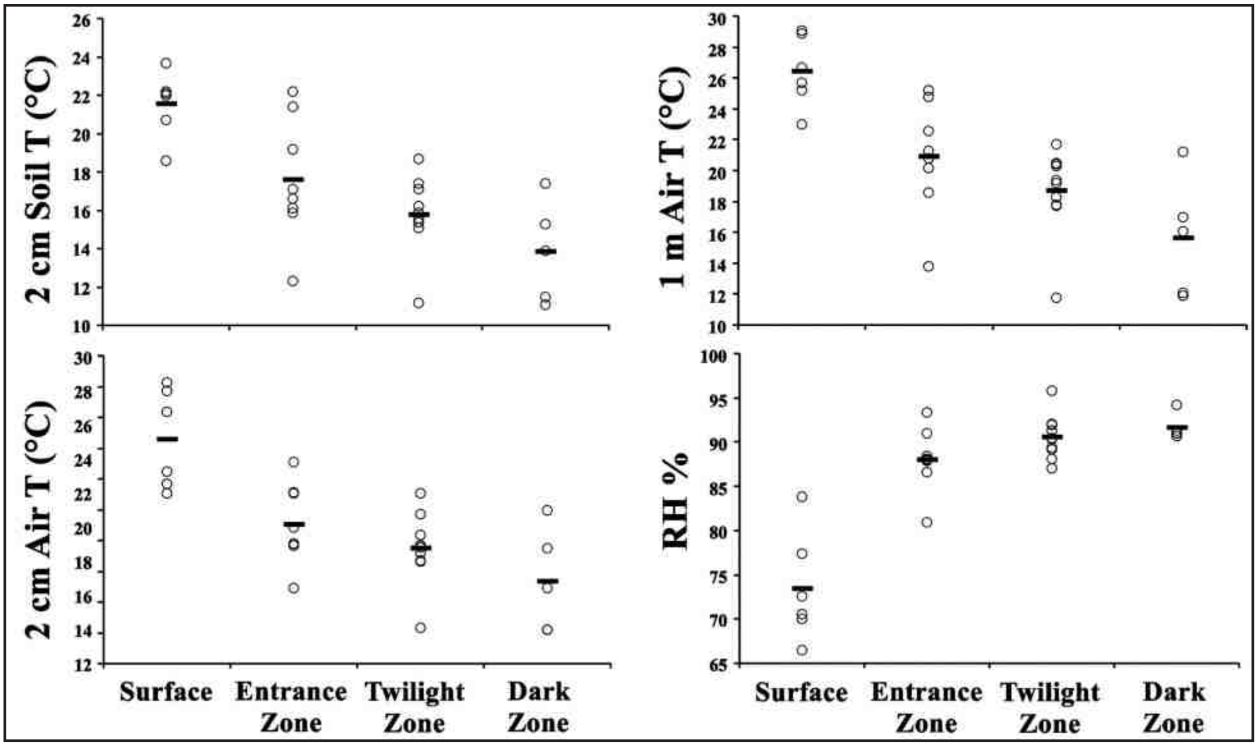

Figure 2 *Temperature (2-cm soil temperature, 2-cm air temperature, 1-m air temperature) and humidity recorded at six mines in summer 2004. Surface measurements were recorded 5 m outside the drip line of each site. Open circles (○) represent individual measurements, while black rectangles (■) represent means.*

test, *Z* ratio = -1.85, $p = 0.06$). There may be several reasons why no difference was detected. One reason may be the difference in sample sizes. These eight mines may not be typical, and increasing mine sample size might lower the average number of troglobites per mine. However, sampling additional mines could also increase the average number of troglobites per mine, because sampling intensity is known to influence number of species (Culver et al. 2000, Elliott 2007, Fong et al. 2007). Another explanation for the lack of significant difference may be because of sampling technique. Two techniques, visual searches and baited pitfall trapping, were used to inventory the mines, but most of the 50 Missouri caves were not sampled using baited pitfall traps. However, none of the troglobites from the eight mines were collected just from baited pitfall traps or only collected after pitfall trap placement. The lack of significant difference between the average number of troglobites is intriguing and warrants a more detailed study. We suggest that, in the Ozarks, abandoned mines in carbonate rocks may contain similar numbers of troglobites as in naturally occurring caves, and represent additional habitats for biological inventory and ecological study of cavernicoles.

Acknowledgments

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Table 2 *Faunal characteristics of the 15 abandoned mines. Mines were ordered by number (No.) of taxa, and "TB" is an abbreviation for troglobite.*

Site	TB Taxa*	No. Taxa	Total Individuals	No. TB Taxa	Total TB Individuals
Toney Bend Mine #3	1, 2, 3, 4, 5, 6	54	1137	6	40
Long Ear Mine	1, 6	48	1052	2	80
Toney Bend Mine #2	3, 4, 5, 6, 8	45	1094	5	8
Morning Star Mine #5	1, 6	41	330	2	3
Morning Star Mine #6	1, 2, 5, 6	33	349	4	23
Morning Star Mine #7	1, 3, 6, 7, 9	31	169	5	35
Morning Star Mine #15	3, 4, 5, 6	10	46	4	4
Boat Creek Mine	9	10	40	1	2
Red Cloud Mine	1	7	367	1	1
Prospect Cave	--	7	8	0	0
Sixteen Mine	5, 9	6	34	2	5
Fox Den Mine	--	6	8	0	0
Bonanza Mine	7	6	13	1	1
Groundhog Mine	--	5	5	0	0
Bice Mine	--	4	4	0	0
Mary Agnes Mine	--	2	2	0	0
Mean		19.69	291.13	2.06	12.63
Standard Error		4.67	104.87	0.52	5.52
Minimum		2	2	0	0
Maximum		54	1137	6	80

***1 = Arrhopalitidae; 2 = *Brackenridgia* sp.; 3 = Campodeidae; 4 = *Causeyella* sp.; 5 = *Crosbyella* sp.; 6 = Entomobryiidae; 7 = *Eurycea spelaea*; 8 = Japygidae; 9 = *Stygobromus* sp.**

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FIFTY YEARS OF DATA COLLECTING: THE MISSOURI SPELEOLOGICAL SURVEY'S CAVE DATABASE

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Abstract

The first statewide cave "catalog" for Missouri was published in 1952. After the publication of J Harlen Bretz's *Caves of Missouri* in 1956, the Missouri Speleological Survey was organized. Acting in cooperation with the Missouri Geological Survey, the MSS began actively adding to the list of caves. By the late 1960's this listing was computerized, originally as simple text lines. By 1990 a better system was needed and new platforms were developed. Today the Missouri Cave Database exists as a functional and flexible dataset written on a FileMaker Pro platform. A history of data collection in the state is presented with a description of the database and how it interacts with other digital data, physical cave files, cave maps and other sets of information.

Key words: cave database, cave geography, data security, Missouri Speleological Survey

Introduction

The first statewide cave "catalog" for Missouri was published in 1952. After the publication of J Harlen Bretz's *Caves of Missouri* (1956), the Missouri Speleological Survey was organized. Acting in cooperation with the Missouri Geological Survey, the MSS began actively adding to the list of caves. By the late 1960's this listing was computerized, originally as simple text lines. By 1990 a better system was needed and new platforms were developed, including Microsoft Access®. Today the Missouri Cave Database exists as a functional and flexible dataset written on a FileMaker Pro platform. A history of data collection in the state follows with a description of the database and how it interacts with other digital data, physical cave files, cave maps and other sets of information.

The state of Missouri contains over 6,200 known caves of all shapes, sizes, and kinds. While this is remarkable in itself, no less remarkable is the history of how these caves have been documented over the years, as well as the process, methodologies and philosophy by which information is gathered today.

History

In the 1800s and early 1900s Missouri caves received occasional mention by geologists writing reports for the Missouri Geological Survey. In the 1930's, Willard Farrar, a Survey geologist, compiled a list of caves in the state. Farrar was killed in World War II but his "Partial Catalog" of the caves became the resource base for J Harlen Bretz as he began assimilating data for his landmark *Caves of Missouri* (1956). Bretz's book was more than a listing of caves in the state; it was a tome on the origin of caves in the Ozarks, which supported Bretz's geomorphologic theories. The excitement generated by the publication of the book resulted in the formation of the Missouri Speleological Survey (MSS), also in 1956. Particularly cave enthusiasts recognized that hundreds of caves were not listed in the publication, and they sought to document these additional sites. The MSS was organized as a survey, not a society, whose primary purpose was to gather data, rather than act as a social group. That purpose has been continuous now for over 50 years.

With the additional interest in caves, the Geological Survey hired Jerry Vineyard to update the list. Eventually it was conceded that perhaps it was not in the best interest of the caves to have lists available for purchase by the general public. Thus, the responsibility for actually publishing the catalog was handed over to the MSS, and the first major revision of the catalog was published in 1964 by the MSS.

Along with the development of good lists, a high priority was the writing of detailed descriptions of the caves and creating quality cave maps. Missouri has long been a leader in both of these areas. These descriptions and maps began to be published in *Missouri Speleology* and the appearance of these issues inspired more people to take part in the process.

The cave list was computerized beginning in the late 1960s. Bulky, slow, and costly, one list eventually would be printed out on multilith masters and copies were printed and bound. This process was performed twice before faster printers made it possible to actually print out a catalog on demand. Eventually the antiquated software and hardware needed to run it became hard to maintain. Further, as Geological Survey workers had less time to deal with incoming data the data process began to slow. As output suffered, so input was affected and contributions slowly began to decline. Finally the state was not able to support the software, and the MSS alleviated the problem by moving the data to a more accessible platform. A new front end, written in Microsoft Access®, was utilized for a while beginning in the late 1990s. While detailed and thorough, this system was fairly hard for ordinary users to operate, and it was relatively inflexible. Eventually the data were ported over to FileMaker Pro, a stand-alone, run-time database. For a few years the data were kept in both formats before the Access format was abandoned. Since 2000, the data have been kept in the FileMaker Pro database, rechristened The Missouri Cave Database (MCD), and is maintained by the MSS and its cooperators.

Features of the Database

FileMaker Pro is the largest-selling, stand-alone database for small applications and yet it is powerful, while easy to use and customize. For the MCD application, the power lies in the ability to import and export different types of data while also being able to cull out sections of data for remote data entry. Further, by utilizing run-time versions the data can be distributed to users without requiring the additional purchase of stand-alone units. Finally, the program is cross-platform and can be used with a variety of operating systems.

The field structure of the MCD is not terribly involved. There are three tables and a variety of views or forms, which are easy to access. The main table with 63 fields contains the bulk of the location and attributes data. The location fields include UTMs, latitude/longitude and Public Land Survey System (PLSS), using township, range and section. The bulk of the cave locations were in PLSS, but this is slowly being refined into point location data, preferably in UTM, NAD 27 (Universal Transverse Mercator coordinate system, North American Datum 1927). Locations in any format are accepted and recorded with conversions into other systems. Additionally, a text field includes a description of and directions to the cave entrance. Attribute information includes the host rock, basic hydrology, length, and other information. Lastly information relating to the management of the cave, including owner, status, and classification is included.

A cave maps table includes 10 fields. This part of the database is actually maintained by the Geological Survey, in an Access format, and records those cave maps that are actually on file. This data are periodically imported into the MCD.

A reports table contains 13 fields, including a text field, and is used for including text reports on the caves. This section of the data can be worked on separately and imported into the MCD. A database design report is available from the author.

Data Overview

At the date of this writing (2007) the database main table contains 6,266 records, which represent the entrances of caves. Some caves have multiple entrance records although this is not necessarily the norm. The maps data contains 3,095 records which represents the number of cave maps on file at the Missouri Geological Survey. The reports table currently contains over 1,500 records, a number that is rapidly growing as this table is utilized and populated more frequently. A sampling of the database reveals that there are over 60 "bear" caves (caves with "bear" as part of the name) squeezing out "bat" caves which number about 40. Over 500 caves have "spring" as part of their name, while 170 have "bluff" (Ozark for cliff) in their name. There are nearly twice as many "little" caves (115) as there are "big" caves (59). Over 300 caves are noted as "closed" with another 225 as "restricted." Perry County, in southeast Missouri, leads the state with 659 caves, followed by Shannon County, in the southeast Ozarks, with 578 caves. Greene County, in southwest Missouri, has 369, closely followed by central Missouri's Pulaski County with 358.

Information Flow, Policies and Restrictions

Material flows into the database from a variety of sources through a variety of media. Much information, probably the bulk, comes from emailed text messages. Others write more formal reports and send those in. Some location submissions are in the form of simple GPS output while others are exported from DRG (Digital Raster Graphics of scanned topographic maps) programs, such as National Geographic's Topo! program.

The data in the MCD are restricted. That said, the information is available to those who need it, have a valid use for the data, will add to the data and agree to provide security for the data. A committee is called to consider requests that are beyond the norm of simple approval or disapproval. If need be, the MSS board is consulted. Data printouts are no longer provided; the information is exported in either FileMaker run-times, text files, or Excel format. Data exports are easily tailored for the needs of the recipient and to insure data security.

The Missouri Cave Database is a cooperative project. While the MSS is the organizing and administrative body, the effort is supported by a number of government agencies including the National Park Service's Ozark National Scenic Riverways (OZAR), the U.S. Forest Service's Mark Twain National Forest (MTNF), the Missouri Department of Conservation (MDC), the Missouri Department of Natural Resources (including both the Geological Survey and the Division of State Parks), The Missouri Department of Transportation (MoDOT) as well as the Department of Defense's Fort Leonard Wood and Army Corps of Engineers. Most of these are major cave owners as well: MTNF has over 560 caves on its lands, while OZAR has 300 and MDC about 260. These agencies share their data, support the gathering of data and get data in return. OZAR, MTNF, and MoDNR use FileMaker run-times as their data standard with exported data used in GIS (Geographic Information System) and other applications. Cave Research Foundation supplies database software, hardware and developmental costs to the project.

The Missouri Speleological Survey's data-gathering mission continues into the rest of its first century with a well-developed and supported mission.

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THE MANAGEMENT OF BEROME MOORE CAVE, PERRY COUNTY, MISSOURI

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Abstract

Berome Moore Cave is connected to Tom Moore Cave, forming the Moore Cave System, Perry County, Missouri. The cave contains many important natural resources. This paper is a brief history of the evolution of the Middle Mississippi Valley Grotto's management of the cave over 40 years. The grotto's management, by means of a lease from the landowner, changed over time because of changes in focus, landowner relations and refinements in caving culture. After 20 years of survey and exploration, many groups were allowed into the cave, which eventually caused problems, and the owner threatened to fill the entrance. A policy was adopted to admit fewer but more experienced people, with a purpose of low-impact exploration, science and mapping.

Key words: cave management, landowner relations, Berome Moore Cave, Perry County, Missouri

Introduction

Berome Moore Cave was discovered in the 1960s by Tex Yokum in a cornfield sinkhole in southeastern Missouri (Figure 1). The first priority of the Middle Mississippi Valley Grotto was establishing an agreement with the landowner that would allow Middle Mississippi Valley Grotto to long-term access to the cave. With the help of a lawyer we agreed upon a lease that was renewable every two years and gave Middle Mississippi Valley Grotto access to the sinkhole entrance. A verbal agreement allowed Middle Mississippi Valley Grotto to park their cars in the lanes around the farm buildings close to the site.

To protect the cave from unauthorized entry, a barrel gate was constructed at the entrance, which originally had been dug open by the discoverers.

Figure 1 The sinkhole entrance to Berome Moore Cave lies in a cornfield.

Surveying

The next and obvious phase was surveying. Because early survey trips involved working the whole weekend, a base camp in the cave was established at a convenient point about 365 m (1,200 feet) from the entrance. In addition to the base camp, wires were hung and hooked up to local utilities (Figure 2). By the 1980s Middle Mississippi Valley Grotto had surveyed >26 km (16 miles) of passage.

Recreation

Sometime later Middle Mississippi Valley Grotto decided to provide an educational experience for groups of Boy Scouts, Girl Scouts, church groups etc., in which the members of these groups were given a sound cave conservation message, while enjoying camping overnight in the cave. At the same time, Middle Mississippi Valley Grotto benefitted by earning funds from donations from the groups. The money received was then plowed back into the cave in the form of base camp improvements, purchase of surveying equipment, and the like.

As time passed and most of the known cave had been surveyed, the cave was primarily used for the group trips. Unfortunately, as might be expected when taking groups in over a period of many years, occasionally one event or another would irritate the landowner. Although groups had been escorted into the cave over a period of 30 years, and there were only a few instances where something occurred to upset the landowners, it was enough that eventually the landowners threatened to close the cave.

Prior to this, Middle Mississippi Valley Grotto itself had debated the pros and cons of continuing to lead noncavers into Berome, especially as we realized that the landowner was becoming more concerned over liability issues, whether above or below the ground.

Landowner Relations

As it turned out the landowner made our mind up for us in the late 1990s. In an initial meeting with the landowner he had decided that he would close the cave—literally, by filling in the sinkhole. After some discussion, we were able to come to a compromise. We agreed that we would no longer bring noncaver groups into the cave. From this point forward, Middle Mississippi Valley Grotto would visit the cave, on average, only once per month, the size of the group would be limited, the group would consist primarily of cavers, and our trips would serve some purpose other than recreation—primarily surveying, biology studies (Figure 3), exploration of leads etc. In addition, we would no longer park in the farmyard, but on the side of the road next to a gate that is always open, and limit ourselves to no more than four or five cars. In a sense, we had come nearly full circle, concentrating our efforts on surveying. Although the "big" passages were already mapped, we continue to discover new, usually uncomfortably tight passage, and so the cave "grows."

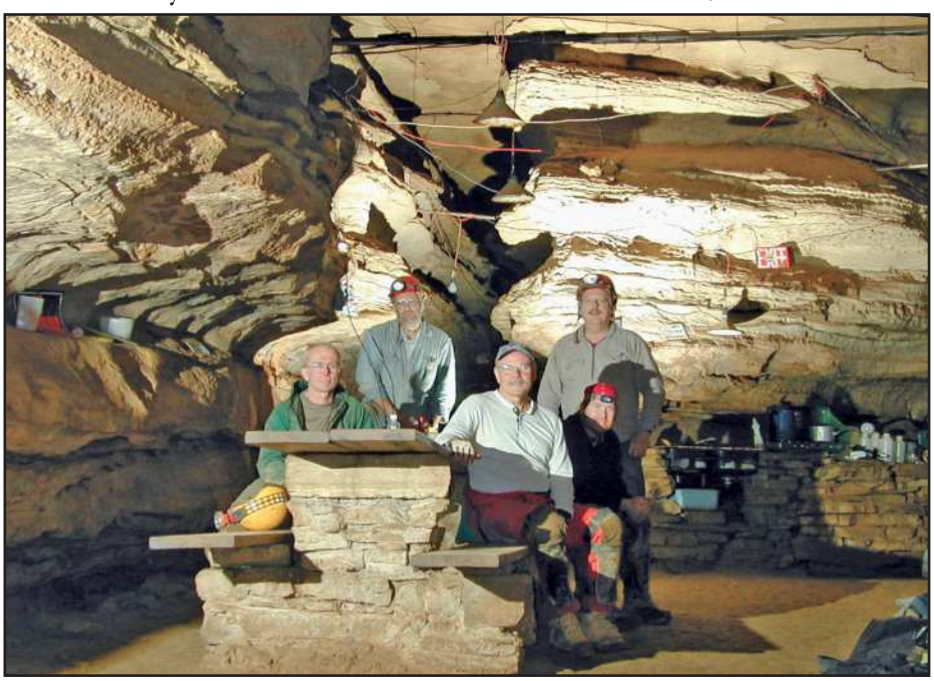

Figure 2 Left to right: Don Dunham and biologists David Ashley (standing), Horton H. Hobbs III, Bill Elliott (standing) and Mike Slay at the base camp in Berome Moore Cave, May 2003.

Discussion

Because of the long span of time of our cave management, the board has had to make frequent alterations in our policies, sometimes even in the face of opposition from the general membership of Middle Mississippi Valley Grotto. It is important that the grotto

Figure 3 *David C. Ashley's cave biology students from Missouri Western State University conduct a stream census in Berome Moore Cave, February 16, 2003.*

remain proactive in its management and attempt to foresee potential problems under present policies. We have to place ourselves in the position of the landowners, and try to understand how we would react to certain activities of cavers if we owned the land. Underground, we also need to police ourselves, altering any behaviors or activities that no longer seem appropriate, both in relation to caving safety and to the conservation of the cave.

Since Middle Mississippi Valley Grotto adopted this new low-impact visitation in our management of the cave, our relationship with the landowner, over time, has been repaired, and we feel fortunate that we have been able to maintain access to the cave. Berome Moore Cave is a precious resource to be studied and enjoyed (Figure 4), and it is Middle Mississippi Valley Grotto's goal to preserve access to this underground gem into the indefinite future.

Figure 4 *Paw print, probably of a Pleistocene jaguar,* Panthera onca augusta*, in Berome Moore Cave. The print is about 80–90 mm wide. A track of this large cat is protected by flagging. A partial mandible of this species was also found in the cave by Oesch (1969).*

Acknowledgments

This paper was presented at the Symposium by Joseph E. Walsh on the author's behalf. William R. Elliott and David C. Ashley provided photos.

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POTATOES AND CAVE OWNERS: THE MANAGEMENT OF MYSTERY CAVE, PERRY COUNTY, MISSOURI

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Abstract

This paper is actually a collection of true stories about the management of Mystery Cave, Perry County, Missouri. Even though some of these events happened a long time ago, I believe they are still useful today, because they probably will happen again somewhere, sometime. The management of this cave has had a long and turbulent history. Perhaps you may recall that some of them happened to you.

Key words: cave management, Mystery Cave, Rimstone River Cave, Tom Moore Cave, Perry County, Missouri

Introduction

Mystery Cave begins as a kind of "Artesian Well" with water that bubbles up out of the ground in considerable volume and flows a few hundred meters along a spring branch, where it drops into the historic, main cave entrance (Figure 1). This entrance was once only a crack in the rocks with water flowing into it until the early 1930s, when it collapsed and opened up to reveal the cave.

The first few hundred meters of the cave were explored by local farmers. Southeastern Missouri Grotto first entered the cave in 1964, and explored a few hundred meters downstream.

Little Egypt Student Grotto of Southern Illinois University, learned of the existence of the cave, and entered it to begin exploration in 1965. The cave immediately was adopted by the grotto, and mapping began, mostly under the leadership of Jim Rodemaker.

I became President of the grotto and director of the Mystery Cave Survey Project, October 4, 1967. By that time, we had a small but very enthusiastic and dedicated group of cave mappers, and exploration and survey shifted into high gear. We enjoyed an excellent relationship with the cave owner. Unfortunately, that idyllic situation was not to last.

Too Popular

The cave was becoming too well known and very popular. More and more people were visiting the cave. Many of them had no interest in scientific exploration and survey. They only wanted to run down big virgin passage and leave the difficult survey work for others to do.

Every weekend, dozens of cars were parked along the gravel road near the cave. Neighboring farmers, one in particular, began to complain about the crowds. He had never been particularly friendly to cavers anyway. Party activity began to happen in the cave. Some of our own grotto members were among the guilty. Please understand that I have nothing against recreational caving. Sport caving is a legitimate activity. I simply believe that it should be done safely and responsibly, with as little impact and damage to the cave as possible. Wild caves are not good places to party in.

Figure 1 Ginny Adams at the historic or main entrance of Mystery Cave.

Cave Gated

It became obvious that we were about to lose the cave unless something was done immediately. We decided to gate the cave. The entire grotto pitched in to do the hard work required. The result was a magnificent, state-of-the-art edifice that promised to solve all of our problems.

You have probably guessed what happened next. The obvious question was, "Who should be allowed to have copies of the key and access to the cave?" After much discussion, it was decided that a committee or board should be elected by the grotto membership to decide.

The Grotto Board

A few qualified "leaders" would be appointed by the Grotto Board, and nobody would actually "own" a copy of the key. Qualification requirements for "trip leader" were rather stringent. This was, in part, an attempt to control the party attitude that was growing among our own membership. Many applied, but few were chosen. The stage was set for contention. Resentment between those who were "leaders" and those who were not began to grow.

As it happened, our grotto was composed of about 75% Southern Illinois University students, from all around the state, and 25% students from the Chicago area, who were also members of that grotto. Please understand that many of the Chicago people were friends and good cavers. They taught me the rudiments of surveying caves, and I looked up to them. They were my mentors.

One Tuesday evening, in September 1967, the situation finally came to a head. One of the "have not" cavers called me from Chicago. He was going to bring down a large group for exploration in Mystery on Saturday, and was demanding a key to the gate.

I told him to come on down, and I would try to find a leader to meet them there at the cave, and go in with them, as per the rules of the Board. Technically, as Grotto President, I was a member of the Board, but could not vote, except to break a tie. That never happened. I said I would try to convince the Grotto Board to revise the leadership qualifications so that more of the Chicago members could have their own copies of the key. That way, they could go directly to the cave, and would not have to come to Carbondale to pick up a key. That, of course, was not what he wanted to hear.

A Dispute Erupts

Very late Thursday evening, a large and very irate group of Chicago cavers showed up on my doorstep after a long and tiresome drive down from Chicago to Carbondale.

What followed next was a noisy altercation that almost resulted in my being evicted from my apartment after the neighbors called the cops. I finally just gave them my copy of the key and told them to "go for it."

Unknown to me, a group had been to the cave the day before and, finding the padlock corroded and silted up, they were able to get into the cave only with great difficulty. They put a new padlock on the gate, and had neglected to tell me about it as yet. Of course, the Chicago group could not get in with the key I had given them. They were not happy cavers!

They hacksawed the padlock off, doing some damage to the gate in the process, and put a new lock of their own on it.

They told me that they would not give us a copy of the key unless "some changes were made," and that if we tried to do anything about it, they would dynamite the gate.

Those who were interested in the ecology of the cave began saying that the gate was already changing the critter population downstream in the cave. The critters had previously depended upon the input of decomposing wood and organic debris that the gate was now blocking.

Thankfully, the cave owner seemed to be oblivious to all of these political and ecological squabbles. He did not have a key, and did not want one. He had said that we were responsible for the management of the cave, and that "party crowds" were not allowed.

Cave Closed

One such "party crowd" had already been responsible for the closing of nearby Harrington Cave a few years before my time. The Mystery Cave owner was well aware of that problem since he and the Harrington Cave owner were close friends and neighbors.

The Harrington Cave owner told me that he came home from church one evening to find an enormous crowd of cars parked along the road, and smoke pouring out of the cave entrance "like a volcano." Investigating, he found a boisterous party going on in the main room of the cave. Most of the participants were drunk and high on (something). Later he discovered extensive damage done to the beautiful formations in the rear of his cave. He closed the cave immediately, and it was only after considerable negotiations that we were able to get in for a few trips to finish the survey of his cave.

What had I done to deserve these problems? I was only a college kid interested in cave science as a hobby.

As it turned out, it never was a good idea to put a gate in the main entrance of Mystery Cave in the first place. The cave entrance was an orifice into which large volumes of water poured during rainy weather. Mud, sticks, logs and debris clogged the gate to the cave ceiling almost immediately. We had to dig it open several times. Cleaning out the debris was a laborious and very time-consuming process. Copperheads were an ever present problem. Nobody wanted to do it. Eventually, we simply removed the padlock and left the gate open.

Mother Nature finally solved the problem for us, in a way. Frost action from increased moisture caused the entrance above the gate to collapse, cutting off entry.

Another Entrance

We were forced to develop another more difficult entrance directly down into the Cathedral Room through a tight joint crack that Terry Pitchford and I had found early in our survey of that part of the cave. That became another long story about political harmony.

Some cavers contended that they had "discovered" this entrance first, and therefore, they had the right to open it by "right of discovery," not that it makes any real difference who actually found it first, anyway.

Contaminants

The real reason for the decline in population of cave life downstream in the cave turned out to be the result of increasing pollution from several sources; (1) agri-chemicals, such as nitrogen and phosphorous fertilizers, insecticides and herbicides; (2) organic waste from hogs and cattle; (3) sewage and laundry detergents that came from cesspools and piping directly down into sinkholes; (4) increasing siltation, the result of bulldozing away the woodlands for the construction of houses; and (5) clandestine industrial dumping in convenient sinkholes late at night.

Once, there had been a shoe factory in Perryville, and shoe soles were stamped out of leather sheets. The left over scrap was dumped into sinkholes as fill all over Perry County. Today, cavers can still follow the trails of these scraps to discover entrances to caves underground. "Follow the shoe leather boys" was advice we often gave to explorers in those days.

One day in September 1969, some friends and I entered the Little Freezy Entrance to nearby Rimstone River Cave for a short tour. Immediately upon emerging into Echo Avenue, we became aware of an awful odor. It was sweet, and yet sickening. It tickled our throats and made us cough. I became almost nauseous. There was a blue scum upon the water. I collected a small amount and ran some chemical tests upon it in the lab back at Southern Illinois University. Nuclear magnetic resonance spectroscopy data indicated the presence of chlorinated hydrocarbons, methyl and cyanide radicals. We never discovered the identity of this blue scum upon the water. It was probably an insecticide, or a solvent used in the manufacture of plastics, and dumped into a sinkhole upstream.

At one point, sewage pollution became so bad in Tom Moore Cave that the population of isopods increased dramatically (Figure 2). They were so thick you could have scooped them up to make soup out of them.

As pollution began to enter the groundwater in the aquifer far below the caves, the Perry County Planning Commission began to consider ways to solve the problem.

A Park Proposal

One proposal was the creation of a karst preserve state park. I still have a copy of that proposal in my files.

One of our best known and most influential cavers bought into this proposal, and he began talking to cave owners about it. The land owners saw this as a potential, governmental take-over of their land, which had been in their families for generations. Developers opposed the plan because it would remove vast tracts of land from the market. The influential caver and the Planning Commission wanted the Missouri Speleological Survey to get involved and support the plan.

Wisely, the MSS wanted no part of it. The resulting controversy and political squabble almost split the MSS in half.

Probably, the plan never would have worked even if the park had become a reality. The South Perry Coun-

Figure 2 *The stygobitic isopod* Caecidotea antricola *in Mystery Cave. The stygophilic* Caecidotea brevicauda *also occurs there. Photo by David C. Ashley.*

ty karst area is 30 or 50 km (20 or 30 mi.) on a side. To be effective, the park should have covered 1,500 km^2 (600 $mi.^2$) of land, probably as large as or larger than Mammoth Cave National Park in Kentucky.

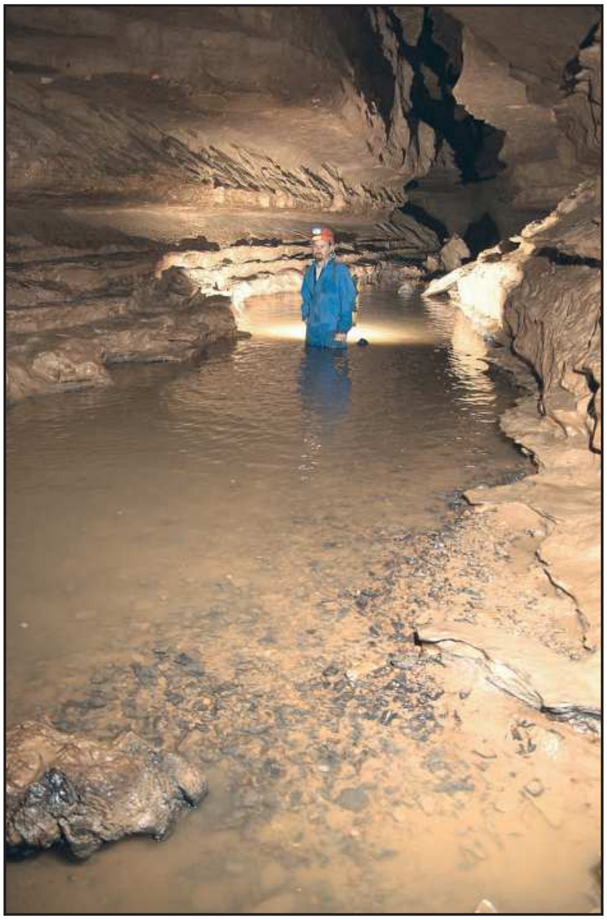

Figure 3 *Ben Roberts in Mystery Cave. Photo by Jean Krejca, 2007.*

Of course many farmers blamed cavers for this proposal, and we soon discovered we were no longer welcome in several of the caves we used to visit. It was not the first time, and would not be the last time that cavers were blamed for something they did not do. Yes, cavers make very good scapegoats. But, we continued to have access to Mystery Cave (Figure 3).

Conclusion

So by now, you are probably wondering what do potatoes have to do with all of this? One very hot day in mid-July I was talking to various farmers, trying to learn more about cave leads. One of them was involved in digging out his potato crop and he had very little time for me. Seeing that he was elderly and obviously needed help, I grabbed a pitchfork and pitched in to help him do the job. It was hours of backbreaking work with a pitchfork in the broiling July sun. Upon completion of the task, as we sat together under a shade tree enjoying a few cold beers, he shared with me a wealth of information about the nearby landscape. One of his tips led me toward the eventual discovery of Rimstone River Cave, connected to Mystery Cave. What is the moral of this story? It isn't enough to just grill land owners for information. You have to give them something back in return. Sometimes, you have to dig potatoes.

Acknowledgments

My thanks to Dr Ginny Adams and Dr David C. Ashley for providing photos.

WATERBORNE CONTAMINANTS IN TUMBLING CREEK CAVE, MISSOURI

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Abstract

Tumbling Creek Cave (TCC) is an educational and research cave and a National Natural Landmark in southern Missouri. TCC's recharge area is 2,349 ha, located in a rural area, and part of the Ozark Underground Laboratory. TCC has the highest recorded biodiversity of any American cave west of the Mississippi River. TCC harbors three endangered species: Gray bats (*Myotis grisescens*), Indiana bats (*M. sodalis*) and the Tumbling Creek cavesnail (*Antrobia culveri*). The latter declined severely since the early 1990s, is nearly extinct and is the focus of this study.

The major goals of this study were to analyze SPMD and POCIS samplers in the cave stream for organic contaminants, and to search suitable habitat in the area for cavesnails, including cave streams, springs and groundwater. These goals were accomplished between 2002 and 2007:

Wells, springs and caves in the immediate TCC area were examined for fauna, but no cavesnails were found. Cavers were supported in searches of 25 caves in Taney County. Although a few caves had marginal pool habitat, none had suitable stream habitat like TCC.

Of the nonpolar organic compounds analyzed, one out of 28 PAHs (polyaromatic hydrocarbons) and eight out of 30 OCPs (organochlorine pesticides) were found in the samples. Only minute levels (pg/L or parts per quadrillion) of some nonpolar compounds and no polar organic compounds were detected in the TCC stream, lessening concerns about long-term contamination of the system. It is possible that some chemical(s) could have been transported through the system over a short time, and would not have left a trace, but there were no known spills or large industrial waste sites in the area. Siltation, septic system wastes, oxygen depletion and farm dump sites in sinkholes remain as possible causes of the decline in the

Antrobia cavesnail, but siltation is the most likely cause. However, the Tumbling Creek cavesnail may be sensitive to minute amounts of chemicals. Other ecological factors, such as the decline of Gray bats, *Myotis grisescens*, in the cave also could have had an influence on *Antrobia*. Gray bats have recently increased again at TCC because of conservation work.

An assessment of a chip-seal, highway-resurfacing project by the Missouri Department of Transportation found no effect on water quality in the cave, based on analyses of water samples from the road ditch and in cave stream collected at times when tracer dyes demonstrated that road runoff water was present.

Antrobia still exists in small numbers, and a project started in 2006 is providing additional cavesnail habitat (terra cotta tiles) in the stream as well as a potential cavesnail-propagation laboratory in the cave. Conservation work in the recharge area of the cave is creating improvements in the cave ecosystem and groundwater.

Key Words: Tumbling Creek Cave Missouri, water quality, contaminants, nonpolar and polar organic compounds, SPMD samplers, POCIS samplers, siltation, *Antrobia culveri*, cavesnail, *Myotis grisescens*, Gray bat, endangered species, ecology, land use

Introduction

Tumbling Creek Cave (TCC) is an educational and research cave and a National Natural Landmark located on a 1,032-ha (2,550-acre) tract in Taney County, southern Missouri (Figure 1). The cave is in a rural area, part of the Ozark Underground Laboratory, established in 1966 (Aley and Thomson 1971, Thomson and Aley 1971, Neill et al. 2004, Elliott et al. 2005 and 2006). TCC's

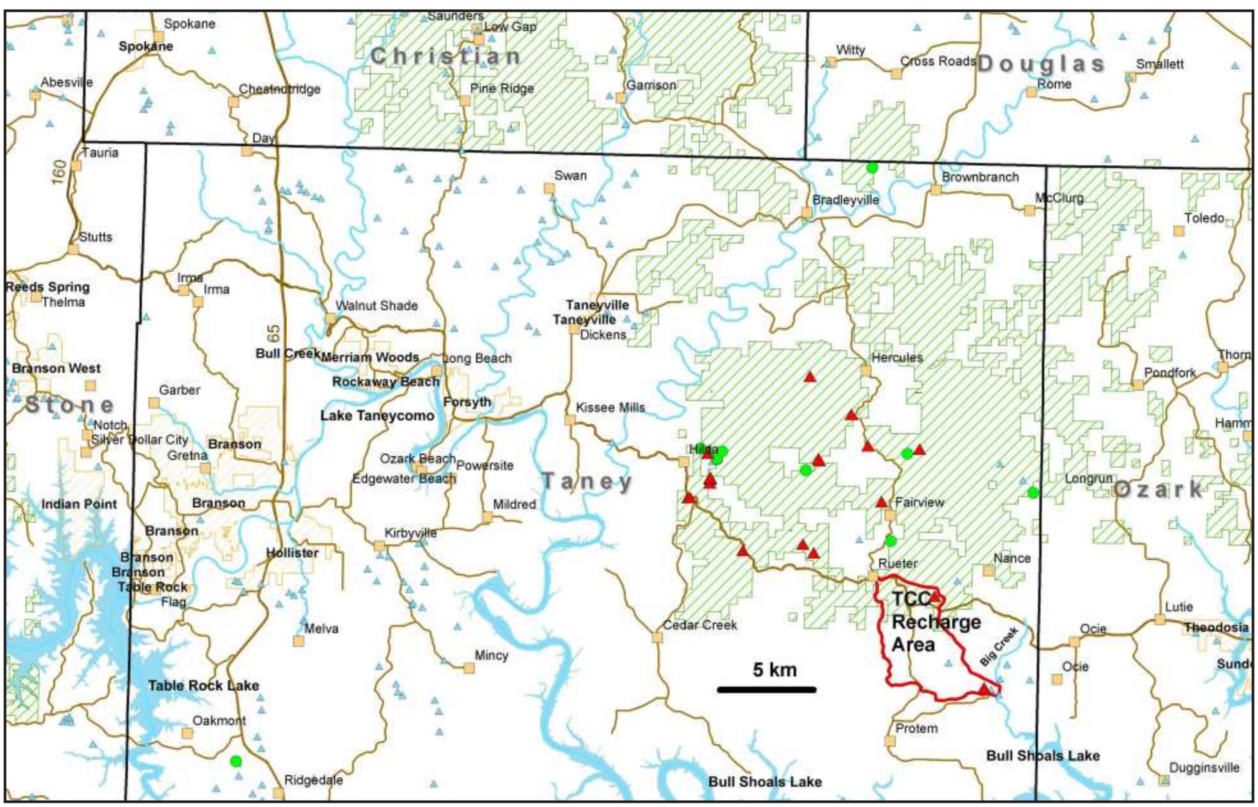

Figure 1 *Map of Taney County area showing the location of Tumbling Creek Cave in the southeast, its recharge zone, caves that were targeted for investigation (green dots), caves that were investigated (red triangles) and known springs (blue triangles).*

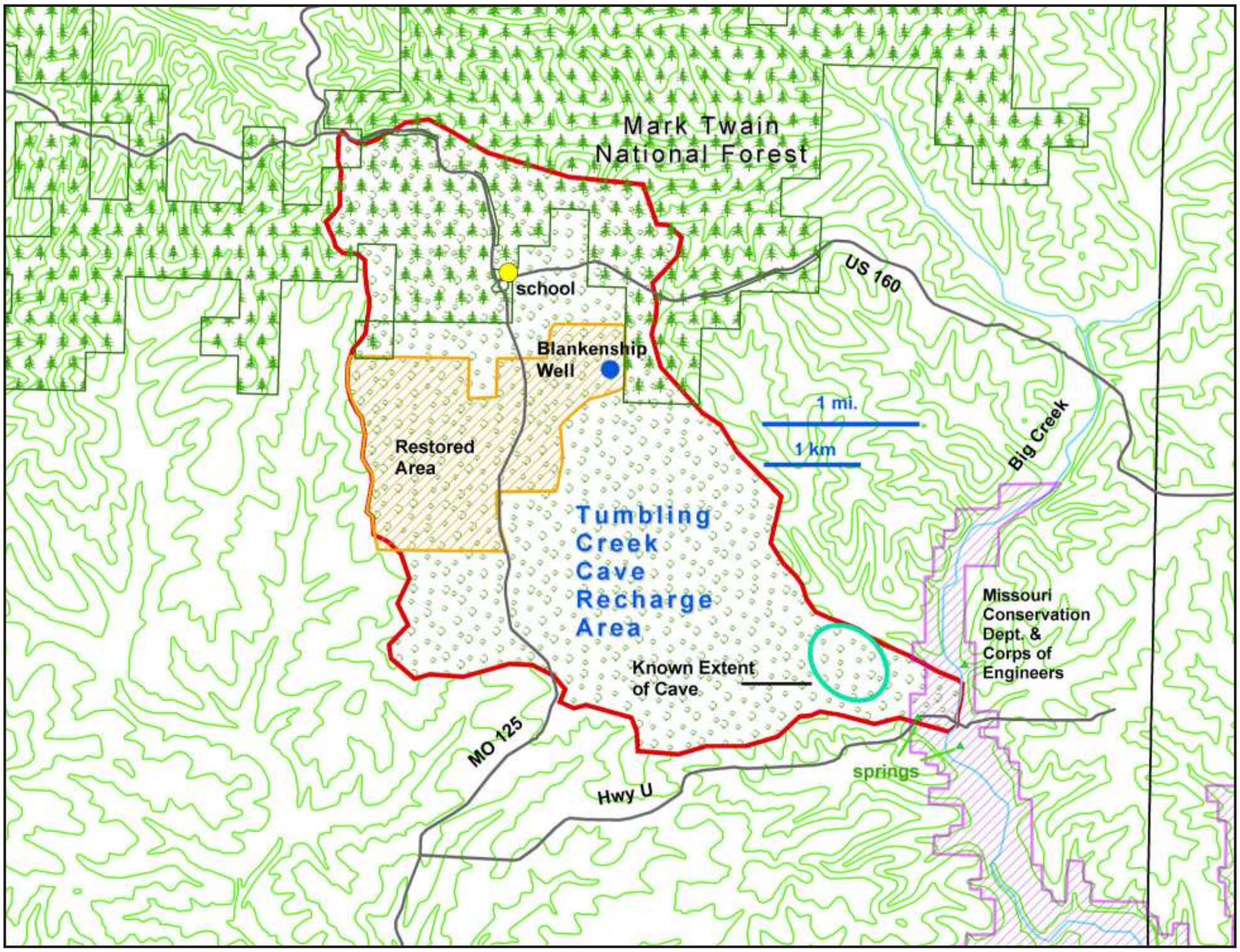

Figure 2 Map of Tumbling Creek Cave recharge area showing the locations of Tumbling Creek Cave, Mark Twain School, Blankenship Well, a restored area, area roads and features.

recharge area is 2,349 ha (5,804 acres, Figure 2). TCC has the highest recorded biodiversity of any American cave west of the Mississippi River, with about 112 species, including 11 or 12 species of obligate cave dwellers, or troglobites (Elliott *in press 2007*). TCC harbors three endangered species: Gray bats, *Myotis grisescens*, Indiana bats, *M. sodalis*, and the Tumbling Creek cavesnail, *Antrobia culveri* (Figure 3). The latter declined severely since the early 1990s, is nearly extinct, and is the focus of this study (U.S. Fish & Wildlife Service 2001, 2003, Ashley 2003).

Three major goals of this study were to

- Analyze SPMD samplers that were deployed in the cave stream in 1995.
- Deploy new SPMD and POCIS samplers in the cave stream for additional analyses.
- Search suitable habitat in the area for cavesnails, including cave streams, springs and groundwater.

SPMD (semi-permeable membrane device) samplers (Figure 4) are useful for investigations of waterborne contaminants because they mimic an organism's fat in their ability to absorb nonpolar organic compounds in a synthetic lipid.

This report discusses other scientific and conservation projects related to the fate of *Antrobia*, with references, tables and figures provided. *Antrobia* still exists in small numbers, and a project started in 2006 is providing additional cavesnail habitat (terra cotta tiles) in the cave stream as well as a potential cavesnail propagation laboratory built in the cave.

Figure 3 *The Tumbling Creek cavesnail, Antrobia culveri. Photo by David C. Ashley.*

Figure 4 *SPMD deployed by William R. Elliott in Tumbling Creek Cave. The membrane sampler is inserted into a perforated cover and anchored in the stream. Photo by Steve Samoray.*

Materials and Methods

Searches of Caves, Springs, and Wells

In 2002–2003 David C. Ashley, Michael E. Slay, Philip Moss, and William R. Elliott examined groundwater in the TCC area for cavesnails. Samples were taken from the "karst window" near the cave, wellpoint (hand pump) samples along Big Creek, springs on Big Creek and Blankenship Well north of TCC.

A contract between Missouri Department of Conservation (MDC) and Cave Research Foundation (CRF) provided support for eleven volunteer cavers to search for potential cave stream habitat. Field trips were taken in December 2004 and January, February, April, and May 2005. The January trip was largely washed out by extremely heavy rains. The area was limited to Taney County. Most of the sites investigated were in southeastern Taney County, in areas closest to Tumbling Creek Cave (Figures 1 and 2).

Twenty-five caves were searched, besides Tumbling Creek Cave: Stafford Cave, Skull Cave, Tiny "Cave," Dicus Cave, Spring Cave, Marholtz Cave, Decker Cave, Hercules Lookout Cave, Mores Branch Cave, Hercules Glades Pit, Little Bear Cave, Clayton Cave, California Cave 1, California Cave 2, Gilbert Cave, Twenty-five Sink Cave, Cane Bluff Cave 1, Cane Bluff Cave 2, Cane Bluff Cave 3, Little Cane Bluff Tunnel, Cane Bluff Shelter, Double Cave, Midden Cave, one unnamed cave, and Jack Cave. In addition several other cave locations were found to be in error and duplications of other caves were removed (this included Dicus #2 and Armadillo Cave). Most of the above caves are on land belonging to Mark Twain National Forest. Attempts to investigate several other caves (Fairview Church Cave, Blowing Spring, Willies Pit, China Hole, Coyote Collapse, and Wolf Cave) were stymied by failure to find landowners at home or otherwise get permission to cross lands to access other lands. Absentee landowners are prevalent in the area, and this makes it difficult to easily gain legal access. Additionally several springs in the area of Tumbling Creek Cave (two were resurgences) were investigated for potential "wash-outs" of snails. The entrance zone of the Bear Cave or natural entrance of Tumbling Creek Cave was investigated for snails and checked for wintering bats (there also is an artificial entrance). Several more trips were taken to areas with potential caves and springs.

Contaminants Study

Background

In 1995 David C. Ashley did a limited study of waterborne contaminants in TCC and Fantastic Caverns (FC, near Springfield, Missouri) using SPMDs from EST Lab in St. Joseph, Missouri. The Fantastic Caverns sample provided a comparison with another large stream cave in Southwest Missouri. Dr Ashley provided his sample extracts for this study, which had been stored in ampules at EST Lab, and they were analyzed in 2006-2007.

SPMD extracts that had been returned from the field were provided by Elliott to the Columbia Environmental Research Center (CERC) for analysis of organic contaminants including polychlorinated biphenyls (PCBs as total PCBs), organochlorine pesticides (OCPs) and polyaromatic hydrocarbons (PAHs). Cresol was evaluated in the full scan PAH analysis and polybrominated diphenyl ethers (PBDEs) also were screened. These chemicals comprise several classes of environmental contaminants.

SPMD preparation and deployment

SPMDs deployed in the field were provided by EST, and they were manufactured as standard size SPMDs (2.5 cm x 152 cm, 85 µm membrane thickness, 1.64 g triolein) (Huckins et al., 1993, 1996). Post-manufacture SPMDs were sealed in airtight metal cans prior to field deployment. Trip blanks accompanied the samplers to the field and were exposed to air during the deployment and resealed in cans.

The samplers, manufactured by EST Lab, were taken into the field by university and/or state personnel. The 1995, samplers were deployed by David C. Ashley in Tumbling Creek Cave and Fantastic Caverns for 30 days. The 2002 -2004 TCC samplers were deployed by William R. Elliott, Steve Samoray, and Philip Moss for 61 days in the cave stream at the foot bridge, inside a perforated stainless steel container (Figure 4), then retrieved and returned to EST for dialysis and high performance size exclusion chromatography. The resulting extracts were then solvent-reduced and stored in amber ampules at 3 SPMDs per ampule for the 1995 samples and 1 mL per SPMD for the post-2000 samples.

POCIS deployment

A new type of sampler, the POCIS, for polar organic compounds, was deployed once with a trip blank in Tumbling Creek Cave in 2004. The round sampler was deployed in a solvent-rinsed, air-dried, stainless-steel steamer basket in the cave stream. A representative set of target residues was selected, including various pharmaceuticals, antibiotics, caffeine, and other waterborne polar compounds. A very large array of possible substances could be found in the environment, but not all can be detected in a study with limited duration and funding.

Summary of analytical methods

Sample preparation. Sample extracts were prepared and analyzed for OCPs, total PCBs and PAHs using USGS-CERC standard operating procedures. Total PCBs are reported as a summation of congeners. The following quality control (QC) samples were incorporated into the various analyses:

- Procedural blank—to measure laboratory background and to establish method detection limits,
- Procedure spikes (PCB, OCP, PAH spiked)—to demonstrate recovery through the analytical method,
- SPMD dialysis blank—to demonstrate the background of a freshly prepared SPMD from dialysis step onward,
- SPMD trip blanks—SPMDs that went to the field and were exposed to cave air conditions during deployment and retrieval of the sample SPMDs.

Mixtures of Aroclors 1242, 1248, 1254, and 1260 (in a 1:1:1:1 ratio), OC pesticides (29 compounds), and PAHs (27 compounds) were added to a procedure blank. The following recovery compounds were added to all sample extracts before the cleanup steps described below were performed, including samples used for QC (procedure blank and procedure spike):

- PCB 029 (2,4,5-trichlorobiphenyl),
- PCB 155 (2,2',4,4',6,6'-hexachlorobiphenyl),
- PCB 204 (2,2',3,4,4',5,6,6'-octachlorobiphenyl),
- Deuterated PAH mix (16 priority pollutant PAHs),
- Deuterated p,p'-DDD.

The PCB compounds selected are used for recovery because they are rarely found or are undetectable in Aroclors and they are chromatographically resolvable. The three PCB surrogates are used to correct for analytical recoveries of the PCBs (PCB 029, a trichlorobiphenyl, is representative of more volatile early eluting PCBs (Cl_1 - Cl_3), PCB 155, a hexachlorobiphenyl, is representative of mid-range eluting congeners (Cl_4 - Cl_6), and PCB 204, an octachlorobiphenyl, is less volatile and representative of later eluting PCBs (Cl_7 - Cl_{10})) and several pesticides which are found in the PCB fraction off silica gel fractionation. The deuterated p,p'-DDD is the surrogate for pesticides in the second silica gel fraction. The deuterated PAH mixture compounds are surrogates for the PAHs found. Evaluation of the spikes also gives recovery information. Table 1 lists deuterated PAH surrogates that were added to all samples and QC samples before extraction for PAH analysis. Table 2 lists the 27 native PAH solutions used for standard checks, procedural checks and spiking.

Table 1 Deuterated PAH surrogates that were added to all samples and QC samples before extraction for PAH analysis.

Naphthalene-d_8	Fluoranthene-d_{10}	Benzo[*a*]pyrene-d_{12}
Acenaphthylene-d_8	Pyrene-d_{10}	Indeno[*1,2,3-c,d*]pyrene-d_{12}
Acenaphthene-d_{10}	Benz[a]anthracene-d_{12}	Dibenz[*a,h*]anthracene-d_{14}
Fluorene-d_{10}	Chrysene-d_{12}	Benzo[*g,h,i*]perylene-d_{12}
Phenanthrene-d_{10}	Benzo[*b*]fluoranthene-d_{12}	
Anthracene-d_{10}	Benzo[*k*]fluoranthene-d_{12}	

Table 2 The 27 native PAH solutions used for standard checks, procedural checks and spiking.

Naphthalene	2-Methyl Anthracene	Chrysene
2-Methyl Naphthalene	4,5-Methylene Phenanthrene	Benzo[*b*]fluoranthene
1-Methyl Naphthalene	1-Methyl Phenanthrene	Benzo[*k*]fluoranthene
Acenaphthylene	Fluoranthene	Benzo[*e*]pyrene
Acenaphthene	Pyrene	Benzo[*a*]pyrene
Fluorene	Retene	Perylene
Dibenzothiophene	1-Methyl Pyrene	Indeno[*1,2,3-c,d*]pyrene
Phenanthrene	Benzo[*b*]naphtha[*2,1-d*]thiophene	Dibenz[*a,h*]anthracene
Anthracene	Benz[*a*]anthracene	Benzo[*g,h,i*]perylene

The SPMDs were dialyzed at EST according to standard procedures. Dialysates were then run through a HPSEC (high performance size exclusion chromatography) cleanup to remove residual lipid and polyethylene waxes from the dialysis. Once they were received for analysis by CERC the extracts were spiked with the appropriate recovery compounds discussed above before proceeding with chemical-class-specific cleanup steps.

In the analytical protocol targeting total PCBs and organochlorine pesticides, a 1 SPMD equivalent amount of the extract was analyzed. The extracts were spiked with recovery compounds and then fractionated on a two-layered octadecyl silica/activated silica gel column into two fractions: one fraction containing PCBs and six of the targeted OCPs (SODS-1), and a second fraction containing the remainder of the OCPs (SODS-2). The sample extracts were adjusted to a final volume of 1 mL and two instrumental internal standards were added: PCB congeners 030 and 207 (40 ng each).

The resulting fractions were prepared for gas chromatography with electron capture detection (GC/ECD). The sample extracts were adjusted to a final volume of 1 mL. Two instrumental internal standards were added: PCB congeners 030 and 207 (40 ng/mL each).

For PAH analysis a 1-SPMD equivalent portion of the extract was split after dialysis and HPSEC. The 1-SPMD equivalent portions were spiked with recovery compounds and the extracts were purified by potassium silicate preparative column chromatography and a silica gel (3% water deactivated) preparative column chromatography. The resulting extracts were evaporated to ~100 µL final volume and prepared for gas chromatography with mass spectrometry by adding an instrumental internal standard *p*-terphenyl-d_{14}.

Summary of gas chromatographic method for total PCBs. PCBs were measured in SODS-1 fractions by gas chromatography with electron capture detection (GC/ECD). Analyses were performed using Hewlett-Packard 5890 Series II GCs with cool, on-column capillary injection systems and Hewlett-Packard model 7673 autosamplers. For all analyses, a 3-m section of 0.53 mm i.d. uncoated and deactivated capillary retention gap (Agilent, Palo Alto, CA) was attached to each analytical column by a Press-Tight® (Restek Corp., Bellefonte, PA) union. The analytical columns were 60-m x 0.25-mm x 0.25µm DB-5 (5% phenyl-, 95% methylsilicone, Agilent, Palo Alto, CA) and DB-17HT (0.25µm 50% phenyl-, 50% methylsilicone, Agilent, Palo Alto, CA). The H_2-carrier gas was pressure regulated at 25 psi. The temperature program for the PCB analysis was as follows: initial temperature 60°C, immediately ramped to 150°C at 15°C/min, then ramped to 250°C at 1°C/min, and finally ramped to 320°C at 10°C/min, and held for 1 min. The ECD temperature was 330°C.

PCBs were matched and identified on one GC capillary column with known PCB peaks from the standards. For this report single column matching and ID were used on the DB5 column as the analysis called for total PCBs only. The total was determined as a sum of congeners from the one column. The capillary GC/ECD data were collected, archived in digital form, and processed using a PerkinElmer chromatography data system, which included the model 970 interface and version 6.1 of Turbochrom Workstation chromatography software (PerkinElmer, Waltham, MA), on a microcomputer. A mix of several Aroclors is used to produce the PCB congener calibration standards. These standards have been quantified based on pure, primary PCB standards (Accustandard, New Haven, CT) and are used as secondary standards. Up to nine levels of calibration for each individual congener are used to quantify approximately 140 congeners in the samples. In terms of total-PCB concentrations, the calibration curve covers a range from 10 to 8000 ng/mL.

The "method detection limits" (MDLs) for individual PCB congeners and for total PCBs were based on procedural blank (PB) results following the method outlined by Keith *et al.* (1983, 1991). Briefly, a mean ($\overline{X}_{PB}$) and standard deviation (SD) are determined using PB, trip blank SPMD and dialysis blank SPMD results. This produces a MDL (ng/SPMD) calculated using the following formula:

$$MDL = \overline{X}_{PB} + 3(SD_{PB})$$

The MDL is then expressed in units of concentration, e.g. mass of analyte per SPMD. If a concentration is below its respective MDL it will be censored with a "< MDL" (where MDL is a value).

The "method quantitation limits" (MQLs) for congeners is calculated in the same manner as above using the following formula:

$$MQL = \overline{X}_{PB} + 10(SD_{PB})$$

Data that fall between the MDL and MQL were censored in all the data tables. However, data above the MQL have a greater degree of confidence—i.e. when the analyte signal is 10 or more times greater than the standard deviation of the measurement there is a 99% probability that the true concentration of the analyte is within ±30% of the calculated concentration.

Recoveries of analytes are monitored by the following measures:

- Procedural internal standards spiked into each sample,
- PCB/OCP/PAH-spiked blank.

Three procedural standards are used to account for analytical recoveries of the PCBs: PCB 029, a trichlorobiphenyl, is representative of more volatile early eluting PCBs (Cl_1 - Cl_3), PCB 155, a hexachlorobiphenyl, is representative of mid-range eluting congeners (Cl_4 - Cl_6), and PCB 204, an octachlorobiphenyl, is less volatile and representative of later eluting PCBs (Cl_7 - Cl_{10}).

Summary of gas chromatographic method for pesticides and PBDEs. Pesticides were measured by GC/ECD using Hewlett-Packard 5890 Series II GCs with cool on-column capillary injection systems and Hewlett-Packard model 7673 autosamplers. For all analyses, a 3-m section of 0.53 mm i.d. uncoated and deactivated capillary retention gap (Agilent, Palo Alto, CA) was attached to each analytical column by a Press-Tight® (Restek Corp., Bellefonte, PA) union. The analytical columns were 60-m x 0.25-mm x 0.25µm DB-5 and DB-17 phase columns. The H_2-carrier gas was pressure regulated at 25 psi. The temperature program for the PCB analysis was as follows: initial temperature 60°C, immediately ramped to 150°C at 15°C/min, then ramped to 250°C at 1°C/min, and finally ramped to 320°C at 10°C/min, and held for 1 min. The ECD temperature was 330°C.

The dual column method accurately identifies and quantifies pesticide peaks from one or both columns based upon known standards. The GC/ECD data were collected, archived in digital form, and processed using a PerkinElmer chromatography data system, which included the model 970 interface and version 6.1 of Turbochrom Workstation chromatography software, on a Pentium III microcomputer. Six levels of organochlorine pesticide standards (29 components) were used for calibration, with each pesticide at concentrations ranging from 0.1 to 80 ng/mL. Concentrations are expressed as nanograms of analyte per SPMD (ng/SPMD). Detection limits were calculated as discussed above for PCB congeners.

Polybrominated diphenyl ethers (PBDEs), flame retardants, were screened using a nine-congener standard with three calibration levels—1 ng/mL to 200 ng/mL. Recoveries of analytes are monitored by the following measures:

- Procedural internal standards spiked into each sample,
- OCP-spiked control fish analyzed with each set.

Two recovery-method compounds are used to account for analytical recoveries of the pesticides in the two analyzed fractions: PCB 029, a trichlorobiphenyl and d_8-p,p'-DDD. Since the PBDE values were just a screen they were not corrected for analytical recovery.

Summary of gas chromatographic mass spectrometric method for polyaromatic hydrocarbon.

The sample extracts were adjusted to a final volume of ~100 µL and the instrumental internal standard p-terphenyl-d_{14} (100 ng) was added. Sixteen perdeuterated and 27 native PAHs were measured in the PAH fraction from silica gel by GC/MS in the full scan mode. Analyses were performed using a CE Instruments 8000Top GC with cool on-column capillary injection systems and an AS800 autosampler (2 µL injected) interfaced with a Voyager quadrupole mass spectrometer (Thermo-Finnigan Corp., San Jose, CA). For all analyses, a 2.5 m section of 0.53 mm i.d. uncoated and deactivated (Restek Corp., Bellefonte, PA) capillary retention gap was attached to the front of each analytical column by a Press-Tight® (Restek Corp., Bellefonte, PA) union. The analytical column was a 50 m x 0.20 mm Ultra-2 (0.11 µm 5% phenyl-, 95% methyl-silicone, Agilent, Palo Alto, CA). Helium carrier gas was flow-regulated at 1 mL/minute. The temperature program for the PAH analysis was: initial temperature 60°C, hold time 2.5 minutes, ramped to 300°C at 5°C/minute, and held for 15 minutes. The direct transfer line to the mass spectrometer was maintained at 305°C.

The mass spectrometric method acquired full scan data (m/z 50-550 0.75s scan time) from 12.5 to 60 minutes. The photomultiplier was set to 350V. The mass spectrometer was tuned using PFTBA (m/z 50-614). This method is confirmatory, where background-corrected spectra in samples are compared with standard spectral libraries and with authentic spectra acquired from the calibration standards. The data were collected, archived in digital form, and processed using the Thermo-Finnigan XCalibur GC/MS data system. Depending on the dynamic range required, calibration up to eleven levels of calibration standards, ranging from 0.250-625 pg/µL were analyzed with an analytical set.

Method detection limits were estimated from low-level standards and the blanks determined by both the signal-to-noise ratio of the peak in the quantitation ion channel and the gradual loss of unique characteristics of the background-corrected mass spectrum.

For the positive identification and quantification of each PAH, the following criteria were established and met in this study:

- Peak areas for the selected ion responses must be greater than three times background noise.
- Native ion peaks must occur at relative retention times (to the perdeuterated surrogate) that are equivalent to those for the correspond-

ing calibration standards.

The m/z pattern for the major ion responses in the background-corrected mass spectrum must closely match that of the calibration standard for each specific analyte.

Highway study. In November 2006 Ozark Underground Laboratory (Aley 2007), in cooperation with Missouri Department of Transportation (MODOT), studied the potential runoff of petroleum hydrocarbons from a "chip seal project" on U.S. Highway 160. About 3,725 m (15,500 ft.) of highway crosses the northern part of the recharge zone of TCC, 4.8 km or more from accessible portions of the cave stream (Figure 2). The highway was treated with a emulsified asphalt and rock chips. This is a relatively new road-surfacing method that reduces hydrocarbon runoff. A dye trace was conducted after the application, and water samples were taken from the cave stream and tested at a commercial laboratory for Total Purgeable Hydrocarbons (TPH) at a detection limit of 0.1 mg/L (0.1 ppm).

Results

MDC's cave conservation program staff took 11 field trips to TCC from October 2003 to July 2004. Trips included field work as well as participating in meetings of the Cavesnail Working Group and the draft and revision of the federal recovery plan.

In October 2003, the first SPMDs were collected and exchanged with new ones. Lab reports from the October collection indicated low levels of some possible combustion products captured on both the sampler and the field blank, but little else. These combustion products could have come from cave dust, residues from fires in the area, or from a carbide lamp used by a person who retrieved samplers. Electric headlamps were used thereafter. In February 2004 an SPMD sampler in the cave stream was exchanged for a POCIS (polar organic chemical integrative sampler) a new type of sampler from EST Lab, similar to the nonpolar SPMD sampler.

In October 2003, Elliott and Steve Samoray visited Stafford Cave on private land in northern Taney County. No cavesnails were found in Stafford, it appeared to be a small, wet-weather resurgence with only a muddy pool and no appropriate habitat.

Groundwater sampling from Blankenship Well, the Karst Window, and wellpoint samples yielded a few small invertebrates, including a few remains of shells, but none appeared to be *Antrobia culveri*.

In March 2004 a large chute gate was built at the entrance of Tumbling Creek Cave to provide greater security from intruders, while affording the Gray bats an ample flyway. Eighteen people from different organizations worked on the project. Simultaneously, OUL workers removed the internal "barrel gate" far inside the cave. This opened a larger flight path for the bats. Insofar as the Gray bat colony is an important component of the cave community, and may contribute directly or indirectly to the nutrient flow into the cave stream, the cave gate may be a step in the recovery of both the Gray bat and the cavesnail at this site. The total cost was $25,000 paid from MDC funds. Gray bats began using the gate immediately.

In April, May, June, and July of 2004, Elliott and others recorded seven bat exit flights at the cave gate using a digital 8 camcorder and NIR (near-infrared) illumination, so as to avoid disturbance of the bats (Elliott et al. 2006).

MDC 's cave conservation program staff took 18 field trips to Tumbling Creek Cave from July 2004 through June 2005. Trips included field work as well as participating in meetings of the Cavesnail Working Group. The group met on May 22-23, 2005, at Ozark Underground Laboratory. On May 23 Paul Johnson and Stephanie Clark from the Tennessee Aquarium Research Institute observed 67 cavesnails when they crawled upstream from the usual transect. Some were upstream of the last bat area, some downstream of "Bill's Bath," and a few were in the tributary stream. This find gave hope for attempting a captive propagation study in the cave, first using a suitable surrogate species for testing.

In 2004 we estimated a population of about 19,000 Gray bats in May, peaking at 34,000 in July, which was up from the previous visual count in July 1998 of about 12,000 Gray bats. The July counts were about 32,000 in 2005 and 37,000 in 2006. In August and September the numbers vary from night to night, probably because of emigration and immigration to/from other caves. We continue to monitor the population with NIR and TIR (thermal infrared) imagery.

Of the caves checked in the area in 2004-2005, the following had streams with some gravel substrate in them: Spring Cave, Dicus Cave, Hercules Lookout Cave, Clayton Cave, and Gilbert Cave (Figure 2). Decker Cave should be reinvestigated. However, probably none of these stream caves are extensive enough to support cavesnail populations. The best sites were Gilbert Cave and Hercules Lookout Cave,; both were extensively studied by Dr Mick Sutton and found to lack aquatic snails.

MDC and the USFWS assisted the owners, who bought a nearby, abused farm with their own funds. With cost-share funds they replanted 70,000 trees to restore the mostly cleared land. They oversaw the planting of native species, such as black oak, northern red oak, white oak, black gum, black walnut, green ash, dogwood, redbud, sycamore, and a few short-leaf pines. Other native species will re-establish naturally from the surrounding areas. Another cost-share project with the National Park Service helped to clear the land of trash, which was dumped or buried in several places. These projects probably have already helped to clear the cave stream of sediments, and may be aiding in the reappearance of cavesnails. Increased input of Gray bat guano may also be important for the long-term recovery of the cavesnail (Elliott and Aley 2006).

MDC's Private Lands Division and the USFWS worked with the Mark Twain School in the recharge area to correct a leaking sewage lagoon that could have affected the cave ecosystem. A modern peat-filter septic system was implemented in 2005-06 with at least $90,000 in donations from local, state and federal sources.

Analytical results are given in Tables 3–6, condensed from Tables 1–8 in Elliott and Echols (2007). EST Lab provided analyses of the first round of samples in 2003, but could not continue because of problems with laboratory instruments (Table 3). Total PCBs exceeded those detected in the trip blank in 2002, but not in 1995. Those exceeding the 2002 trip blank residues in 1995 included acenaphthene, fluorene, phenanthrene, anthracene, and fluoranthene. In 2002 acenaphthylene and acenapthene exceeded the trip blank results, as did fluoranthene, pyrene, and total PCBs. These minute amounts were not quantitated to water concentrations.

MDC contracted with CERC to complete the analyses in 2006-2007. CERC found one of 28 PAHs (Table 4) and 8 out of 30 OCPs (Table 5). Two brominated flame retardants (PBDEs) out of nine congeners were detected, but not quantitated to water concentrations (Table 6).

CERC's analysis of SPMDs (Table 4) found the PAH, benzo[g,h,i]perylene, in TCC and FC on several occasions. "Legacy organochlorine pesticides" and PCBs (commonly used in the past and persistent in the environment) were evaluated in the SPMDs from 1995 and 2003, and they were below detection or quantitation limits of the methodology for almost of the compounds evaluated. Those that were detected were typically barely above the MQL. Five OCPs were found in TCC, and six were found in FC. TCC had somewhat higher concentrations of 4 OCPs than did FC. In the1995 samples, pesticides that we detected were pentachlorobenzene, HCB, PCA, dieldrin, oxychlordane, cis-chlordane, trans-nonachlor and p,p'-DDT. The highest level found was for cis-chlordane at 5.6 ng/SPMD in FC. For the 2003 TCC samples there were fewer hits for pesticides—only HCB, delta-BHC and endosulfan I. Levels of PAHs were likewise typically below the calculated MDLs or MQLs for each compound, except for low levels (1-2 ng/SPMD) of benzo[e]pyrene (but less than the trip blank) and benzo[g,h,i]perylene from several of the samples. These two PAH compounds have low water-solubility and would typically be associated with sediment or particulate organic carbon. Sediment samples from TCC collected in 2004 were below detection limit levels of the same list of OC pesticides, total PCBs and PAHs, including benzo[e]pyrene and benzo[g,h,i]perylene. It is uncertain what the source of these two PAHs was. Cresol was also evaluated in the GC/MS analysis with the PAHs because creosoted timbers had been found buried within the recharge area, none was found in any of the samples.

Table 3 EST Laboratory analysis of TCC cave stream samples in µg/SPMD (ng/SPMD for total PCBs). Results that exceeded trip blank levels are in bold.

Analyte	Dialysis Blank	EST# 02-379 Trip Blank	30001E 1995	EST# 02-380 Bridge 2002	EST# 02-381 Weir 2002
Naphthalene	0.36	1.3	0.06	0.13	0.03
Acenaphthylene	ND	0.04	0.03	**0.09**	0.04
Acenaphthene	ND	ND	**0.01**	0.14	0.1
Fluorene	ND	ND	**0.05**	ND	ND
Phenanthrene	ND	ND	**0.28**	ND	**0.04**
Anthracene	ND	ND	**0.02**	ND	ND
Fluoranthene	ND	ND	**0.08**	**0.08**	ND
Pyrene	ND	ND	ND	**0.16**	ND
Benzo(a)Anthracene	ND	ND	ND	ND	ND
Chrysene	ND	ND	ND	ND	ND
Benzo(b)Fluoranthene	ND	ND	ND	ND	ND
Benzo(k)Fluoranthene	ND	ND	ND	ND	ND
Benzo(a)Pyrene	ND	0.7	ND	0.49	ND
Indeno(123-cd)Pyrene	ND	ND	ND	ND	ND
Dibenzo(ah)Anthracene	ND	ND	ND	ND	ND
Benzo(ghi)Perylene	ND	ND	ND	ND	ND
Total PCBs ng	6.21	18.47	14.03	**21.27**	**41.33**

Table 4 PAHs detected in cave waters in pg/L (parts per quadrillion).

Detected	Fantastic Caverns 10/16/95	TCC Upstream 10/16/95	TCC Downstream 10/16/95	TCC at Bridge 5/20/03	TCC at Bridge 10/29/03	TCC at Bridge 12/10/03
	11			6.8	8.9	7.5

Table 5 OCPs detected in the cave stream in pg/L (parts per quadrillion).

Analyte	Fantastic Caverns 10/16/95	TCC Upstream 10/16/95	TCC Downstream 10/16/95	TCC at Bridge 5/20/03	TCC at Bridge 10/29/03	TCC at Bridge 12/10/03
Hexachloro-benzene (HCB)			35	3.9	6.8	
Pentachloro-anisole (PCA)	29		58			
Dieldrin	4.4	5.5	6.3			
Oxychlordane			18			
cis-Chlordane	67					
cis-Nonachlor	11					
trans-Nonachlor	43					
p,p'-DDT	42		38			

Polybrominated diphenyl ethers (PBDEs) were evaluated in SPMDs from Tumbling Creek Cave and Fantastic Caverns, sampled in 1995 (Table 6). Low levels of PBDE-47 and 99 were detected in the 1995 SPMD samples, but it is most likely because of contamination from indoor air or indoor dust. There were no trip blanks with the 1995 SPMDs to verify whether these are due to this contamination, therefore, the PBDE data probably are not valid for those samples.

Table 6 PBDEs (fire retardants) detected in cave waters in ng/SPMD, not quantitated to water concentrations. ND = none detected. The 1995 results probably are not valid because a trip blank was not collected to evaluate airborne contaminants.

Cave	PBDE-47	PBDE-99
Fantastic Caverns 10/16/95	10	20
TCC Upstream 10/16/95	9.5	15
TCC Downstream 10/16/95	7.6	11
TCC at Bridge 5/20/03	ND	ND
TCC at Bridge 10/29/03	ND	ND
TCC at Bridge 12/10/03	ND	ND

Quality control (QC) associated with samples showed that laboratory procedure blanks were either ND (not detected) or less than the MDL for all of the compounds evaluated. Trip blanks showed some low background for some pesticides—lindane, some of the pp-DDTs—and PCBs. There were also background levels of PAHs in the trip blanks. Most of the background levels of PAHs were <1 ng/SPMD, but naphthalene, methyl-naphthalene and phenanthrene all were found at 10-20 ng/SPMD. These are typically problematic as background PAHs in SPMDs. PBDEs in the trip blanks were found at 2-3 ng/SPMD for congeners 47 and 99, which are both typically found in indoor air and/or dust backgrounds.

Recovery spikes for OCPs, PCBs and PAHs added to the extracts that were received at CERC, and they were processed through several cleanup steps, analyses were good, typically within acceptable QC parameters (50-125%). Procedure spike recoveries were also in acceptable QC range for most of the compounds.

Water concentrations can be estimated from SPMD data using an Excel® spreadsheet calculator developed from calibration data. When modeling these low levels of persistent organic pollutants we used the detection limit or quantitation limit values to estimate potential levels in water. For example, the MDL for total PCBs was determined to be 22 ng/SPMD and the MQL was determined to be 41 ng/SPMD, the water concentration estimated from these two values would be < 75 and < 140 pg/L, respectively. The water temperature in Tumbling Creek Cave was 13.9° C over a long period, but is not precisely known for Fantastic Caverns. All water concentrations were estimated for the OCPs, PCBs, and PAHs and are presented in Tables 3 and 4 using a calibration point of 18° C. Any value with an MDL/MQL was flagged as MDL/MQL in water concentration tables.

Very few studies showing the levels of these compounds in cave waters or groundwater have been published. In 2002 the Oklahoma Conservation Commission (Twin Cave Water Quality and Pollution Source Assessment, Final Report) found concentrations of technical chlordane in all of the samples analyzed ranging from 0.071 µg/L to 0.22 µg/L. Two samples had low levels of p,p'-DDT and p,p'-DDE (<0.009 µg/L). USGS evaluated surface water, groundwater and sediments in 1992-1995, and they had limited hits for pesticides or other semivolatile chemicals in the Ozark Region (Petersen et al. 1998). The Tumbling Creek Cave samples had estimated chlordane concentrations in water ranging from 0.001 µg/L to 0.016 µg/L, however the concentration values were below MDLs and

MQLs in the SPMDs and the estimated water concentrations are not valid.

The POCIS sampler deployed in 2004 contained no detectable residues of any type, with detection limits similar to the nonpolar compounds.

No TPH and no dye were detected by a commercial laboratory in the cave stream after a rain event that followed the chip-seal application on Highway 160 by about eight days.

Discussion

Only minute levels (pg/L or parts per quadrillion) of some nonpolar organic contaminants were detected in the TCC stream, far below those allowed by drinking water and other standards. Neither polar organic compounds nor petroleum hydrocarbons were detected. These results lessen concerns about long-term contamination of the cave system. However, it is possible that some nonpersistent chemical(s) could have been transported through the system over a short time and could have left no trace. However, there were no significant, known spills or large industrial waste sites in the area.

The Oklahoma Conservation Commission (2002) studied contaminants in Twin Cave, Delaware County, Oklahoma, using SPMDs. They found small amounts of 48 organic compounds, including chlordane, 4,4' DDE and 4,4' DDT, legacy organochlorines now banned from use. Using large volume injections, they also found caffeine and o-benzyl-p-chlorophenol, indicators of human waste contamination. Yet Twin Cave is in a rural area, like Tumbling Creek Cave. No contaminants were found at unusual levels, even though volatile chemicals had been found previously, probably caused by episodic dumping of waste materials into a sinkhole. Toxicity testing led to the conclusion that the levels found were not threatening to cave fauna, but they used standard test species, *Ceriodaphnia dubia*, a "daphnia," and *Pimphales promelas*, the fathead minnow. These species may not be representative of troglobitic species, the sensitivities of which are generally unknown.

Neill *et al.* (2004) characterized agricultural practices around Tumbling Creek Cave and their influence on water quality. Neill *et al*. discussed sources of chloride and nitrate from a now-restored area near TCC, which had been cleared of trees by a previous owner between the late 1980s and mid-1990s, and converted to little more than a cattle feed lot. Chlorides could have come from salt blocks for the cattle, and nitrates from cattle waste, but were diluted greatly by the time they entered the cave stream. The restored area, also within the TCC recharge area, apparently provided cleaner waters to the system. By 2004 a leaking sewage lagoon was discovered at the Mark Twain School within the recharge area, but its contribution to nitrate in the cave stream has not been quantified.

Neill *et al.* discussed possible metal sources in sinkhole dumps within the area. John Besser and Kathy Echols at CERC are examining cave stream sediments for metals. Sediment samples from TCC collected in 2004 had below-detection-limit levels of OC pesticides, total PCBs and PAHs.

Elliott and Aley (2006) discussed studies in the cave, land use practices and corrective measures recently undertaken in the recharge area. In early 2006 the Working Group constructed a cavesnail propagation laboratory in the cave. The laboratory apparatus is being tested at this time, using local well water and cave water piped in through plastic line or garden hose, respectively. A test surrogate species, *Physa halei*, from Perry County, Missouri caves, died off after being tested in well water in the propagation laboratory. Further tests indicated that *Physa* thrives in cave water. At this time we do not know what killed the *Physa*. There will be further work on this problem.

In 2006 32 terra cotta tiles were placed in the cave stream by Paul Johnson and Stephanie Clark at the request of the Working Group (Figure 5). The tiles provide a clean surface above the sediments for the snails. From February 2007 to May 2008 David C. Ashley observed cavesnails crawling on the tiles over four trips, an encouraging development.

The MODOT/OUL study of Highway 160 found no petroleum hydrocarbons in the TCC road ditch or cave stream in water samples collected at appropriate times. This result does not eliminate road spills as a potential threat to the cave, but it is reassuring that the road now can be maintained with a low-impact method.

Our study has eliminated many potential, persistent organic carbon contaminants from serious consideration as causes of the decline in *Antrobia*. POCIS samplers could still be used to detect pharmaceuticals, antibiotics, caffeine and other waterborne polar compounds. A very large array of possible substances could be found in the environment, but not all could be detected in this study because of limited duration and funding.

Siltation was one of several possible factors in the cavesnail's decline outlined in the Fish & Wildlife Service's recovery plan (2003) and Elliott and Aley (2006). Siltation in TCC may be decreasing, as measured by turbidity (Figure 6). Additional data are needed to be sure that this is a real trend. Septic system wastes such as nitrates and ammonia, farm dump sites in sinkholes, and oxygen depletion remain as possible influences. Based on observations by Tom Aley and Cathy Aley, David C. Ashley, and others, we conclude that an unusual influx of sediments was the probable cause of the decline in the Tumbling Creek cavesnail, but other factors may have contributed to the decline. We have little or no information on the sensitivity of aquatic snails to chemicals, as illustrated by the die-off of *Physa* in the new laboratory apparatus.

Other ecological factors, such as the decline of Gray bats for decades in the cave, also could have had an adverse impact on *Antrobia*. Gray bats have increased again since 2004 at TCC because of conservation work at the cave. We do not yet know to what extent bacterial biofilms on the rocks in the cave stream provide food for the cavesnail, and if that biofilm is especially nourished by Gray bat guano. We do not know if guano caused significant oxygen depletion as well. TCC and many Ozark cave streams also have black coatings of maganese oxide on the cobbles and bedrock, which may be deposited with microbial influence, the details of which are not known to us.

The "Tumbling Creek Cave Ecosystem" is now recognized by MDC and its partners as a "Conservation Opportunity Area" within the new initiative called the "Comprehensive Wildlife Strategy." This is a long-term, statewide conservation planning effort that recognizes certain areas for their high biodiversity, wildlife and natural resources (Elliott 2006).

Figure 5 *Drs Stephanie Clark and David C. Ashley, March 30, 2006, with terra cotta tiles placed in Tumbling Creek for the cavesnail,* Antrobia culveri.

Acknowledgments

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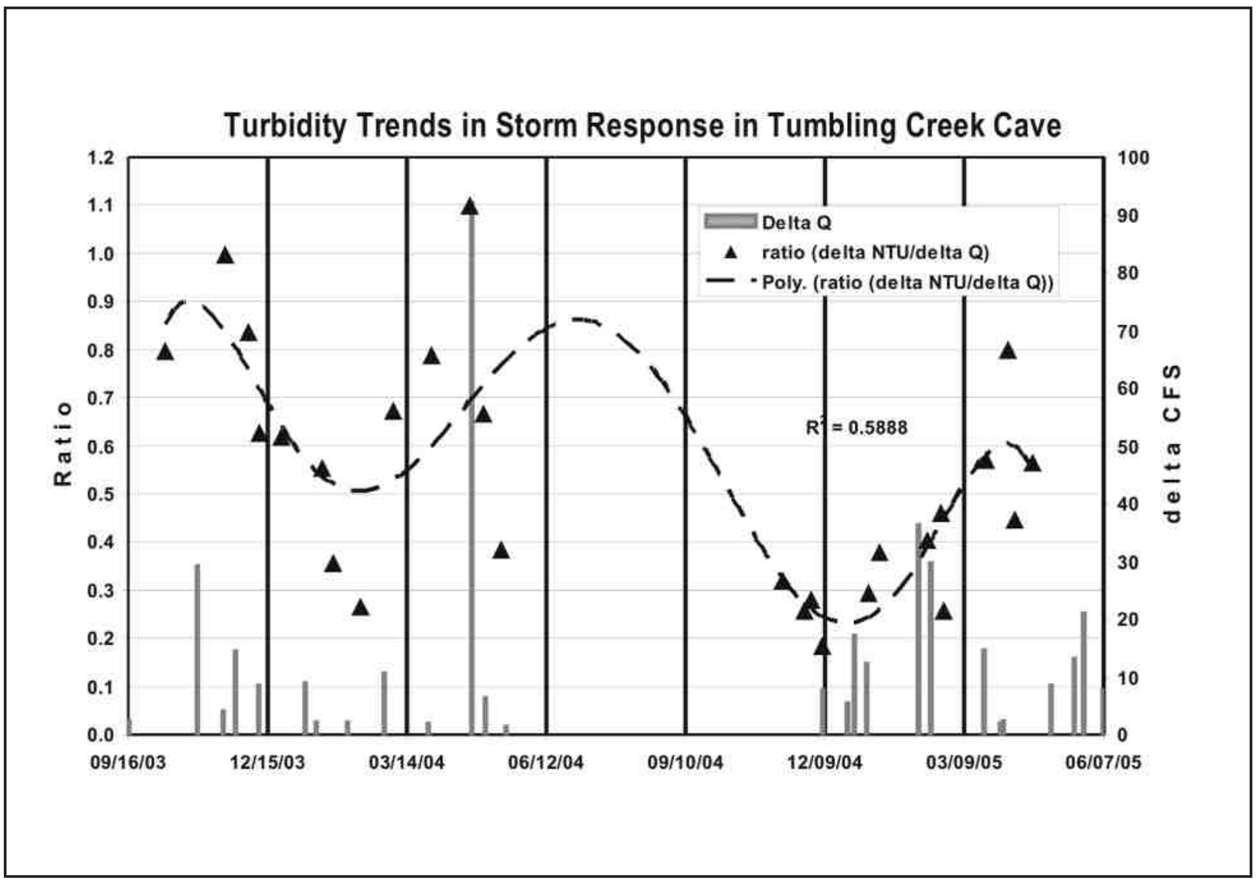

Figure 6 *Turbidity trends in storm response in Tumbling Creek, using the delta values for both turbidity and discharge, as measured with in-stream sensors and a data logger. There are two apparent trends: more intense storms and turbidity in the summer and a trend towards lower ratios of turbidity to discharge from 2003 to 2004. Graph by Philip Moss, OUL.*

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CARVING UP THE PRE-ILLINOIAN CENTRAL HIGHLANDS:TRANSVERSE SPELEOGENESIS AND EMERGENT BEDROCK MEANDERS IN THE OZARKS

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Abstract

New data fail to support the prevailing theory that meandering bedrock valleys inherit their sinuosity from ancient alluvial rivers. In the Ozarks, observations indicate that bedrock meanders emerge during incision as a result of erosion by emergent groundwater and surface flow. Crustal tilting pressurizes deep aquifers that feed a huge base flow to large springs. Because of their large size and persistence in time, these artesian conduits have the potential to create new base levels of erosion. Transverse speleogenesis causes groundwater flow lines and surface streams to converge toward the springs, thereby further increasing the rate of landscape lowering and creating bedrock meanders. Groundwater outflow accelerates stream piracy, creates asymmetric drainage patterns and cuts channels across structural upwarps. By contrast, the antecedent meander theory favors long-term drainage stability that cannot explain the incredible diversity of the freshwater fauna found in the Central Highlands. Widely disjunct species of highland fish that thrive only in clear, high-gradient streams indicate that the Ouachitas, the Ozarks and the Eastern Highlands were once a continuous upland connected by a "land bridge" in southern Illinois. This connection allowed ancestral species to become widespread enough to be affected by a vicariant event, usually attributed to onset of glaciation. However, a 400-km eastward shift in Gulf of Mexico sedimentation indicates this vicariant event may have occurred in the middle Pleistocene, when it is proposed that the Mississippi River dissected the Central Highlands, separating the Interior Highlands from the Eastern Highlands.

Key words: United States/Middlewest, Ozarks, Quaternary geology, bedrock meander, karst, speleogenesis, biogeography, phylogeography

Introduction

A bedrock meander is a resistant, sinuous channel that forms a relatively steep-sided, narrow, winding valley on the surface of a terrestrial planet. The large bedrock meanders of Missouri Ozark streams were among the first to attract the attention of scientists (Davis 1893). Ever since this early work, subaerial bedrock meanders on earth have traditionally been described as "incised" or "entrenched," terms that bear a genetic meaning based on overland flow. One purpose of this manuscript is to propose an alternative origin for the Ozark bedrock meanders based on the upward discharge of meteoric groundwater. Recognition that Ozark streams exist, in part, to efficiently drain confined aquifers has significant implications for the geomorphic history of the midcontinent region.

Artesian transverse speleogenesis is the hypogenic karst process whereby conduits evolve as result of vertical hydraulic communication between aquifers across a soluble bed (Klimchouk 2003). In transverse speleogenesis, water comes to a soluble unit from an adjacent, generally underlying, aquifer. Hypogenic karst is a relatively new concept in which the source of groundwater aggressiveness originates beneath the surface of the earth, implying some degree of confinement or rising flow. Artesian conduit systems are built from the bottom up by transverse speleogenesis, for example Lechuguilla Cave in Carslbad Caverns National Park, where deep basinal brines provided the aggressive fluids. Less familiar are hypogenic karst examples in less deep-seated, more meteoric, but still somewhat surface-independent systems such as the Ozark Salem Plateau. Traditional epigenic karst processes that rely upon downward percolation of surface recharge cannot explain many Ozark landscape enigmas, such as underwater caves that extend down to sea level and huge springs with extraordinary base-level flows of ancient meteoric water. These caves and springs commonly occur in rock units that yield relatively small amounts of water to wells. The water that transforms low-permeability dolomites into conduits comes mainly from adjacent, initially more porous layers such as the Gunter Sandstone and the vuggy Potosi Dolomite.

For 200 years John Playfair's (1802) theory that rivers carve the landscape has dominated geomorphology. Most researchers today regard the groundwater table as merely a subdued reflection of the surface topography and not an important part of forming the landscape itself. But this river theory has recently met with a problem, and that is the surface features found on the planet Mars. The Martian landscape features intricate networks of recent channels that include bedrock meanders and asymmetric drainage basins. Yet conditions on Mars preclude persistent rivers. Most Martian valley networks form by the process of groundwater sapping (Malin and Edgett 2000). The strong focus on river erosion on Earth cannot explain many landforms. An alternative framework advocated here views groundwater erosion as an important process vector along with surface tools such as glaciers and rivers. Playfair is still relevant. Zones favorable for transverse speoleogenesis (groundwater's sharpest erosion tool) are typically found in the rock layers beneath rivers (Klimchouck 2003). The emerging idea that the surface topography can be influenced by groundwater also has important phylogeographic implications. Groundwater erosion can isolate species by relocating rivers. Groundwater erosion can also aid species dispersal by helping stream piracy cut across upland barriers (Pederson 2001).

Perhaps nowhere on Earth is groundwater's important role in the formation of landscapes more apparent than the Ozarks. Dye tracing has shown that groundwater basins can extend well beyond surface watershed boundaries and there is a general lack of fine-scale dissection on interfluves. This study reinterprets Ozark landforms, such as bedrock meanders and transverse drainages, taking into account both groundwater and surface-water-process vectors. The purpose is to produce paleogeographic maps that are based on hydrogeological and biological observations to help explain the current Ozark landforms and the distribution of species within the area.

The maps presented here differ from most interpretations by linking the pre-Illinoian Teays River with Texas along a broad topographic low that extends in an arc from northeastern Oklahoma to the Missouri River in central Missouri (Figure 1). The connection is based in part on biology, such as fish and mollusk distribution (Barnhart 2001) and in part on stratigraphy, such as Appalachian-derived sediments in Pleistocene Sabine River sediments (Mange and Otvos 2005). The connection implies that the Ouachitas, the Ozarks and the Appalachians were once a continuous upland—The Central Highlands (Mayden 1988).

The first part of this paper reviews the concepts of bedrock meanders. A theory is then proposed that explains how bedrock rivers can meander as a result of the natural processes of groundwater and surface water erosion. The second part of the paper compiles some diverse geohydrological and biological evidence that indicate the Ozark landscape was preceded by the Central Highlands and not a low elevation plane as previously implied by the antecedent meander theory. The experimental ideas presented here are meant to elicit a dialogue concerning the landscape evolution of this complex region.

"Entrenched" Bedrock Meanders

The very term "entrenched meander" is an indication of geologists' confidence in the correct-

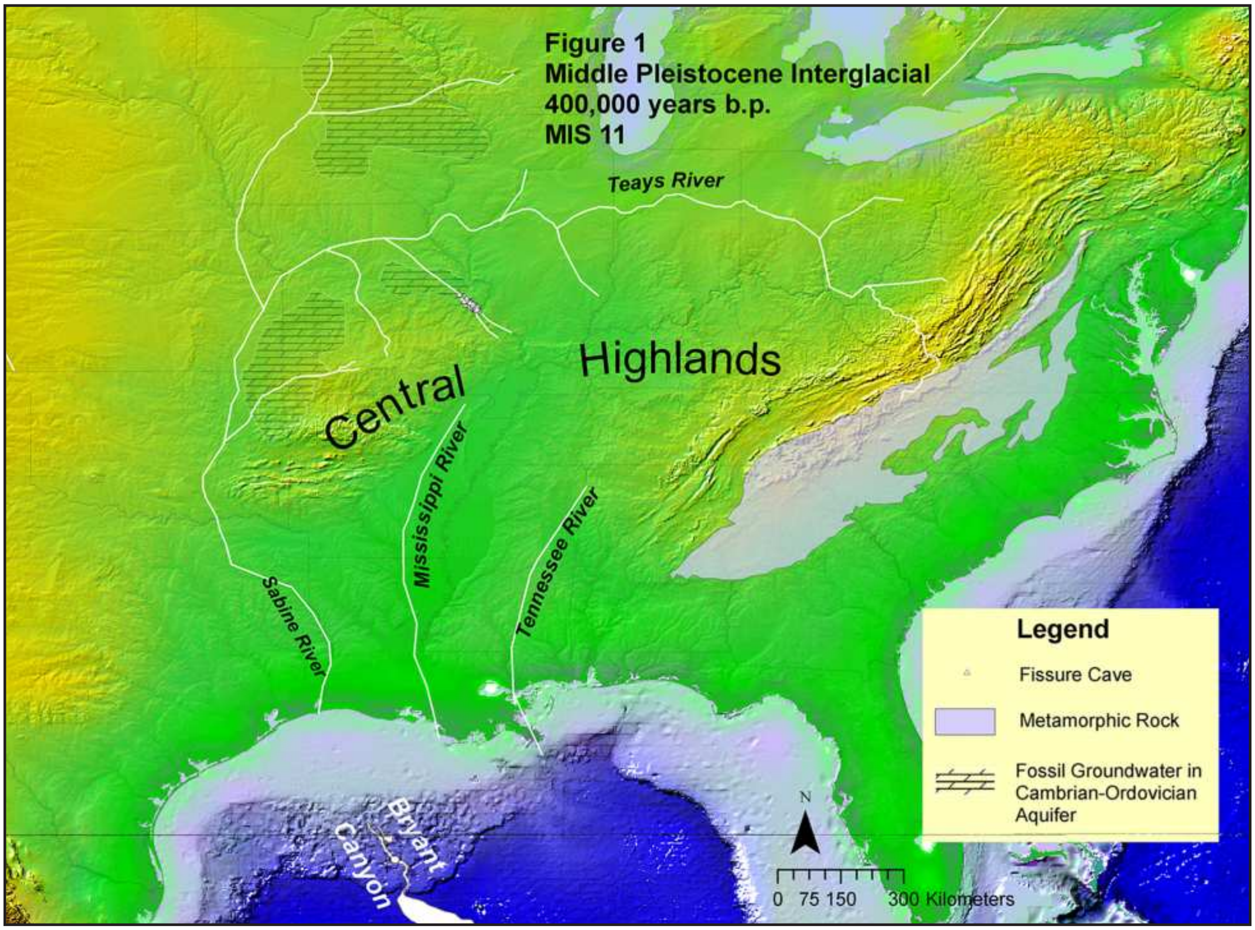


Figure 1 *Reconstructed pre-Illinoian drainage routes, shown just before the Mississippi River captures the upper Teays valley, splitting the Central Highlands. High-grade metamorphic sediments erode from the Appalachians, flow down the Teays River to the Ancestral Neosho River in Kansas (Aber, 1997) and are deposited in the Sabine River Valley of Texas (Mange and Otvos 2005). Precipitation falls on exposed Cambrian-Ordovician rocks of the Salem Plateau and the Wisconsin Arch feeding an underflow that recharges confined aquifers (Jorgensen et al. 1986). Today, groundwater flow directions have changed and these confined aquifers are no longer downgradient of their former recharge areas.*

ness of the landform's inferred origin. The standard explanation for "entrenched meanders" is that they are relics of an ancient, low-gradient floodplain or peneplain. However, bedrock meanders have now been identified in other environments that are unlikely to have ever included low-gradient meandering rivers. The alluvial inheritance theory is unable to explain bedrock meanders carved on Mars, the deep ocean and Taiwan. Mars and the sea floor lack persistent rivers, while meandering low-gradient rivers are rare on Taiwan, one of the most tectonically and erosionally active regions on earth (Stark et al. 2003). Rather than antecedent alluvial meanders, what all these environments may have in common is groundwater discharge.

Renowned geomorphologist William Morris Davis (1893) called attention to the wide meanders of the Osage River in Missouri and proposed that the meanders were inherited from an ancient river wandering almost aimlessly on nearly level ground, a floodplain or peneplain. As later uplift progressed the meanders were no longer able to wander and instead became entrenched. Winslow (1893) objected, citing gravel deposits common on Ozark ridgetops that indicate a fairly rapid flow of sediments within a landscape similar to modern Ozark rivers, as opposed to fine-grained sediments that might be expected from a low-gradient, freely meandering river. Marbut (1896) proposed a theory whereby erosion in tributaries could deflect a

Figure 2a (see page 6 for explanation)

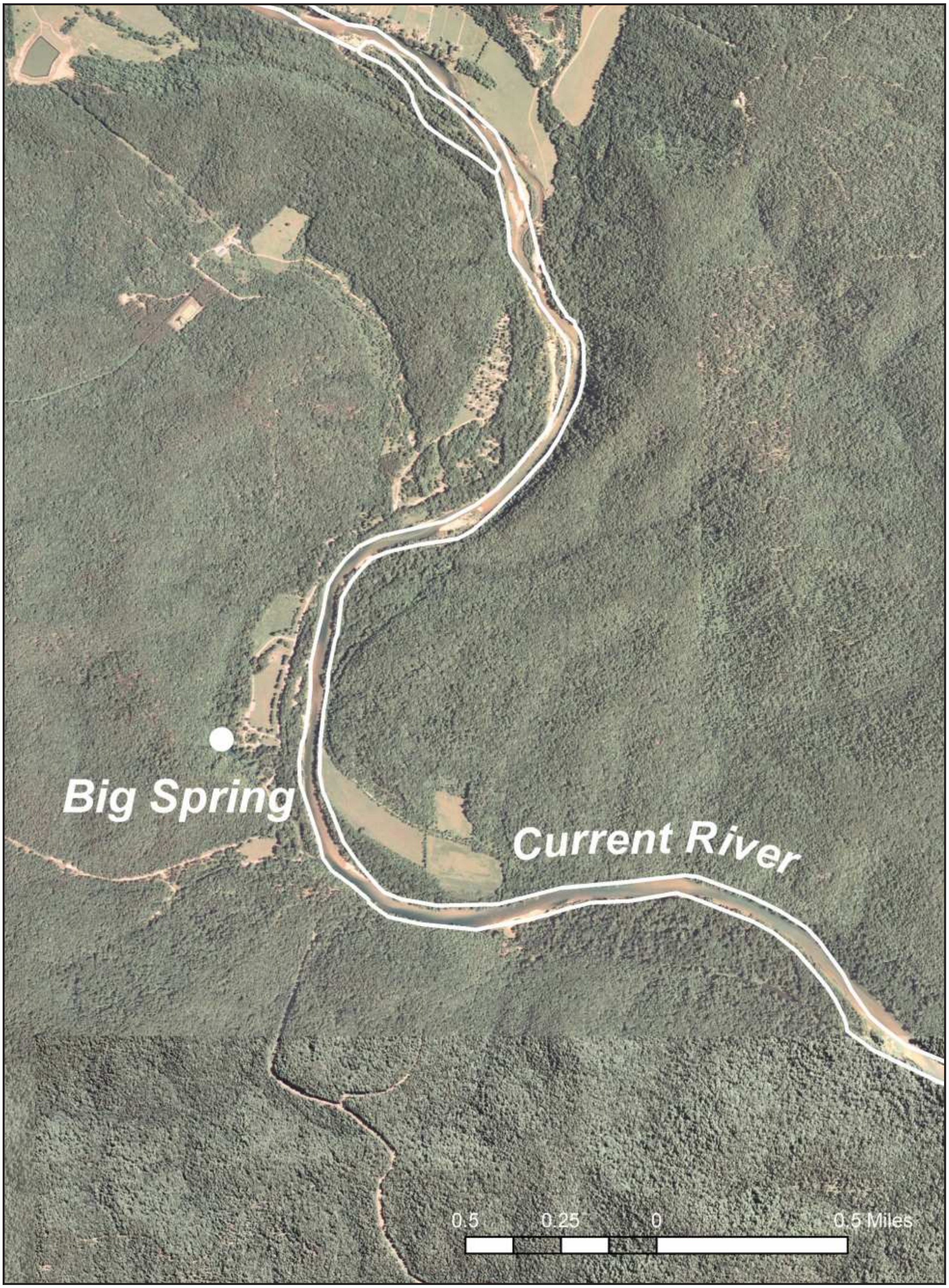


Figure 2b (see page 6 for explanation)

Figure 2
Previous pages *A comparison of (a) the Eleven Point River and (b) the Current River shows how a meander can naturally initiate within a relatively straight bedrock channel and grow into a highly sinuous reach. Greer Spring (a) represents the early stage of the process. Big Spring (b) is the largest spring in Missouri and Greer Spring is the second largest. Each spring produces over 9,500 L/sec. The Greer Spring Branch is one of the steepest streams in Missouri, dropping approximately 18 m in 2 km. As groundwater continues to flow from Greer Spring, the steep spring branch will incise deeper and deeper, deflecting the Eleven Point River toward the spring in a manner first described by Marbut (1896). Eventually the Eleven Point River may engulf Greer Spring, just as the Current River is now trying to flood Big Spring.*

stream and create emergent meanders. However, Davis' alluvial-inheritance argument was regarded by most scientists of the day as the accepted explanation because typical bedrock-meander wavelength and amplitude were seen to increase downstream, just like alluvial meanders. Today Davis' alluvial-inheritance explanation of the landscape remains popular among geologists. However, hydrologic data collected by scientists is starting to show there is more to the history of the Ozark landscape.

A newly released study on Big Spring, the largest spring between Florida and Idaho, has determined that much of the spring's huge base flow may have been underground for several hundred years or longer (Imes et al. 2007). In the case of Big Spring, the soluble Cambrian Eminence Dolomite forms the confining unit as the baseflow water comes from the underlying vuggy and prolific Potosi Dolomite. It is proposed that throughout the pressurized portions of the Ozarks' multistory, artesian, aquifer system, old groundwater moves upward from deep aquifers bringing tons of dissolved rock to the surface and lowering the landscape. The idea that a large artesian spring can erode faster than neighboring streams may come as a surprise to many researchers who tend to think the base level of erosion is determined by sea level. In transverse speleogenesis, the base level of erosion is determined by hydraulic pressure in the confined aquifer (Brod 1964).

The creation of an emergent bedrock meander is illustrated in Figure 2. Greer Spring represents the early stage of the process. Surface streams tend to meander from spring to spring, at times engulfing a spring, masking and eventually erasing the work done by underground waterways. Big Spring would be drowned by the Current River now if not for a system of levees. Thus, the meandering valleys that are a trademark of the Ozarks are primarily a consequence of spring and karst processes that lower the landscape and direct valley alignment as surface streams incise.

Transverse speleogenesis can also explain why bedrock meanders tend to increase in size downstream. Spring erosion is a competitive process and only a few major, deeply incised springs feed the surface streams as they encompass more watershed area. As the discharging aquifer is drained, the "cone of depression"around large springs and gaining streams naturally widens with incision and exploitation/interception of more remote, discrete, discharge features and additional volumes of pressurized groundwater. Groundwater discharges tend to increase with contributing area in a downstream direction and the springs tend to get larger and farther apart. Streams that meander between the springs tend to carve bedrock meanders that increase in size and amplitude in a downstream direction, the logical consequence of hydraulic optimization. Furthermore, a longer, meandering river allows more water to escape from underlying aquifers than a straight channel.

Biogeography

Biogeographic evidence suggests a relatively recent faunal connection between the Ozarks and the Appalachians (Mayden 1988). Many sister species of fish (Pflieger 1997), crayfish (Crandall and Templeton 1999) and salamanders (Routman et al. 1994) occur across these regions. The studies show that northern Ozark populations tend to be most closely related to populations in the Ohio River drainage. While Southern Ozark populations may be related to populations from the Tennessee River.

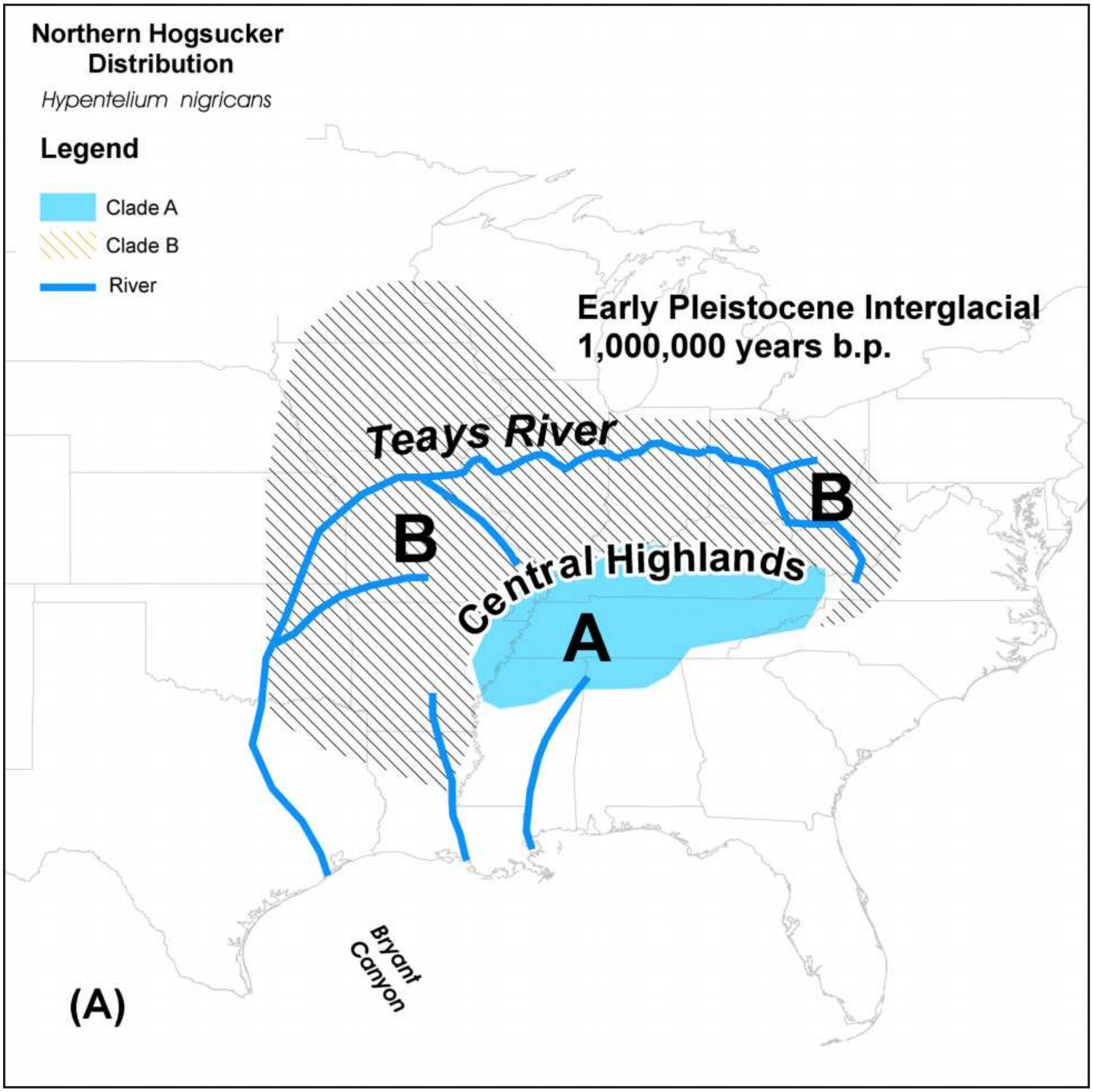
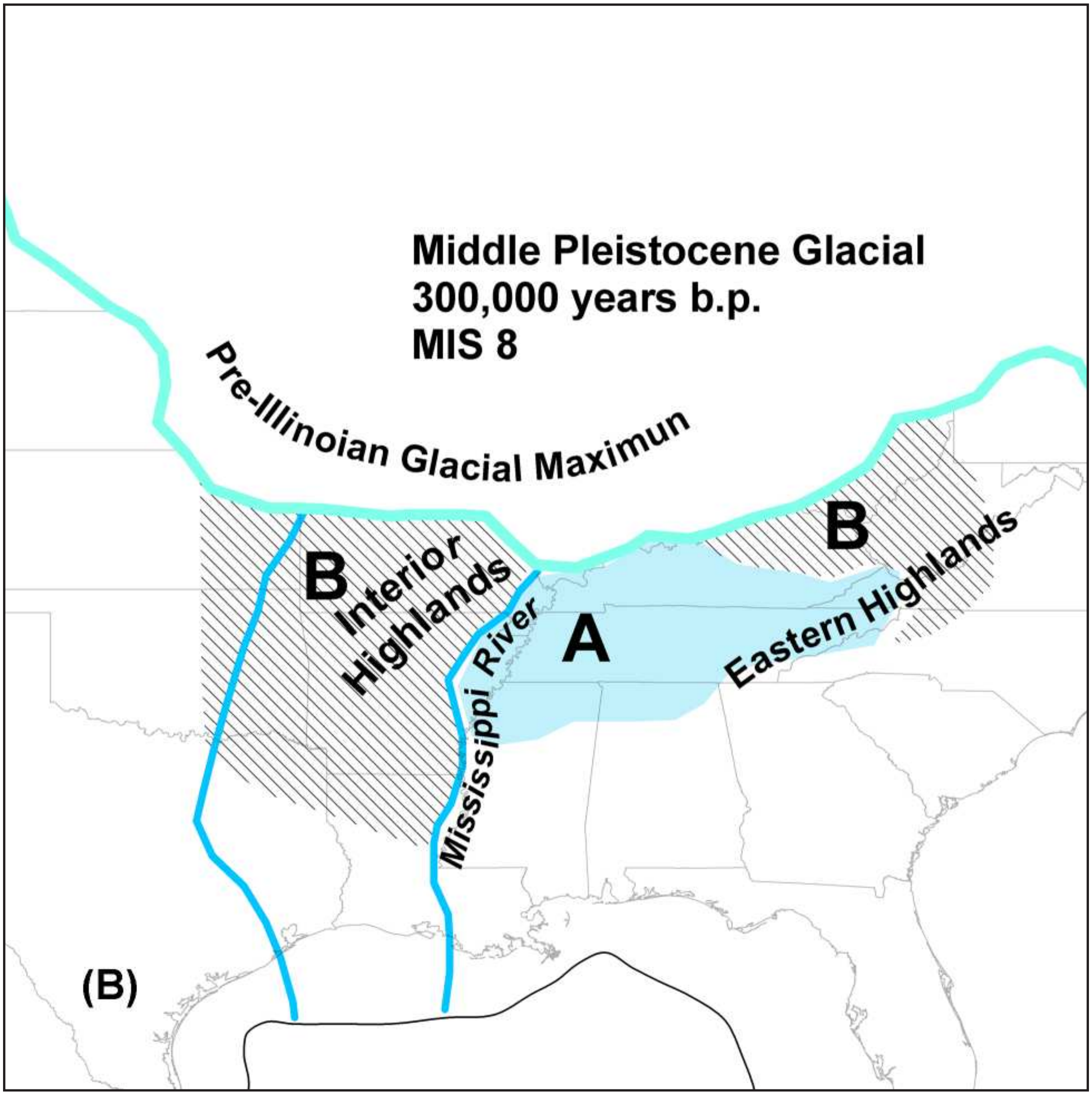


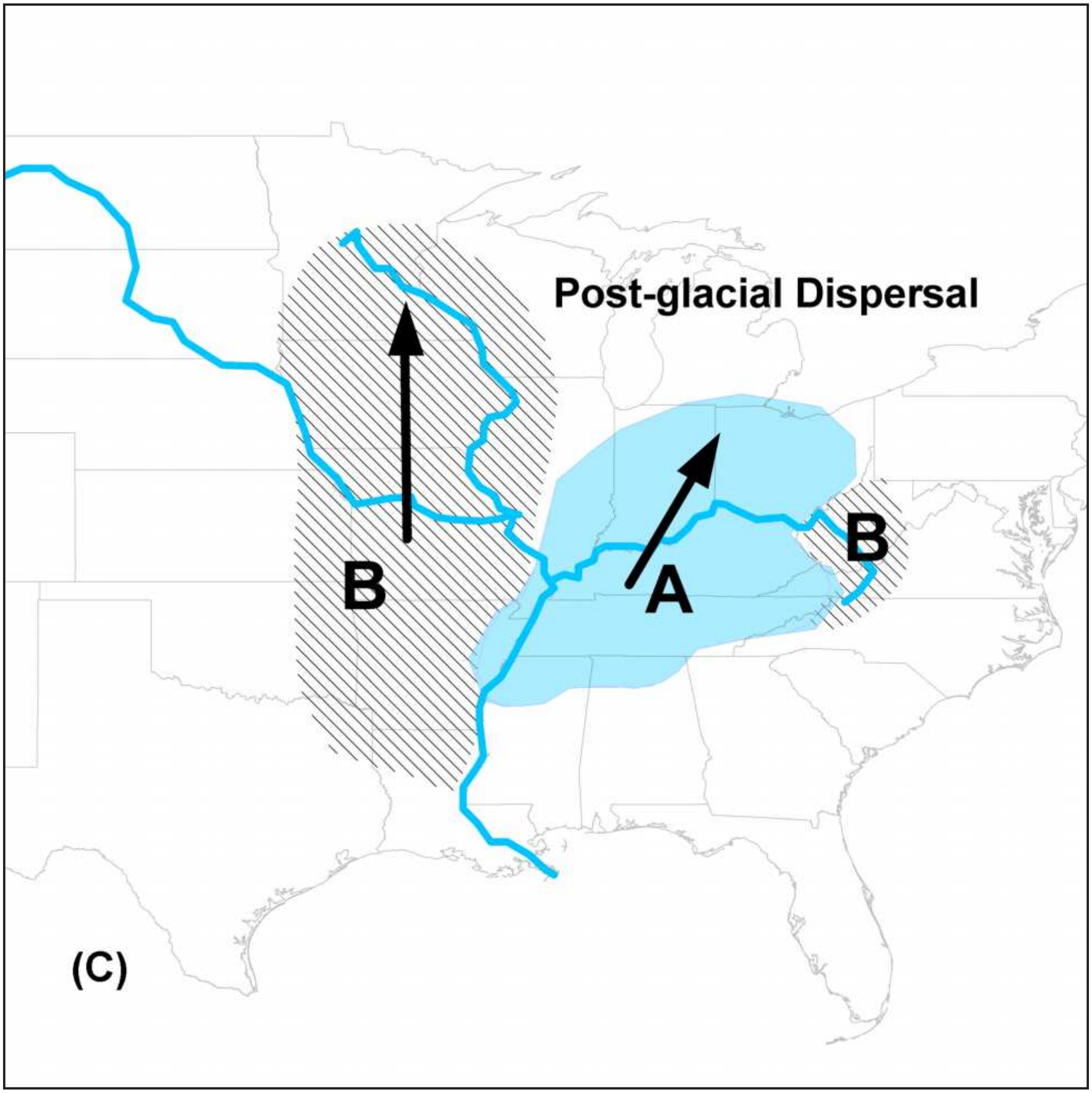
Figure 3 *(a) Hypothetical early Pleistocene distribution of Hypentelium nigricans, northern hogsucker, across a continuous Central Highlands. Clades A and B are separated because the Mississippi River does not extend north of the Central Highlands.*
(b) The Mississippi River breaches the Central Highlands. The first glacial outwash reaches the lower Mississippi valley, resulting in deposition of the Crowley's Ridge Loess (Rutter et al. 2006).
(c) Post-glacial distribution of H. nigricans. The widely separated, disjunct pattern of clade B is replicated in other clades of fishes (Berendzen et al. 2003).

This deep divergence is difficult to explain if the Mississippi River has been in its present position for millions of years. In contrast the Mississippi River itself is not a continuous barrier as evidenced by the current distributions of many modern taxa not expected to survive in large muddy rivers (Austin et al. 2004). The existence of a continuous Central Highland that was fractured in the Middle Pleistocene by the Mississippi River can better explain these patterns. The process is illustrated in Figure 3 using now disjunct clades of a fish, the northern hogsucker (Berendzen et al. 2003).



The Mississippi River is a barrier to some species such as the American Bullfrog and biological dates of isolation match the Middle Pleistocene vicariant event proposed in this report (Austin et al. 2004). In other cases, vicariant dates proposed in this study are younger than molecular estimates of isolation. For example, the abandonment of Bryant Canyon (Figure 1 and Figure 3a) in the Gulf of Mexico suggests that the Arkansas River separated the Ouchitas and the Ozarks sometime before the end of Marine Isotope Stage 5 (MIS 5), about 110,00-130,000 years before present (Tripsanas et al. 2007). Most molecular clocks estimate this vicariant event occurred earlier.

There are examples of karst-related relicts separated by the Mississippi River such as the blind Caney Mountain crayfish, the only cave-adapted *Orconectes* found west of the Mississippi (Elliott 2007). It is closely related to the crayfish, *O. pellucidus*, found in Kentucky. Kentucky and Tennessee's southern cavefish, *Typhlichthys subterraneus,* also has close relatives in Missouri and Arkansas (Niemiller and Fitzpatrick 2008 in this volume). Once again, the vicariant event that separated these stygobites is estimated by molecular methods to be older than what geological evidence presented in this manuscript would suggest. However, headward erosion up the Ozark segment of the Mississippi



River may have caused vicariant events prior to the final connection that eventually integrated the entire drainage system.

Tectonism

Antecedent entrenched meanders are tectonically significant because they require uplift without significant tilting in order to form. However, global positioning system (GPS) studies suggest that the Northern Mississippi embayment may be slowly subsiding relative to the Salem Plateau (Mattioli and Jansma 2007). GPS stations on both sides of the Reelfoot fault in the tectonically active New Madrid Seismic Zone appear to be subsiding. Subsidence rates emerging from the GPS surveys are fast enough to lower the Mississippi Embayment a few hundred meters since the early Pleistocene. Mississippi Embayment subsidence can generate tectonic relief, create high hydraulic heads, reorient the groundwater flow fields and influence drainage-basin development, thus setting up conditions favorable for transverse speleogenesis.

I propose that vertical tectonic movements produce the high hydraulic pressure in the confined portions of multistory Ozark aquifers. Once the surrounding seals of the overlying massive carbonates are broken, groundwater will flow through

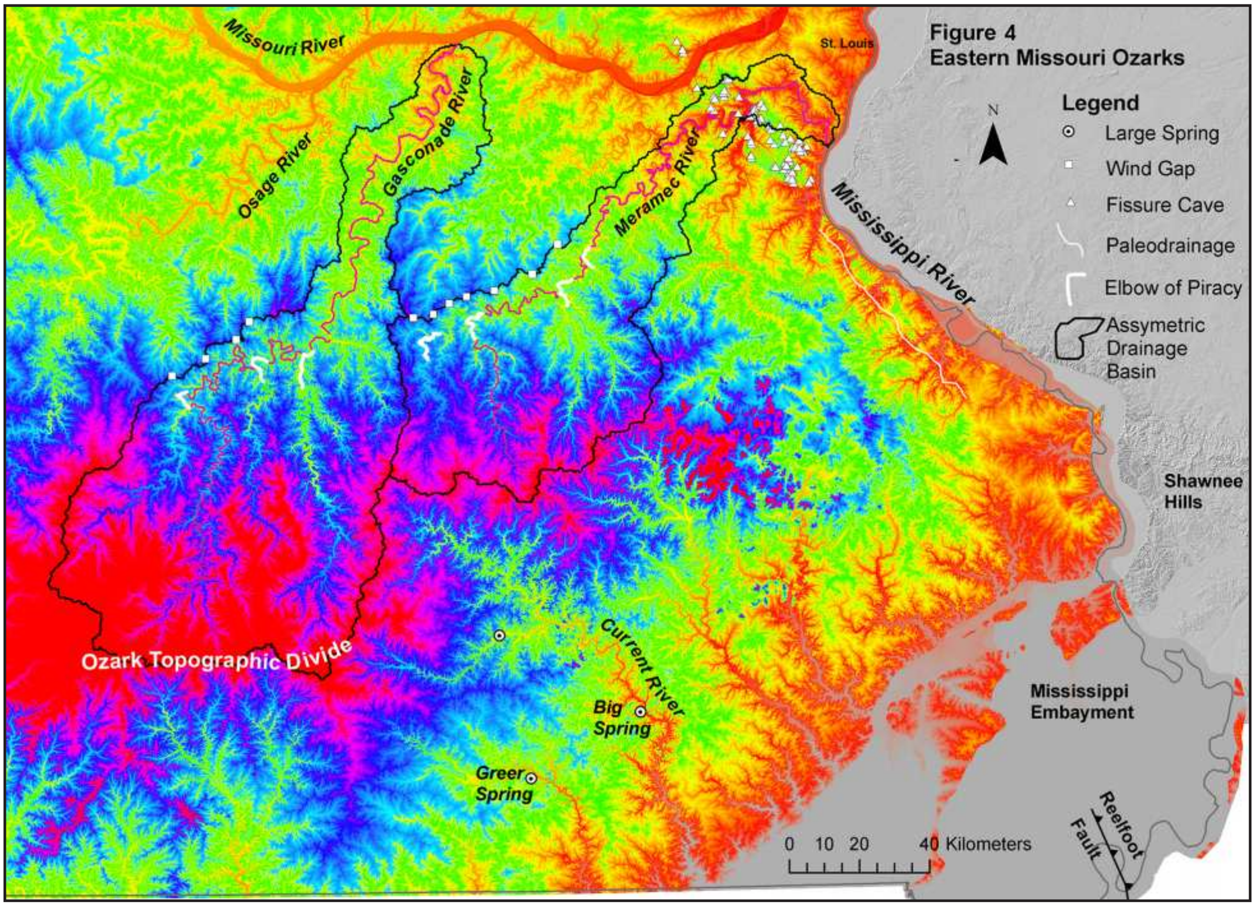


Figure 4 *Study area showing modern rivers and a paleochannel that is now followed by Interstate 55. Headwaters of the Gasconade and Meramec Rivers flow north to northwest, relicts of a drainage network that once flowed off the Central Highlands. Their diversion to the east has created asymmetric drainage basins.*

fracture outlets to the surface.

Fissure Caves of Eastern Missouri

The flow of pressurized groundwater along primary conduits that results in speolegenesis can be seen in an area known for its "fissure caves." The caves are found in a 5-km-wide by 60-km-long belt southwest of St. Louis and are comparable to large Ozark spring conduits as reported by SCUBA divers. These include many caves in Jefferson County such as Crankshaft Pit, Pleasant Valley Cave and Rice Cave, and St. Louis County, such as Horneker and Rankin caves. The artesian nature of the fissure caves and their ability to affect base level was initially recognized and described by Brod (1964). According to Brod, conduits evolve as a result of vertical hydraulic communication between aquifers across a soluble bed. Brod's recognition that an artesian spring can erode the landscape below the level of nearby streams is a critical observation for the groundwater-outflow theory of emergent bedrock meanders.

Ford (2006) agreed with Brod's interpretation, but considered this type of transverse speleogenesis to be rare. However, the recent discovery of pre-modern groundwater feeding the huge base flow of one the nation's largest springs (Imes et al. 2007) suggests that transverse speleogenesis may be widespread in the Ozarks' big spring country (Figure 4). It now appears that what is really rare is for the underground voids and karst features created by transverse speleogenesis to be preserved. Because of their position beneath rivers, karstic shafts produced by artesian speleogenesis are generally destroyed as the landscape lowers. However, due to a major drainage reorganization that cut the Central Highlands in two, the fissure caves of eastern Missouri were left high and dry and the underground features were preserved.

Caves serve as storehouses of information on past landscapes. Eastern Missouri fissure caves are evidence of a focused, paleogroundwater discharge beneath a large river. Ridgetop, alluvial gravels (Brod 1964) and anomalous, inactive groundwater bodies (Jorgensen et al. 1986) indicate that the pre-Illinoian drainage network in Eastern Missouri was significantly different from the modern one. Paleovalleys in the northeastern Ozarks and in the St. Louis area initially drained off the Central Highlands toward the northwest, but were later disrupted by the middle Pleistocene appearance of the Mississippi River. This flow-reversal resulted from a combination of Pleistocene subsidence in the Mississippi Embayment and pre-Illinoian glaciations. The fissure caves mark the position of a pre-Illinoian river that once flowed northwest toward the Teays River (Figures 1 and 4).

South of St. Louis, Interstate 55 follows remnants of an old headwater valley through Jefferson, Ste. Genevieve and Perry Counties. This lost valley has been interpreted as a south-flowing, proglacial, diversion of the Mississippi River (Brod 1964). However, stream barbs suggest a northerly flow was more likely. The spatial correlation of anomalous groundwater north of the Missouri River, a fossil drainage pattern to the south of the fissure cave corridor and Lafayette gravels found on ridgetops is supporting evidence that suggests that a former path of Central Highlands runoff flowed north through the fissure-cave corridor (Figure 4).

Anomalous Aquifers

Freshwater found in the deep, confined aquifers that ring the Ozarks to the north and to the west provide the best evidence that a Central Highland existed in the relatively recent geologic past (Figure 1). The proposed eastward migration of regional base levels has caused widespread stream piracies, leaving behind large, fossil-groundwater bodies that are now out of equilibrium with the modern Mississippi drainage network (Jorgensen et al. 1986). These anomalous, freshwater, Cambrian-Ordovician aquifers have been cut off from their former recharge areas on the Central Highlands. Modern precipitation falling on Cambrian and Ordovician exposures in the Salem Plateau now flows east and south toward the Mississippi valley. North of the Missouri River, fresh water in the confined Cambrian-Ordovician aquifer is currently being recharged by saline groundwater from the northwest. Flow directions have reversed. Total dissolved solids are supposed to increase in a downgradient direction as water-rock interactions progress. The aquifer is now cut off from its former recharge area on the Salem Plateau by the Missouri River. The anomalous concentration gradients indicate that the freshwater remnants were emplaced under hydrologic conditions that are very different than what exist today.

Transverse drainages

The fissure caves are now found on the uplifted flanks of the Eureka-House Springs Anticline. However, the shafts originally formed beneath a river. Erosion since the conduits' abandonment has greatly altered the landscape. Emergence of groundwater from the structurally disturbed noses of folds is typical of artesian speleogenesis (Klimchouk 2003). Erosion can thin confining units above upwarps, further encouraging transverse speleogenesis near the crest of anticlines.

Rivers intersecting upwarps at their highest structural and topographic position have long puzzled geologists. The dominant theory posed by Powell (1875) for such relationships is that of antecedence. According to this view, the rivers were already in their present positions when the upwarps began to grow. The Osage River is a typical example of a cross-axial, or discordant, drainage that appears to take a most difficult route across the Ozarks. The Mississippi River between the Shawnee Hills of Illinois and Missouri's Ozarks is another river that crosses an upwarp near its apex. Transverse speleogenesis and stream piracy can explain both these cases without appealing to antecedent rivers. One reason rivers carve channels into what appears to be the paths of greatest resistance is because that is where the pressurized groundwater can find disturbed structures that can act as nozzles, focusing groundwater discharge upward and creating springs by hydraulic fracturing. Headward erosion of more hydraulically advantaged streams expands, and in this manner groundwater divides can migrate beneath uplands and produce a stream piracy.

Asymmetric Drainage Basins

It is proposed that paleodrainages, in what are now the Northern Ozarks, flowed to the ancestral

Teays River system to the north and west. A subsequent tectonic phase resulted in the subsidence of the Mississippi Embayment and the St. Louis depression disrupted the pre-Illinoian drainage. Hydraulically advantaged tributaries of the Missouri and Mississippi Rivers have captured the headwaters of other northwesterly flowing Ozark paleodrainages, creating the asymmetric drainage networks of the modern Meramec and Gasconade Rivers, where most inflow to the mainstem is from the south and relatively little from the north. The asymmetric basins contain a series of nested elbows of capture (Figure 4). Initially the flow of the rivers is to the northwest as if going to the old Teays River but this flow has been intercepted and now flows to the east reflecting subsidence in the Mississippi Embayment and the St. Louis area. If the diversion-elbows theory is correct, then the interfluve closest to the main stem should be notched by windgaps that roughly correspond with tributaries that once flowed off the opposite side of the valley. Interstate 44 follows such an undulating interfluve as it rolls along the northern edge of the Meramec Valley and crosses dry valleys. The dry valleys are windgaps where streams once flowed to the northwest before being pirated by a more direct route to the Mississippi River. The I-44 wind gaps should get younger in a westward direction as areas under direct hydraulic control of the Mississippi River expand.

Stratigraphy

Sediments from the Gulf of Mexico show that the mouth of the main mid-continent trunk stream has migrated eastward approximately 400 kilometers since the Middle Pleistocene (Prather et al. 1998). Migration of the river system has caused a profound change in sediment supply during the late Pleistocene. The once abundant fluvial source that previously fed the sand-rich barrier islands off the Texas coast was cut off (Tripsanas et al. 2007). Geohydrologic and biological evidence for a similar eastward shift of mid-continent rivers is the focus of this paper.

Drainage shifts in Kansas and Missouri have left Cenozoic alluvial gravels on modern hilltops (Aber 1997). Aber proposed ongoing crustal tilting toward the Mississippi Embayment to explain this complete inversion of topography. The older parts of what are known as the Lafayette gravels occur on top of an erosional surface that once drained the Central Highlands.

Loess lithology of the modern river system provides evidence that the modern river system was integrated during Wisconsin time. For example, in the Mississippi Valley, only the late Pleistocene Peoria Loess shows any deposits from Rocky Mountain or Great Plains sources. The older Roxana Loess that is found in the Mississippi Valley has a more characteristic reddish color along with a higher magnetic susceptibility. This is an indication that a significant contribution of sediment has come from the more mafic Lake Superior source area (Rutter et al. 2006).

Discussion

There is a growing body of evidence from diverse disciplines supporting the idea that in the early Pleistocene, the Missouri Ozarks comprised the northwest slope of a continuous Central Highland. Patterns of topography, tectonics, drainage, sediments, groundwater chemistry and biogeography in the midcontinent provide evidence for recent subsidence and river capture. Such active tectonics contrasts with the traditional view of the midcontinent, which is seen as a stable craton.

Sustained groundwater outflow requires that hydraulic gradients be maintained by ongoing subsidence. Groundwater outflow is closely linked to subsidence. Ozark karst is in the early stages of erosion, when plenty of water is available from the large upland, and sapping processes dominate. I do not imply that all caves, incised meanders, asymmetric drainages and valleys located near the crests of topographic bulges are formed by dewatering of overpressurized aquifers. Nevertheless, emerging groundwater may have been an important and often overlooked landscape-process vector in other karst regions where vertical movements have subsided and aquifers have reached equilibrium. Dewatering is self-terminating after vertical motions cease and aquifers reach equilibrium, which may help explain why huge springs are present in relatively few karst areas. The south central Ozarks are currently in a very active cave-forming period. Active bedrock meanders can be considered karst features in the sense that they facilitate the circulation of regional groundwater fluid in a downgradient direction.

Conclusions

The ancient landscape paradigm, and methods of hydrogeologic and historical biogeographic analysis stemming from it, has produced an inadequate representation of landscape and biological evolution in the midcontinent. This is because of the overlooked importance of groundwater and tectonism in shaping topography and the overly restrictive range of processes (i.e. glaciers and sea-level fluctuations) that can modify drainage patterns and create vicariant events. New reconstructions of Pleistocene landscape based on groundwater chemistry, stratigraphy and geomorphology result in a pattern that is more in harmony with species distribution. The proposed connection between the Teays River and Bryant Canyon modifies and strengthens the Central Highlands vicariance hypothesis. Evidence presented in this paper challenges the ancient landscape paradigm and draws a tentative geohydrologic connection between the big springs of the Ozarks and subsidence in the Mississippi Embayment.

Acknowledgments

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DYE TRACING AND RECHARGE AREA DELINEATION FOR VARIED LAND MANAGEMENT PURPOSES IN THE SOUTHWEST ILLINOIS KARST

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Abstract

The Southwest Illinois Karst underlies a 410 km^2 sinkhole plain located a short distance southeast of St. Louis, Missouri. The Illinois Speleological Survey lists over 100 perennial and ephemeral springs in the sinkhole plain. The Ozark Underground Laboratory has delineated nine groundwater system recharge areas in some detail, has partially delineated two others, and plans work on three more. Dye tracings were done to characterize groundwater flow, identify lands which contribute water to the habitat of a federally-listed aquatic cave species (*Gammarus acherondytes*, the Illinois cave amphipod) and other important cave fauna, and to assess impacts to spring discharge from proposed quarry expansion. Over 100 dye introductions have been made, which were detected at 29 springs resulting in over 120 km^2 (~29% of the karst) shown to lie within the delineated recharge areas. These data are being used for recovery of the Illinois cave amphipod, to recognize special spill response needs, for permit applications for quarrying and subdivisions, and to disclose a flaw in a floodway model.

Key words: recharge area delineation, dye tracing, karst groundwater, southwestern Illinois

Introduction

The Southwest Illinois Karst lies within the Salem Plateau physiographic province (Willman *et al.* 1975) and within the Ozarks Ecoregion (Figure 1). Previous studies of the karst area and its groundwaters are provided by Frankie et al. (1997), IDNR (1998), Panno et al. (1994), and Stueber and Criss (2005).

The Illinois part of the Salem Plateau Karst includes three major areas that are intensely karstified. These are the Columbia, Waterloo and Renault subkarsts, respectively named for proximal towns (Figures 1 and 2, Titus 1976, Aley *et al.* 2000).

The general area is a sinkhole plain developed in Mississippian Period limestones of the Valmeyeran Series, covered on the east and south by insoluble, granular sedimentary rocks deposited during the Pennsylvanian Period. The rocks affecting the karst development are, from oldest to youngest, the Salem Limestone, the St. Louis Limestone, the Ste. Genevieve Limestone and the Aux Vases Sandstone. The karst area is bounded on the west and north by the Mississippi River floodplain alluvium, and is covered in many places by Pleistocene loess that is commonly 40 feet thick between sinkholes.

The area is undergoing rapid urbanization and has Illinois' longest caves, which have the highest

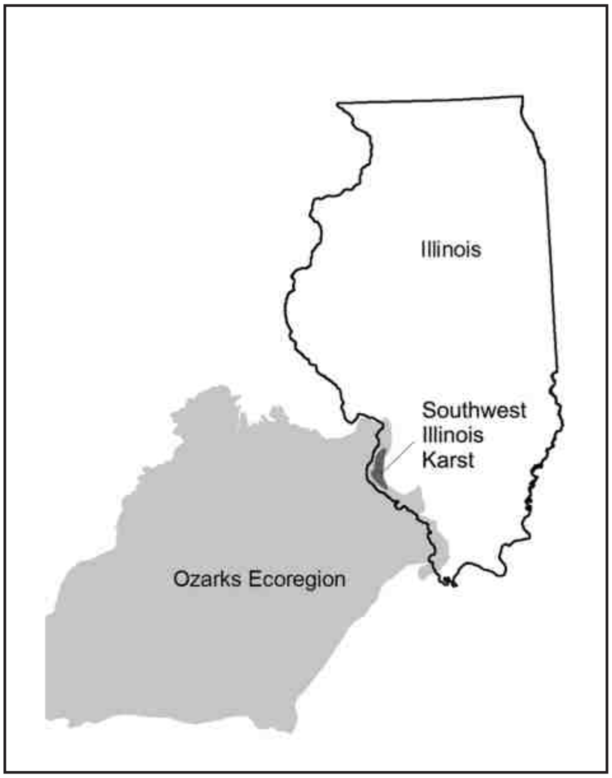

Figure 1 *Location map.*

Figure 2 *The Salem Plateau in Illinois and its major subkarsts.*

number of globally-rare species found in the caves of the Ozarks Ecoregion (Lewis *et al.* 2003). Proposed changes in land use, the listing of the Illinois cave amphipod (ICA, *Gammarus acherondytes*) as federally listed as endangered, and proposed designation of cave-nature-preserve recharge areas as Class III groundwater have driven most of the dye tracing in the Southwest Illinois Karst.

Renault Subkarst Tracing

Thirty-six dye introductions demonstrating 42 flow paths have been made in the Renault Subkarst (Figure 3). Three dye introductions were made to determine if a proposed subdivision would impact the Fogelpole Cave groundwater system, which was known to provide habitat for the ICA. One introduction was made to help cavers determine if a newly discovered cave was part of the Fogelpole Cave system or if it flowed to Collier Spring, which drains a nominally separate cave system. The remaining 32 dye introductions delineate cave system recharge areas and areas that recharge state-managed lands, particularly the Armin Krueger Speleological Nature Preserve, the Illinois Caverns Natural Area and the Fogelpole Cave Nature Preserve. Each of these cave systems provide habitat for the ICA (see Aley *et al.* 2000).

Waterloo Subkarst Tracing

Thirty-one dye introductions demonstrating 34 groundwater flow paths have been made in the Waterloo Subkarst (Figure 4). Continuing work will delineate recharge areas for Frog Spring, Luhr Spring and Dual Spring, all of which are known to provide habitat for the ICA.

Eleven of the dye introductions were done to help characterize groundwater flow in the Southwest Illinois Karst (Aley and Aley 1998), and most proved to be relevant for subsequent recharge-area delineations. Two dye introductions were made to add detail to two of the characterization traces (Moss 1998). The remaining 18 dye introductions were made to help delineate the recharge areas of the Pautler Nature Preserve, Annbriar Spring and the Pautler Cave system, which currently has the highest number (16) of globally-rare species of any cave system in the Ozarks Ecoregion (Lewis *et al.* 2003). Both the Pautler Cave and Annbriar Spring groundwater systems provide habitat for the ICA, as do the Frog, Luhr and Dual Spring systems. The recharge area for the Pautler Nature Preserve was delineated in support of its designation as Class III groundwater. The recharge area delineations were

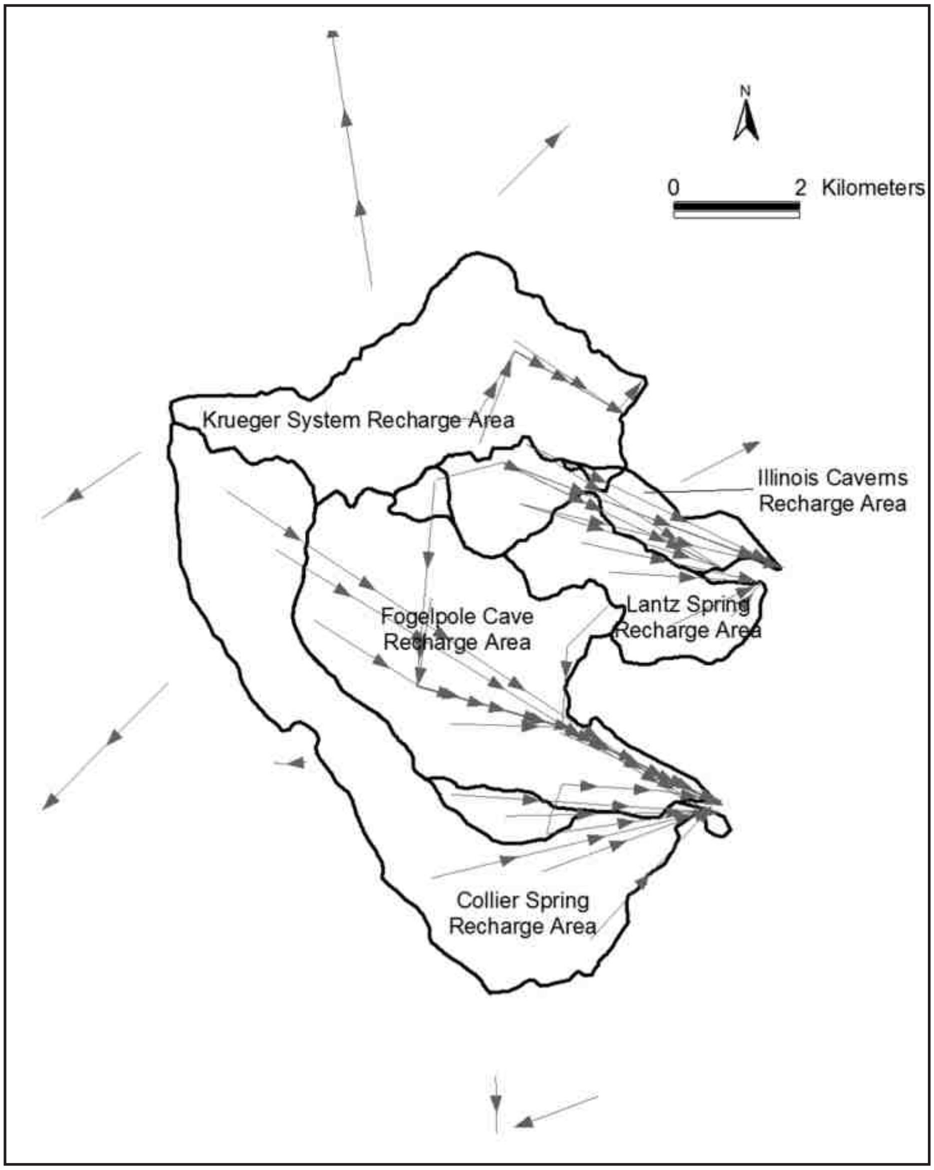

Figure 3 Renault Subkarst: Recharge areas and dye traces.

reported by Aley and Moss (2001).

Columbia Subkarst Tracing

Thirty-one dye introductions demonstrating 35 groundwater flow paths have been made in the Columbia Subkarst (Figure 5). Three dye introductions were made to provide necessary data to help resolve a sinkhole-flooding issue in Columbia, Illinois. All of these traces flowed to Ritter Spring (Aley *et al.* 2000). Two successful dye introductions were made to determine appropriate sampling locations for a closed landfill (Aley and Moss 2007), 19 dye introductions were made to delineate the Stemler Cave system recharge area (Aley *et al.* 2000) and seven dye introductions were made to delineate the Falling Springs recharge area (Moss and Aley 2002). The Stemler Cave recharge area was delineated as well as delineating the recharge area for the Stemler Cave Nature Preserve. The former was in support of the ICA and the latter was in support of Class III groundwater designation. The recharge area for Falling Springs was delineated as part of an assessment of potential impacts to the spring from a proposed quarry expansion.

One of these traces proved relevant in a lawsuit relating to a floodway issue. There was a question of whether or not modeling the topographic basin of Wilson Creek near Columbia, Illinois was appropriate. Trace 99-213 reported in Aley *et al.* (2000)

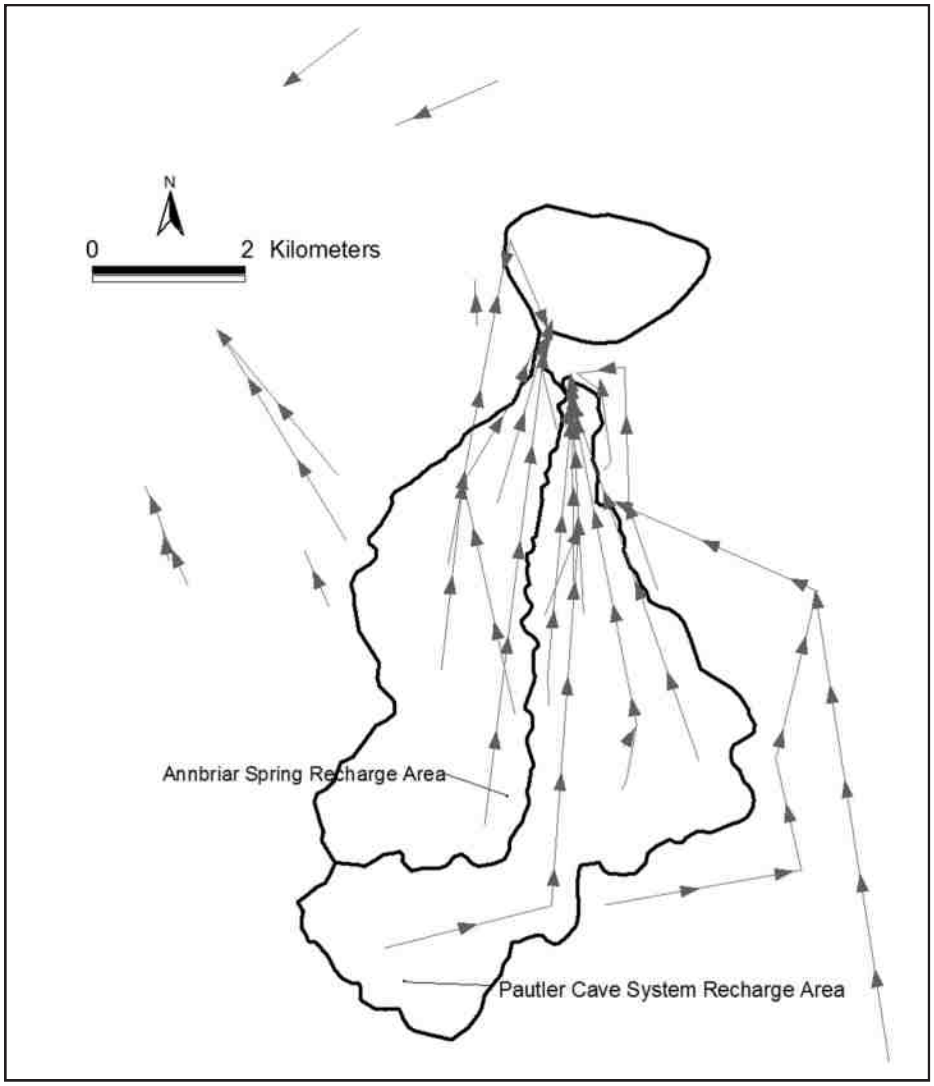

Figure 4 Waterloo Subkarst: Recharge areas and dye traces.

has shown that groundwater is derived from a zone extending at least 1.7 km outside the 9 km^2 topographic basin. Anecdotal reports showed much higher flood levels than the models predicted, and we were asked if we could explain the difference. There are six known springs at the head of Wilson Creek, one of which happened to have had a trace detected by us. It was clear that the topographic model did not successfully predict the amount of water discharged from Wilson Creek during the one-percent-probability flood.

Conclusion

Dye tracing is a versatile tool in the Southwest Illinois Karst, and bears on a number of questions, including:

- How does groundwater behave in the Southwest Illinois Karst?
- Which areas recharge cave systems providing habitat for the ICA?
- Which areas recharge nature preserves and natural areas?
- How would the proposed expansion of a quarry affect the discharge of proximal Falling Spring?
- Is there interbasin transfer of water, and how does that affect flood modeling?
- In which groundwater systems do particular caves lie?
- Where should water be sampled for potential landfill leachate?

The >100 groundwater traces completed in the Southwest Illinois Karst have helped answer these questions. The Southwest Illinois Karst has been

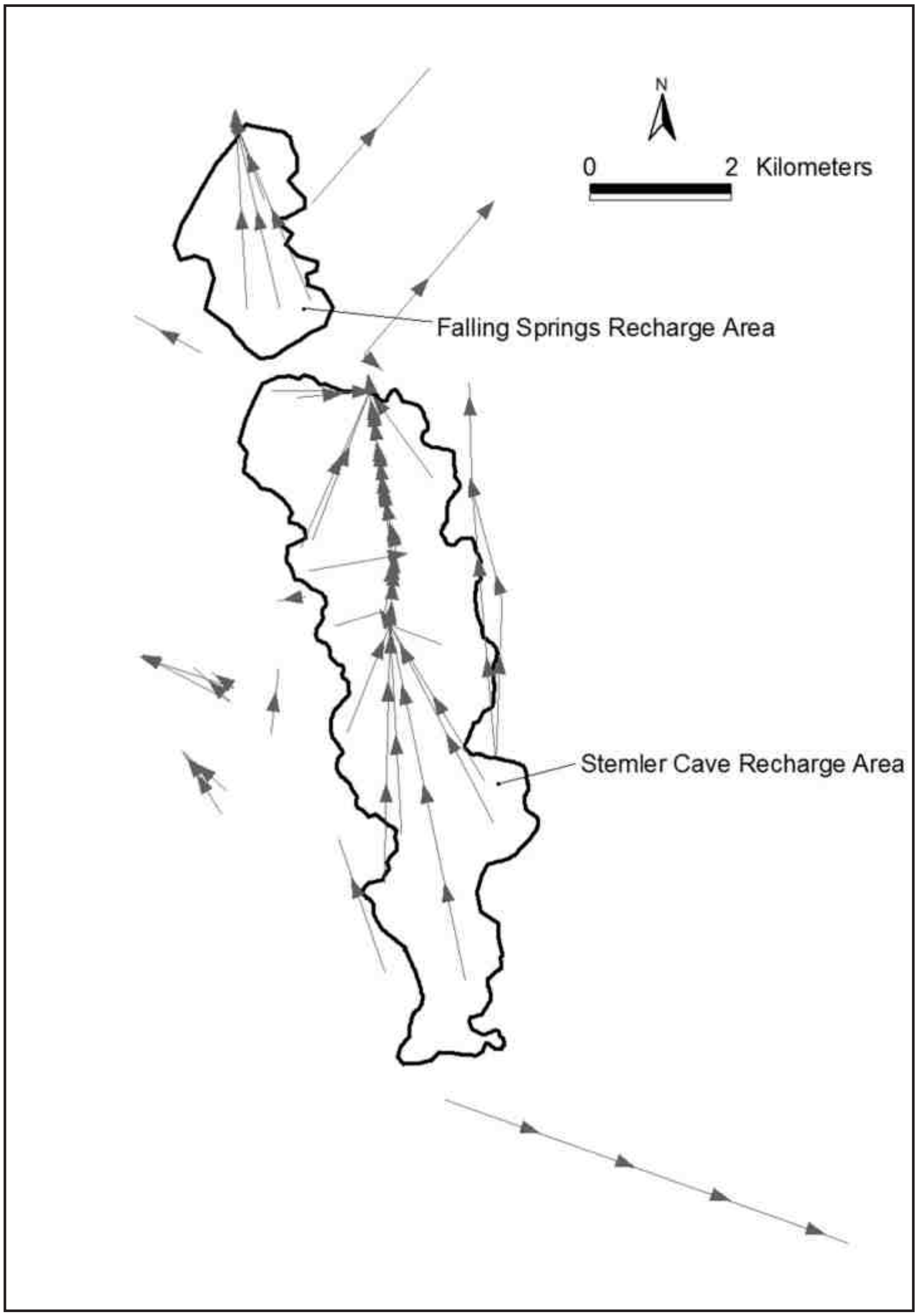

Figure 5 Columbia Subkarst: Recharge areas and dye traces.

shown to have very open conduit systems with large caves and high groundwater velocities. For each trace, we generally report the following:

- the amount and type of dye used,
- the elevation and location of the dye introduction point,
- the date and time of dye introduction,
- water flow conditions at the dye introduction point at the time of dye introduction,
- locations where dye was recovered,
- estimated velocities of groundwater flow paths,
- elevation change between introduction and recovery points,
- gradient of groundwater flow path, and
- a figure showing the trace.

The Illinois Speleological Survey is making the important data in these unpublished reports more accessible. The shape files of the traces and recharge area delineations, as well as the text for most of the reports, are on a website maintained by the Illinois Speleological Survey (http://www.caves.org/iss). As in the floodway case, these data may prove to be useful for purposes other than those for which they were originally conducted.

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SUCCESSFUL WATERSHED PLANNING BY STAKEHOLDERS, BOONE COUNTY, MISSOURI

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Abstract

Successful watershed planning is essential to protection of water quality and aquatic ecosystems, but it is also essential to achieve planned growth that meets the economic goals and quality of life in a community. Development of a watershed plan that is likely to be adopted by a community and its local governments is a daunting task. The approach taken by the Bonne Femme Watershed Project appears, so far, to be successful. Development in the watershed, located near the rapidly growing City of Columbia, Missouri, threatens cave and karst resources including two endemic stygobites that reside in Devils Icebox Cave.

The project placed the task of watershed planning squarely in the hands of stakeholders who represented the diverse interests of business, environmentalists and landowners. Stakeholders were supported by a Steering Committee that provided technical expertise and a Policy Committee. Years of educational outreach and scientific research laid a solid foundation. Keys to successful watershed planning included: the organizational structure of the project, representation of diverse stakeholder interests, willingness to employ respectful engagement in dealing with contentious issues, dedication to reaching compromise, Policy Committee selection of the stakeholders, interested local governments and politicians, giving full control of the planning process to the stakeholders, providing an outline to serve as a "road map," providing progress reports, adherence to deadlines, fostering trust and respect, building relationships, patience and dedication. The stakeholder-led watershed planning process and its keys to success can be implemented in any watershed, to the benefit of the watersheds aquatic resources.

Key words: karst land management, hydrology, contaminants, planning, Devils Icebox Cave, Hunters Cave, Bonne Femme Watershed Project, Boone County, Missouri

Introduction

How do you develop a watershed plan that considers a wide range of community values? By including policy-makers, technical experts and a diverse group of stakeholders in the planning process to help ensure the plan has community support. Getting a diverse group of stakeholders to work together is challenging. Keys to successful stakeholder-led watershed planning included giving stakeholders full control of the plan's content, building relationships and trust, mutual understanding, good communication and a well-designed process. The process employed by the Bonne Femme Watershed Project can serve as a model for people in other areas who are interested in protecting water quality, sensitive habitats such as cave ecosystems and hydrologically vulnerable areas.

Cave and Karst Resources of the Bonne Femme Watershed

The Bonne Femme watershed, located in southern Boone County (Figure 1), has a rare combination of landscapes: former prairie, karst topography (e.g. caves, springs and sinkholes), woodlands and big river floodplain. Particularly noteworthy is the karst topography within the watershed. Within the watershed, this landform includes more than 35 caves , which provide habitat for rare, endangered and endemic species. It also includes losing stream hydrology, including two well-characterized, karst-recharge areas (Wicks et al. 1997, Lerch et al. 2005) that represent extremely

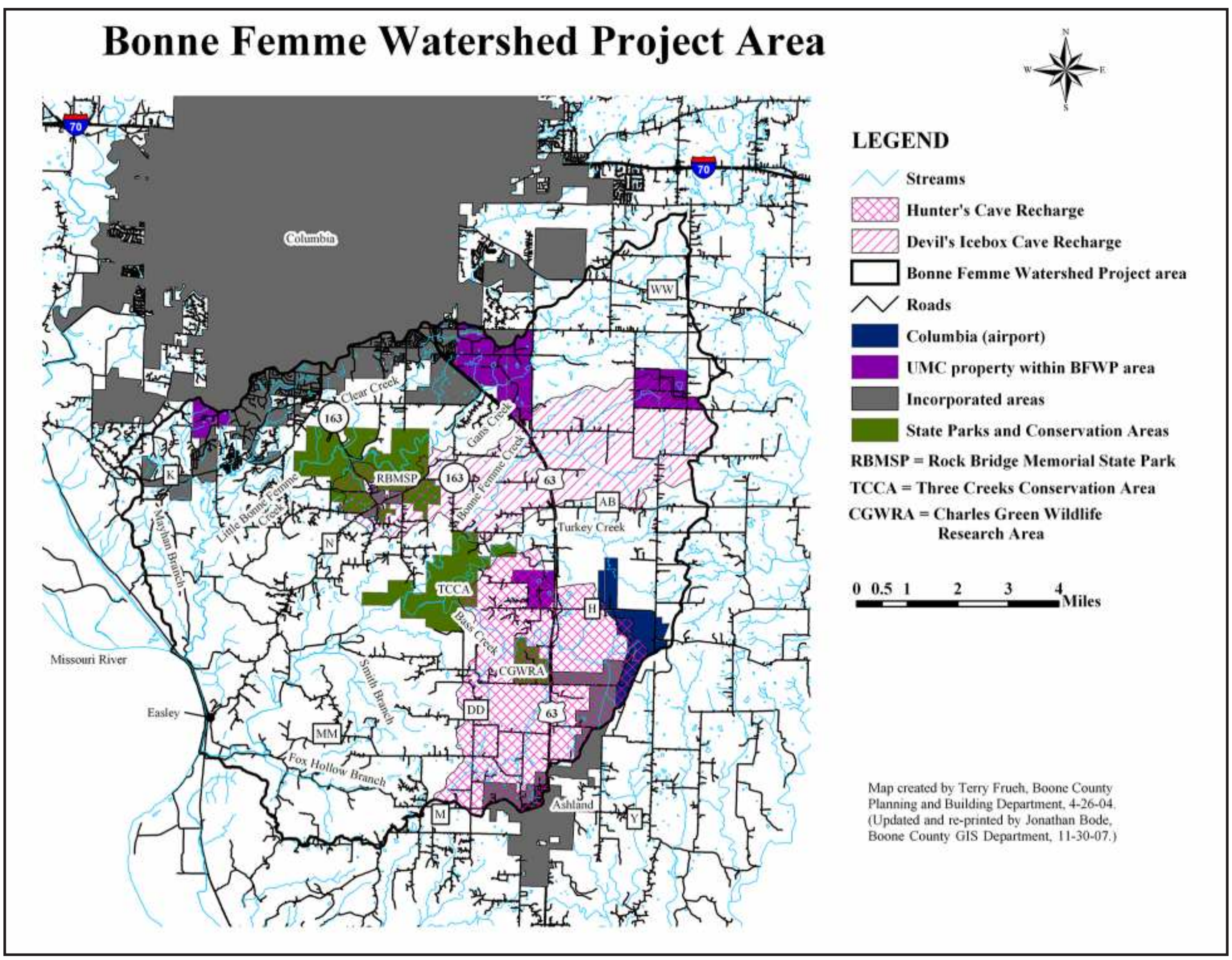

Figure 1. Bonne Femme Watershed Project Area.

vulnerable settings for contamination of groundwater resources. The Devils Icebox and Hunters Cave recharge areas are similar in size (~3,200 ha or 12 mi.^{2}) and land uses. Currently, both recharge areas predominantly include cropland, forest and grasslands, but urban areas are increasing around the cities of Ashland and Columbia. The population in the Bonne Femme watershed grew by 40% in the ten-year period between 1990 and 2000! Boone County's population is expected to grow at a rate of 2% annually through 2030, an increase of over 245,000 people. A key distinction between the two recharge areas is that the Devils Icebox recharge area includes both allogenic (i.e. losing stream) and autogenic (internally drained via sinkholes) recharge components while the Hunters Cave recharge area is mainly allogenic (Lerch et al. 2005).

The Devils Icebox Cave system, the seventh longest cave in Missouri with over 10.1 km (6.25 mi.) of mapped passage, currently ranks second in biodiversity among Missouris ~6,400 caves (Elliott 2007). Two federally listed, endangered bats use the cave, a maternal colony of gray bats and a hibernating group of Indiana bats. Found only in Devils Icebox Cave, the pink planarian (Figure 2) plays a role of both predator and prey in the cave ecosystem. Its numbers are being monitored using a protocol developed by Sutton (2004). Sutton (2004) collected an isopod in 2003 that was determined to be a new species of the genus *Caecidotea*. Both of these endemic stygobites are vulnerable to water quality and quantity changes that may occur because of land use in the Devils Icebox Cave recharge area.

Figure 2. An endemic stygobite, the pink planarian of Devils Icebox Cave is vulnerable to water quality degradation. Photo by William R. Elliott, Missouri Department of Conservation.

Background of the Bonne Femme Watershed Project

There has been a long history of public interest in the natural features of the watershed. The effort to create a park at Rock Bridge began in the 1960s, although it had been a semi-public area for more than a century. It culminated with the formation of Rock Bridge Memorial State Park in 1967. A similar effort to form Three Creeks Conservation Area began in the late 1980s.

Staff at Rock Bridge Memorial State Park initiated educational programs to encourage landowners to protect Devils Icebox Cave life and water quality. Efforts included a Devils Icebox Task Force in the 1970s, Wild Cave Tours from 1980 to the present and landowner outreach programs in the late 1990s. Collaboration began as staff of other agencies and organizations helped with the outreach programs. An EPA Clean Water Act (section 319), nonpoint-source-protection grant was awarded to Show-Me Clean Streams in 1998. Staff of the Natural Resource Conservation Service (NRCS) applied for and received funding through a Missouri Department of Natural Resources' Nonpoint Source Special Land Area Treatment (SALT) grant. The 319 grant was primarily educational while the SALT project provided cost-share assistance for implementation of agricultural conservation practices. Together, they formed the Bonne Femme Watershed Partnership that functioned from 1998 through 2002. The Partnership's focus was the entire Bonne Femme Watershed of 24,087 ha (93 mi.^{2}). It was beneficial to broaden the focus area beyond just the Devils Icebox Cave recharge area, because it drew in more partners and encompassed the caves and karst features of Three Creeks Conservation Area as well as several surface streams.

The Bonne Femme Watershed Partnership provided funding and demonstrations about subjects such as on-site sewage treatment, streambank stabilization, lawn care, fencing and wetland management, sponsored stream clean-ups and tree planting events, held an educational festival for over 350 local fifth and sixth grade students each year, and conducted other educational efforts such as newsletters and meetings. The result was that more people were aware of watershed issues and were involved in some way in watershed protection.

Scientific research added to our understanding of the condition of streams in the watershed and received media coverage, thereby increasing community awareness of the need to protect water quality in local streams. Show-Me Clean Steams collected EPT data (macroinvertebrates that inhabit streams) and correlated it with the amount of impervious land cover in each subwatershed, showing that impervious cover negatively impacted the biological health of the streams. Lerch et al. (2002 and 2005) conducted intensive water quality and hydrological studies of the Hunters Cave and Devils Icebox recharge areas. High levels of fecal bacteria were found in both cave systems and reports of these findings by local media caused concern regarding the safety of recreational activities associated with both streams, particularly of children playing in Devils Icebox Spring Branch in Rock Bridge Memorial State Park.

Some hoped that an educated citizenry aided by scientific research could influence local government and expect tools such as county-wide zoning to be used to protect streams. Others in the community were concerned about property rights and economic development. On numerous occasions, hotly contested debate arose during hearings held by local governments about proposed developments. Community interest and media attention was especially strong concerning the approximately 500-acre Philips Farm development that was situated in the Gans and Clear Creek watersheds upstream of Rock Bridge Memorial State Park. The Columbia City Council tried to reach an acceptable compromise by approving the development with extra protections for the streams. The need for more comprehensive land use planning to protect the watershed was now more apparent than ever.

In 2001, the Directors of the Missouri Departments of Natural Resources and Conservation appointed a technical group to investigate ways to protect the caves and streams in the Bonne Femme Watershed. This group, the Southern Boone County Karst Team, decided to pursue an EPA Clean Water Act 319 grant, to protect the streams from nonpoint source pollution and to develop a comprehensive land use plan. The 319 grant funded the Bonne Femme Watershed Project from 2003 through 2007. The project benefited greatly from the foundation laid by earlier work that resulted in education that heightened community awareness of watershed issues and in research that increased the community's understanding of the risks posed to water quality in this watershed.

Components and Function of the Bonne Femme Watershed Project

Purpose of Watershed Plan—

A stream's health is most affected by the use of the land in its watershed. Thus, in order to maintain the environmental quality of the watershed and its streams, land use and its management in the watershed must be addressed, preferably by means of a land use plan specifically designed to protect streams. A land use plan is a set of policies and guidelines for how land should be used and where growth should occur. Although there are master plans for Boone County and the City of Columbia, these were not designed with stream protection as a specific objective. To facilitate the plan's development, the Bonne Femme Watershed Project was organized into three committees: Steering, Policy and stakeholder.

Steering Committee—

Since most of the watershed is in Boone County's jurisdiction, the Karst Team invited county staff to participate on the team and asked the county commission to sponsor the 319 grant. In November 2001, the Boone County Commission formally applied for the grant, which was to be administered by its Planning and Building Inspection Department. The cities of Columbia and Ashland agreed to be listed as partners in the grant application. The grant was awarded in June, 2003, providing funding for a four-year period. After the grant was awarded, several members of the Southern Boone County Karst Team became the Project's Steering Committee. Members of the committee included representation from Boone County, Missouri Department of Natural Resources, Missouri Department of Conservation, Rock Bridge Memorial State Park and the USDA-Agricultural Research Service. An Urban Watershed Conservationist was hired in October 2003.

The Steering Committee directed the project and its staff. The Steering Committee provided scientific, technical and administrative assistance to coordinate the other two committees' work. In addition, this committee formulated the project mission statement: use watershed planning as a tool to prevent further water resources degradation in order to maintain their long-term quality within the Bonne Femme watershed.

Policy Committee—

One of the first tasks of the Steering Committee was to seek input and support from local political decision-makers. The decision-making agencies that affect the timing and location of development in the watershed were invited to designate a representative to serve on the Policy Committee. The Policy Committee consisted of the following agencies and entities: Boone County Commission, Boone County Planning and Zoning Commission, Boone County Regional Sewer District, Boone County Water District #9, City of Ashland, Columbia City Council, Columbia Planning and Zoning Commission, Consolidated Public Water Supply District #1 and the University of Missouri-Columbia,

This Committee performed several key functions throughout the life of the Project. They established the make-up of the stakeholder Committee and acted as liaisons with their agencies to educate and support project goals. Since the watershed lies in many different jurisdictions, interagency coordination was important to ensure that efforts were synergistic and not counterproductive, while providing interagency communication regarding actions or planned actions within the Bonne Femme Watershed. Members provided input on the legal and political feasibility of the watershed plan's recommendations. The role of these committee members will also be crucial in acquiring the needed community support as the plan moves through legal adoption and implementation.

Stakeholder Committee—

The process used to develop this plan is rare. Often, watershed planning is done by a group of technically trained government staff and the community responds during public hearings, or planning is done by a group of citizens with vested interests. In contrast, this plan combines good technical effort with strong input from a vested group representing a broad spectrum of community interests.

From the beginning of the project, the Steering Committee felt that strong community input was crucial to the plan's success. So, the Steering Committee delegated responsibility for development of the watershed plan to the Stakeholder Committee and in the process, it adopted a support role by providing education, technical advice and facilitation of stakeholder meetings. The Policy Committee aided the stakeholders by providing a political and legal perspective.

The Policy Committee followed three Steering Committee recommendations when choosing the stakeholders:

- Select some people who do not own watershed land, but have a vested interest in the watershed because of development, recreation, or environmental protection,
- Include diverse, even adversarial, interests to provide a necessary spectrum of ideas to be considered,
- Have a Stakeholder Committee of eighteen people, with three general groups represented: business/construction, environmental and landowner.

With such a makeup, the diverse interests were well represented and the Stakeholder Committee had the needed balance to complete a plan palatable to the community. Representing the business group were individuals from construction, development, real estate, engineering, banking and other businesses. The environmental group was represented by educators, recreators and local watershed and environmental organizations. The third group represented watershed landowners, including farmers and homeowners. It should be noted that people within the three general groups often had overlapping interests and thus it was somewhat artificial to place each stakeholder into a single interest "box." The stakeholders held their first meeting in June 2004 and continued to meet on a monthly basis until completion of the plan in February 2007. To reinforce their autonomy, the Steering Committee recommended that the stakeholders elect two co-chairs, who ran the meetings and decide amongst themselves how to organize their meetings and establish voting procedures to be followed. As the stakeholders moved through the planning process, several challenges surfaced. At the first few meetings, many of them held strong, seemingly uncompromising postures. However, over time, their postures softened so that people could still express strong opinions, but with a respect for others and a willingness to compromise. Although the stakeholders received guidance and feedback from the Steering and Policy Committees, they had the final say on the plan's content. This ensured that it was truly a product of citizen involvement and not one controlled by politicians or technical staff.

The watershed planning process involved these steps: (1) identify issues, (2) create a vision of the watershed in 2030, (3) transform the vision into achievable goals, (4) examine complimentary and conflicting aspects of the goals, (5) identify obstacles to achieving the goals, and (6) develop strategies and policy recommendations. For example, one goal developed was to "conserve recharge and karst areas with special protections." Strategies suggested for achieving this goal were to: (1) be more restrictive on the level of service scale when using stormwater manuals, (2) establish new zoning regulations, (3) devise a land purchase strategy, (4) utilize transfer of development rights and conservation easements, (5) provide tax relief incentives and (6) conduct further scientific study and water quality monitoring. The recommendations regarding this goal went into more detail and can be viewed on the project's Web site, www.CaveWatershed.org. Stakeholders decided it was appropriate to leave it to local governments to determine specifically how recommendations would be implemented.

Although the plan's focus is on protecting and preserving water quality, the stakeholders wanted to make sure this was accomplished while maintaining economic vitality and respecting community values. The plan provides policy recommendations that, if implemented, will achieve specific goals that enhance the Bonne Femme watershed while maintaining economic growth. Some stakeholders were motivated to protect streams because doing so can reduce the public and private economic cost of repairing infrastructure and flood damage and maintain ecological services.

Figure 3. Stakeholders sometimes broke out into small groups to discuss aspects of watershed planning.

Keys to Successful Stakeholder-led Watershed Planning

Although the plan has not been fully implemented, the fact that a diverse and divergent group of volunteer stakeholders stayed together to develop a plan is a great accomplishment (14 of the original 18 stakeholders worked through the entire process). One key to success was the organization of the project's committees. While it was more complicated and time-consuming to work with three different committees, each committee played an important role in the plan's successful development.

Good communication and coordination were essential to developing a community-based plan. For example, staff contacted each of the stakeholders periodically to ask for their feedback on the process and how it could be improved. Also, letting everyone know about upcoming deadlines well in advance and enforcing them enabled the process to proceed in a timely and fair manner. The diverse nature of the stakeholders allowed for a large variety of views to be considered. Having opposing viewpoints at the table from the beginning enabled them to be worked out during the process, instead of fighting over the finished product. The group's balanced nature ensured that the plan would not be skewed in any particular direction. The fact that it was completed by members of the community, who were chosen by the Policy Committee, ensured that the plan would have the needed political support for implementation.

Since the process was started by government, many of the stakeholders were initially either fearful or skeptical concerning the degree of autonomy they would have in developing the watershed plan. Some were afraid that eventual regulations would threaten their livelihood, reduce land values, or restrict property rights. Thus, gaining their trust in the process was a crucial element. Several steps helped to gain the stakeholders' trust in the watershed planning process and in project staff, such as:

- Giving them full control over plan content
- Encouraging open dialog
- Addressing contentious issues head-on
- Responding appropriately to criticism (e.g. thoughtfully addressing it, not getting defensive)
- Following through on commitments
- Providing useful, broad-based education related to science issues, future economic growth and examples of successful plans developed in other communities
- Realizing that plan recommendations still have to go through the public process of local political adoption before they can be implemented.

In the first year of meetings, progress seemed to languish at times, but this was a necessary part of the Stakeholder Committee's development that led to their cohesion as a group and eventual ownership of the process. Over time, they took responsibility for working through conflicting opinions and became increasingly focused on achieving specific outcomes from each meeting. This early phase of the process was very challenging and frustrating because the group wanted to accomplish its objectives, but to be effective, they first needed to create a respectful, positive, working atmosphere. Patience was definitely an important virtue as stakeholders and staff sometimes dealt with issues brought forward that seemed to sidetrack the committee from their work. Stakeholders listened to and dealt with these issues in a respectful, but efficient way that retained everyone's involvement. Over time, the members got to know and trust one another, resulting in more progress and a greater sense of satisfaction at the conclusion of their meetings.

An unintended benefit of the process lagging a little was that the stakeholders came to realize they were indeed in control of the plan, not the Steering Committee. Project staff had to walk a difficult line during the stakeholder process. It was important that the group work through problems without external influence, thus, staff had to remain impartial and detached. However, if the stakeholders got mired in minutiae or encountered irreconcilable issues, staff sometimes needed to step in to help direct the meeting towards a more productive path. At times, the Steering Committee sought the advice of Community Development Specialists from the University of Missouri extension office. These skilled facilitators offered valuable suggestions for how to keep the process moving forward.

As time went on, the stakeholders were increasingly willing to compromise for the sake of progress, in part because of friendships that formed. Alliances shifted at times, depending upon the subject. For example, agricultural interests seemed to align with development interests during many discussions, but when stakeholders considered exempting agriculture from certain restrictions, it was construction industry interests who opposed and environmentalists that went along with that aspect of the recommendation. The construction interests did not feel it was fair that they would have to pay or do extra, while agriculture would not. The issue was complicated because Missouri statutes exempt agriculture from many restrictions.

Several other aspects helped to make the planning process a success. At each stakeholder meeting, staff recapped where the stakeholders were in the process, what they were going to work on and what their next meeting would cover. This gave them an understanding of where they were in the process and a sense that they were continually making progress. It was important to have educational presentations to help the stakeholders make informed decisions. The stakeholders also gave some of these presentations, which furthered their ownership of the plan. However, the need for educational presentations had to be balanced with the need for achieving tangible accomplishments at every meeting.

A key philosophy throughout the life of the project was respectful engagement. The stakeholders were strongly encouraged to avoid combative postures or belittling of members with opposing viewpoints. Conversely, conflict avoidance was also strongly discouraged. Instead, the goal was for stakeholders to feel comfortable in voicing their opposition in respectful terms and to focus on finding solutions or acceptable compromises. An important outcome of respectful engagement was that the stakeholders developed their own guiding principle—economic development could occur in an environmentally friendly manner.

It was helpful that the project staff person was officially employed by the Boone County Planning and Building Inspection Department. This enabled him to have the benefit of his colleagues' experience with local builders and developers, learn about legal and practical questions and use county office space and equipment. It is also possible some stakeholders were more willing to trust a local governmental official than a state or federal official. Finally, being formally employed by the local government ensured that other Boone County staff were aware of the stakeholders' progress, which facilitated communications with other local governmental officials. The project was fortunate to have a watershed conservationist who was very well qualified in terms of technical knowledge, interpersonal skills and dedication.

Including the policy-makers from the beginning ensured that they would be well educated about the plan and also have a sense of ownership. Citizens sometimes write policy guidance, and then take it to the policy makers for their approval without their having been included in the process. Conversely, too often governments draw up policies and take it to the citizens for public vetting. Either way, one party is not included in the process, does not have ownership of the end product and is merely being asked to react to a proposal. This too often results in misunderstanding, distrust and emotional reactions rather than objective consideration of a plan's merits. In contrast, our planning process attempted to include both the community and its politicians from the beginning so that it would be adequately discussed as they went through the process.

To keep the public engaged as well as garner community interest and support, the Steering Committee developed several community outreach programs, including two public debates. These were well attended by the public (about 150 in attendance) and by the stakeholders. Local media reports were very positive and involved both TV and newspaper. People in the community genuinely appreciated the opportunity to hear local experts, from both sides of the development debate, deal openly and head-on with differences of opinion in a respectful manner. Thoughtful selection of the debaters and moderators, establishing strict rules, such as time limits for responses and rebuttals and carefully considered questions were crucial to the success of these debates. In addition, seminars and workshops were provided for engineers and developers, bringing in speakers from other cities, who explained the feasibility of using innovative best management practices and the economic viability of low-impact development strategies.

Intergovernmental cooperation on plan implementation is paramount to protecting streams since they cross jurisdictional boundaries. Simply having representatives of each local government entity sitting at a table together, sharing and discussing watershed issues was a huge step forward. The participation of policy committee members created a sense of ownership that resulted in the presence of at least one supporter among each local government entity. But intergovernmental cooperation did not stop there. The Project, with the help of Boone County, hosted a joint Planning and Zoning meeting among Ashland, Columbia and Boone County. This meeting was the first time all three of these Planning and Zoning Committees had ever jointly met, resulting in further intergovernmental cooperation. In addition, a joint resolution among the local governments was drafted which formalized the process of governmental coordination in implementing the watershed plan.

The Steering Committee members also worked well together, which was essential to their successfully managing project staff and adjusting to situations as they arose. Members of this committee provided technical expertise in a variety of scientific disciplines (such as hydrology, conservation and wildlife biology, watershed management and public land administration) and possessed practical experience in dealing with local politicians, developers and grass-roots organizations. Brainstorming sessions were freewheeling, thereby producing a positive environment for creative thinking and problem solving.

Several external aspects synergistically helped the stakeholders' planning effort. Local governments were mandated by the federal government to implement stormwater regulations. There was a joint Boone County-Columbia citizen task force that was working on improving stormwater management. Several stakeholders were also involved with this task force and the two groups had many similar recommendations. The Community Stormwater Education Project further helped to raise public awareness of these issues.

Ultimately, the stakeholders were the ones who accomplished the task of creating a positive working environment that enabled them to craft an excellent plan. The Project was fortunate to have a group of dedicated individuals who were willing to put in long hours and work hard to find common ground. Even the best-designed organizational approach can collapse without people willing to put in the needed effort. Most likely, the request to serve by a local politician enhanced the stakeholders' perception that their task was important, would have a positive impact on their community and sustained them through the challenges they faced in developing the watershed plan.

Room for Improvement

In retrospect, the biggest mistake that staff made was not having a clear road map for how the stakeholders would complete the process. Staff thought that the stakeholders would take full charge of the form of the plan as well as its content. However, since they did not initiate the process, the stakeholders needed a clear outline for the plan. After several months "spinning their wheels" and wondering where they were headed, the Steering Committee developed a clear outline for the stakeholders to follow. This provided them with a clear structure for the plan process, while leaving them the responsibility to fill in its content.

Public Comment and Plan Addendum

After completion of the plan, an open house was held in early March 2007 in which the plan was introduced to the public, followed by a seven-week public comment period. During this period, staff gave educational presentations about the plan to various interest groups and held a series of public meetings. There were public notifications in local newspapers, press releases and numerous media articles covering the plan. In addition, notification of the public comment period was mailed to all watershed landowners. Although this was an unprecedented effort to gather public comments about the plan, only four comments were submitted—perhaps an indication that the plan was well received by the community. These comments were forwarded to the stakeholders for their response. Both the public comments and stakeholder responses were incorporated into a plan addendum. On June 1, 2007, the plan and its addendum were sent to local agencies for adoption and implementation.

Adoption and Implementation: Next Steps for the Watershed Plan

As of November 16, 2007, several local governments and entities have adopted the plan. The primary governing body of the watershed, the Boone County Commission, adopted the plan by resolution on November 13, 2007. Actions that led up to this decision included a unanimous recommendation from the Boone County Planning and Zoning Commission and endorsement by the Boone County Regional Sewer District board. The Board of Aldermen for the City of Ashland unanimously adopted the plan by resolution. The Columbia City Council held a work session on the plan and later referred it to their Planning and Zoning Commission for further public hearings. Columbia's Planning and Zoning Commission unanimously recommended adoption of the plan to the City Council. The City of Columbia has not yet voted on adoption of the Bonne Femme Watershed Plan, but the support of its Planning and Zoning Committee bodes well for its eventual adoption.

Plan adoption is a very important step, but implementation is where "the rubber meets the road." The watershed plan provides guidance, but the details of new ordinances and programs will be determined during the implementation stage. These details are crucial to the effectiveness of any recommendations implemented. Stakeholders felt strongly that enforcement, maintenance and evaluation will be essential to the success of any measures implemented. To help local governments with the implementation stage, the Steering Committee intends to host a facilitated implementation workshop. The Policy Committee has also discussed using some of the remaining cost-share funds to hire a consultant to create new ordinances and zoning regulations, delineate karst areas and 100-year flood plains and develop needed programs to implement the plan's recommendations. These funds will help governments by offsetting the costs of having existing staff develop details of the plan's implementation. Using Project funds to help move the plan forward also shows respect for the stakeholders' hard work in crafting it. Continued involvement by stakeholders through building community support and speaking at public hearings will be important for making sure the plan gets implemented. In addition, stakeholders will hold local governments accountable by asking for annual reports on their progress.

Conclusion

Successful watershed planning is essential to protection of surface and groundwater quality and aquatic ecosystems, but it is also essential to achieve planned growth that meets the economic and quality of life goals of a community. Development of a watershed plan that is likely to be adopted by a community and its local governments is a daunting task that requires organizational skills, forethought and the dedication of those involved in the process. The approach taken by the Bonne Femme Watershed Project appears, so far, to be successful, based on the level of community and political support for the watershed plan. The project placed the task of watershed planning squarely and fully in the hands of stakeholders who represented the diverse interests of business, environmentalists and landowners. It was challenging for this diverse group to work together through a long and difficult process, but they managed to produce a quality plan. They were supported by a Steering Committee that provided technical and organizational expertise and a Policy Committee with a vested interest in their success. Educational outreach and scientific research laid the foundation for this successful process. Keys to success of this stakeholder-led watershed planning effort included: the organizational structure of the project as a whole, representation of diverse stakeholder interests, willingness to employ respectful engagement in dealing with contentious issues, dedication to reaching compromise, Policy Committee selection of the stakeholders, interest in the outcome among local governments and politicians, giving full control of the planning process to the stakeholders, providing an outline to serve as a "road map" for staying on task, providing progress reports, adherence to deadlines, fostering trust and respect in all three committees, building relationships, patience and dedication. This stakeholder-led watershed planning process and these keys to success can be implemented in any watershed, to the benefit of the watershed's aquatic resources.

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HYDROGEOLOGICAL CHARACTERISTICS OF DELINEATED RECHARGE AREAS FOR 40 BIOLOGICALLY SIGNIFICANT CAVE AND SPRING SYSTEMS IN MISSOURI, ARKANSAS, OKLAHOMA, AND ILLINOIS

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Abstract

This paper summarizes the results from recharge-area delineations of cave and spring systems providing habitat for federally, listed threatened and endangered aquatic species in Missouri, Arkansas, Oklahoma, and Illinois. These include 24 sites for the Ozark Cavefish (*Amblyopsis rosae*), the only known site for the Tumbling Creek cavesnail (*Antrobia culveri*), four sites for the Benton Cave crayfish (*Cambarus aculabrum*), one site for the Hell Creek Cave crayfish (*Cambarus zophonastes*), seven sites for the Illinois Cave amphipod (*Gammarus acherondytes*), and three known or potential sites for Hine's emerald dragonfly (*Somatochlora hineana*).

Epikarstic zones known or presumed to provide habitat for Ozark cavefish populations are associated with 79% of the delineated cavefish sites, all of the Benton Cave crayfish sites, and the only known site for the Tumbling Creek cavesnail. All of the studied fens providing known or potential habitat for Hine's emerald dragonfly receive their groundwater supplies from the epikarstic zone rather than deeper groundwater systems.

Seventy-five percent or more of the lands in the recharge areas for the Tumbling Creek Cavesnail, the Illinois Cave Amphipod, the Hell Creek Cave Crayfish, and the Grotto Sculpin are ranked as having High or Extremely High Vulnerability to groundwater pollution. For the 36 sites with one or more of the federally listed cave species, only 7 (19%) are ranked as being highly defensible over the next 30 years.

The delineated recharge areas for the aforementioned species encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. Lands encumbered by right-of-ways for county, state, and federal roads in these recharge areas are estimated to almost equal the amount of land owned by conservation agencies, not-for-profit conservation entities, or that are included in conservation easements.

Key words: hydrogeology, karst recharge areas, cave biology, Missouri, Arkansas, Oklahoma, Illinois, contaminants

Introduction

The recharge area for a cave or spring is the land area that contributes water to the feature. During the past 30 years the Ozark Underground Laboratory has used groundwater tracing and other hydrogeologic data to delineate recharge areas for a large number of significant cave and spring systems. Included in these delineations were the recharge areas for 40 biologically significant cave and spring systems in Missouri, Arkansas, Oklahoma, and Illinois that provide habitat for at least one federally-listed endangered or threatened aquatic species. Several of these sites also provide habitat for one or more other species of conservation concern.

Federally-listed threatened and endangered species for which we have delineated recharge areas include 24 sites for the Ozark cavefish (*Amblyopsis rosae*), the only known site for the Tumbling Creek cavesnail (*Antrobia culveri*), four sites for the Benton Cave crayfish (*Cambarus aculabrum*), one site for the Hell Creek Cave crayfish (*Cambarus zophonastes*), seven sites for the Illinois Cave Amphipod (*Gammarus acherondytes*), and three known or potential sites for Hine's emerald dragonfly (*Somatochlora hineana*). Six other recharge areas have been delineated for other species of conservation concern; these have included one site in Missouri for the Spring cavefish (*Forbesichthys agassizi)* and five other biologically significant cave systems providing habitat for other cavefish or cave crayfish. Finally, recharge area delineation work is underway for five sites for the Grotto Sculpin (*Cottus* sp., similar to *C. carolinae*). This fish is distinctly different from surface-dwelling sculpins and is found only in cave systems in Perry County, Missouri.

This paper has two major objectives. First, to summarize data developed as a part of the recharge area delineations. The delineation studies have been reported in contract reports, but little of this information has reached the technical literature prior to this paper. The second objective is to illustrate the scale of the challenges that must be overcome if groundwater quality is to be protected in these recharge areas and loss of individual populations and extinctions are to be prevented.

Over 430 groundwater traces have been conducted in delineating these recharge areas and this tracing work is continuing with major projects underway in Perry County, Missouri and southwestern Illinois.

Several cavefish populations have been heavily collected in the past for purposes of limited scientific value or for public or private display purposes. Most of the studied sites are on private property and, in some cases, information on the locations of the sites is restricted at the request of property owners or others concerned with the protection of the populations. As a result we will identify most sites based only on the county in which they are located and will not routinely provide site or owner names in this paper. Where sites are protected well we will identify them in the discussions as appropriate. We believe this approach will provide land managers and scientists the information they need while maximizing protection of the populations and honoring property owner requests.

Geologic Settings

All of the sites for the Ozark cavefish are in Mississippian age limestone units. These include the Burlington and Keokuk Limestones in Missouri, the similar Boone Formation of Arkansas and Oklahoma, and the St. Joe Limestone of Arkansas that has sometimes been mapped as a unit of the Boone Formation. In much of the area where the Ozark cavefish populations occur the Mississippian age units are separated from underlying Ordovician dolomites by shale units including the Northview Formation and the Chattanooga Shale. It is possible that the existence of these shales explain the absence of Ozark cavefish in the Ordovician units.

The only known site for the Tumbling Creek cavesnail is within the Cotter Formation of Ordovician age.

The entrance to Hell Creek Cave, the only studied site for the Hell Creek Cave crayfish, is in the lower portions of the Ordovician Plattin Limestone. In or near this cave there are numerous karst features within the underlying Joachim Dolomite and in the overlying Plattin, Kimmswick, and Fernvale Limestones. A second site for the Hell Creek Cave crayfish is now known, but the authors of this paper do not know its precise geologic setting.

All of the Benton Cave crayfish sites are within the Boone Formation and the underlying St. Joe Limestone. One of the Benton Cave crayfish sites also provides habitat for Ozark cavefish.

The Spring cavefish population is located in the Plattin Limestone.

The Hine's emerald dragonfly sites are calcareous fens fed by small springs discharging from the epikarstic zone of dolomitic bedrock.

The Illinois Cave amphipod is found in caves formed in the St. Louis Limestone.

The Grotto Sculpin populations in Perry

County, Missouri are restricted to cave streams in the Joachim Dolomite.

Role of the Epikarstic Zone

The epikarst (or epikarstic zone) is the weathered, upper part of calcareous bedrock units. Common thicknesses of the epikarstic zone are about 10 meters (33 feet) (Ford and Williams 1989), but this value is highly variable and ranges from nearly 0 to 100 m (328 ft.) (Aley 1997). The extent and nature of epikarstic development varies substantially among geologic units. Unsaturated epikarstic development often can be seen in road cuts and quarry faces, but these exposures give only limited insight into the extent, nature, and thickness of the seasonally or perennially saturated epikarstic zones lying adjacent to or beneath valleys. It is these valley-associated epikarstic zones that provide habitat for some of the species discussed in this paper.

Williams (2003) estimates that about 80% of all carbonate dissolution occurs within the upper 10 m (33 ft.) or so of the top of the carbonate bedrock. This extensive and localized solution can produce intensive epikarstic development. The intensity of epikarstic development can be expressed as a percent of the bedrock that has been removed by solution. It can range from less than 1% to more than 50% (Aley 1997). In many epikarstic zones sediments partially or almost completely fill most or all of the voids within the bedrock; in other cases many of the voids are largely free of sediment.

Epikarstic zones with "likely habitat" known or presumably habitable for Ozark cavefish populations are associated with 79% of the delineated cavefish sites, all of the Benton Cave crayfish sites, and at the only known site for the Tumbling Creek cavesnail.

Dye tracing and specific-conductance monitoring has been conducted of springs in the studied fens providing "likely habitat" for Hine's emerald dragonfly. Specific conductance measurements vary dramatically over relatively short periods of time, and dye concentrations from groundwater traces can vary substantially at springs located relatively close together within a particular fen. These findings, plus rapid groundwater travel rates, demonstrate that groundwater for the fens is derived from the epikarstic zone rather than deeper groundwater sources.

Four of the Ozark Cavefish sites are hand-dug wells in which cavefish were sometimes or routinely sighted; one of these sites has two dug wells in which cavefish have been seen. All of the hand-dug wells bottom in the epikarstic zone. These sites are located in Greene, Newton, and Lawrence Counties, Missouri and in Benton County, Arkansas. Most of the hand-dug wells were constructed at points where groundwater initially discharged to the surface during wet periods of the year. In one case a backhoe was used to excavate a spring discharging into a small perennial stream. The backhoe excavated a trench about 30 m (100 ft.) long extending from the bank of the stream to a point where water was rising through a solutionally widened joint in the limestone bedrock. The landowner reported that several cavefish were excavated during the construction of this trench.

Epikarstic development in the Mississippian age limestones commonly yields cutters and pinnacles (Fellows, 1965). The openings resulting from bedrock solution produce a grid-work maze of preferential solutional openings along joints plus interconnecting openings along bedding planes. Fellows (1965) notes that networks of cutters in the Burlington Limestone of Greene County, Missouri, form dendritic patterns. One important cavefish site in Delaware County, Oklahoma, includes small caves in the epikarst that are large enough for a person to enter for short distances. These caves clearly illustrate a grid-work maze of openings. Insufficient bedrock exposures exist in this area to clearly determine if there is a dendritic pattern.

Most of the epikarstic zone sites are located on or near the floor of perennial stream valleys, but there are important exceptions. One of the hand-dug wells providing Ozark Cavefish habitat is on the bank of a small stream that drains a surface area of about 162 ha (400 ac). This site is located about 2.87 km (9,400 ft.) from the nearest stream with perennial flow; this stream is created by the spring that discharges water that passes through the bottom of the hand-dug well. This spring is also a known cavefish site.

Important portions of many Ozark cavefish sites are within the epikarstic zone beneath perennial streams and some intermittent streams. The flow of water through such epikarstic systems is complex and varies with time. Unlike the case with a single karst conduit, pollutants unevenly impact epikarstic zones. This has been demonstrated by dye traces through the epikarstic zone where dye concentrations at different sampling points in the epikarstic zone can vary by two or more orders of magnitude. Even if aquatic life kills do occur from a pollutant following particular flow routes through an epikarstic zone, there are adjacent areas where the pollutant concentrations are lower or even non-existent. These areas can help re-populate affected portions of the epikarstic zone. As a result, aquatic fauna sites that include epikarstic zones are likely to be less subject to acute aquatic life kills that destroy much or most of the fauna than are sites lacking epikarstic zones. Sket et al. (2003) discuss the role of the epikarstic zone in dispersion of biota and the vulnerability of this zone to pollution, although most of the focus in their paper is on epikarst located beneath features other than valleys.

Size of Recharge Areas

Table 1 summarizes the size of delineated recharge areas for federally listed species in our study region. As noted earlier, two of the three Hine's emerald dragonfly sites represent potential habitat rather than known habitat. One site provides habitat for both the Ozark Cavefish and the Benton Cave Crayfish.

We have also delineated one Missouri site for the Spring cavefish (*Forbesichthys agassizi*). The size of this recharge area is 60.3 ha (0.23 mi.^{2}). We are currently delineating the recharge areas for five populations of the Grotto Sculpin.

Interestingly, the mean size of recharge areas for listed, aquatic cave species is typically in the range of 15.5 to 25.9 km^2 (6 to 10 mi.^{2}). With only two exceptions these recharge areas are within Mississippian age limestones where springs with mean annual discharge rates of more than 0.11 m^3/sec. (4 ft^3/sec.) are uncommon. One should not presume that recharge areas of such size are typical for all aquatic cave species in the study region. For example, there are several known populations of the Southern cavefish (*Typhlichthys subterraneus*) found in the recharge area for Big Spring, Carter County, Missouri. The recharge area for this spring is approximately 2,505 km^2 (967 mi.^{2})(Aley and Creath 1989), and this is the largest spring in Missouri.

Sinkholes and Losing Streams

Except for Fantastic Caverns, Greene County, Missouri, all of the delineated recharge areas for populations of Ozark cavefish contain very few sinkholes and a number of the recharge areas have no sinkholes large enough to appear on 7.5-minute topographic quadrangles published by the U.S. Geological Survey. Sinkholes also are absent or minor in recharge areas for the Tumbling Creek cavesnail, Benton Cave crayfish, and Hell Creek Cave crayfish. None of the delineated recharge areas for fens providing likely habitat for Hine's emerald dragonfly contained sinkholes. Much of the discrete groundwater recharge in these areas occurs in losing-stream segments of the surface stream valleys. In contrast, recharge areas for populations of the Illinois Cave amphipod and the Grotto sculpin are sinkhole plains where losing streams are limited and often rare.

Table 1 Size of delineated recharge areas for listed species.

Species	Number of Sites	Max. Size m^2 (mi.^{2})	Min. Size km^2 (mi.^{2})	Mean Size km^2 (mi.^{2})
Ozark Cavefish	24	103.86 (40.10)	0.31 (0.12)	22.87 (8.83)
Tumbling Creek Cavesnail	1			23.36 (9.02)
Benton Cave Crayfish	4	49.25 (19.17)	8.96 (3.46)	24.48 (9.45)
Hell Creek Cave Crayfish	1			12.10 (4.67)
Illinois Cave Amphipod	7	19.97 (7.71)	5.41 (2.09)	15.57 (6.01)
Hine's Emerald Dragonfly	3	1.27 (0.49)	0.08 (0.03)	0.49 (0.19)

Protecting water quality entering karst groundwater systems through sinkholes and losing streams poses very different challenges. While sinkholes are notorious sites for trash dumps and dead animal disposal, these problems are typically confined to very localized areas with relatively few landowners associated with each sinkhole (except when sinkhole areas are urbanized). In contrast, some of the losing-stream segments contributing flow to important cave faunas drain hundreds to thousands of hectares and water quality is impacted by numerous property owners who may be located several kilometers away from the habitats that their land use activities are affecting. For example, sewage effluent from the town of Jay, Oklahoma and its local industries is discharged to a losing-stream tributary to Muskrat Creek where it sinks and ultimately flows through Star Cave and associated springs and epikarstic features 4.58 km (15,000 ft.) or more from the sinking point.

Shared Recharge Areas

A shared recharge area is one that, under at least some conditions, contributes recharge water to two or more springs. Fifty-eight percent of the Ozark cavefish sites share some (but seldom all) of their recharge areas with at least one other spring. In the case of Fantastic Caverns there are eight springs that share recharge areas with the stream that flows through this cave. All of the known population sites for the Tumbling Creek cavesnail and the Benton Cave crayfish have shared recharge areas; there are no known shared recharge areas for the Hell Creek Cave crayfish. Seventy-one percent of the Illinois Cave amphipod sites share some of their recharge areas with at least one other spring. Springs feeding the three fens providing known or potential habitat for Hine's emerald dragonfly also have portions of their recharge areas shared with other springs.

In many cases the springs that share recharge areas with listed-species sites are not known to provide habitat for these species. They are clearly springs that warrant detailed investigation to determine if they may provide previously unknown habitat for the listed species. In our delineation work we have focused substantial effort on identifying springs and caves that share recharge areas with sites that are the focus of our investigations.

Discharge to Multiple Springs

Some of the caves for which we have delineated recharge areas are located hundreds to thousands of meters from their associated springs. The most spectacular example of discharge to multiple springs is Tumbling Creek Cave, which discharges from a single spring under extreme low-flow conditions, but discharges from 15 to 20 separate springs under high-flow conditions. These springs are located along a 730-m (2,400-ft.) segment of Big Creek and an 855-m (2,800-ft.) segment of Bear Cave Hollow, a surface tributary to Big Creek. All but one of these springs (the highest elevation spring) discharges from an epikarstic zone capped by a massive chert unit typically 0.9 to 1.5 m (3 to 5 ft.) thick. Most of the springs are about a 1.6 km (1.0 mi.) from portions of the cave where cavesnails are routinely found.

Where a cave discharges to multiple springs it often occurs that some or all of those springs are located in the channel of a surface stream where the springs are concealed by the overlying waters, alluvium or both. In this situation it is difficult to determine exactly how many springs may be involved and in some cases whether or not multiple springs are involved. Our data indicate that at least 10% of the caves providing habitat for listed species discharge waters to multiple springs.

Groundwater Travel Rates and Distances

Travel rates for waters moving into and through the groundwater systems providing "likely habitat" are routinely in the range of hundreds to thousands of meters per day. Travel rates are typically greatest under storm-flow conditions and slowest under low-flow conditions when there has not been significant precipitation for a week or longer.

One of the most rapid, documented, groundwater travel rates was a trace conducted under storm-flow conditions from a losing-stream segment on Pelham Creek to the bridge in Tumbling Creek Cave. The straight-line travel distance for this trace was 3.81 km (12,500 ft.), and first dye arrival in the cave occurred within 14.5 hours of the time of dye introduction. This represented a travel rate for the first arrival of dye in the cave of at least 6.3 km/day (3.9 mi./day).

Hine's emerald dragonfly habitats that we studied are calcareous fens, which are a unique type of wetland. The water supplies for the three studied fens and four others investigated less intensively are small springs (rather than seeps) with flow rates typically in the range of less than 3.8 to 38 L/min. (1 to 10 gal./min.). There commonly are multiple springs in a particular fen and flow rates plus water quality parameters such as specific conductance typically vary substantially among the springs and through time. The data for the studied fens shows that water quality and source areas for the springs in a fen are generally different from one another. Dye-tracing work has shown that some of the springs in a particular fen share portions of their recharge areas with other springs.

One of the groundwater traces conducted to a fen in Madison County, Missouri, was from a losing-stream segment in a topographic basin separate from, but adjacent to, the fen. The dye was detected in two of the five springs in the fen. The straight-line travel distances from the losing-stream segment to the springs were 506 and 541 m (1,660 and 1,775 ft.) respectively, and groundwater travel times for the first arrival of the dyes were between 12 and 19 days for the trace to the nearer spring and 5 to 12 days for the trace to the more distant spring. Mean travel velocities under these flow conditions were thus > 27.4 m/day (90 ft./day) for the trace to the nearer spring and > 43.3 m/day (142 ft./day) for the trace to the more distant spring.

The recovery plan for Hine's Emerald Dragonfly (U.S. Fish and Wildlife Service 2001) recognizes the importance of groundwater quality to the species, but is silent on the nature of the groundwater flow systems. Some aquifers are reasonably homogeneous and isotropic and can credibly be modeled with conventional groundwater-modeling approaches. In such aquifers flow rates are commonly in the general range of 1 to 10 m/yr. (3.3 to 33 ft./yr.). Epikarstic aquifers are neither homogeneous nor isotropic. In a group of studied epikarstic aquifers mean groundwater flow rates for first arrival of tracer dyes varied from 6.7 m/day (22 ft./day) for perennially saturated epikarstic zones to 60 m/day (197 ft./day) for seasonally saturated zones (Aley 1997). The data from Aley (1997) are based upon 70 traces in epikarstic zones. The Madison County, Missouri, trace from a sinking stream to two springs in a fen clearly demonstrates that an epikarstic aquifer is feeding these springs. While our experience with fens providing known or potential habitat for Hine's Emerald Dragonfly is limited, it indicates that epikarstic aquifers are sometimes (and perhaps commonly) the aquifers supplying water to fens. The role of epikarstic aquifers in supplying water to fens cannot be properly assessed without using groundwater tracing methods.

The distinction between epikarstic aquifers and reasonably homogeneous and isotropic aquifers has important management implications beyond the dramatic differences in groundwater travel rates. Epikarstic aquifers provide far less natural cleansing of waters passing through them than is the case for reasonably homogeneous and isotropic aquifers. As a result, water quality in a fen supplied by an epikarstic aquifer is far more vulnerable to the introduction and transport of contaminants than is a reasonably homogeneous and isotropic aquifer. If one presumes that the aquifer supplying a fen is reasonably homogeneous and isotropic when it is actually an epikarstic aquifer, then strategies for water quality protection are likely to be grossly inadequate, and the area capable of directly impacting water quality in the fen is likely to be substantially under-estimated.

Unlike the Missouri sites, many of the fens providing habitat for Hine's Emerald Dragonfly are in areas glaciated during the Pleistocene. It is sometimes presumed that epikarstic development in glaciated areas is insignificant. While epikarstic zones in recently glaciated areas may be thinner than in unglaciated regions, preferential solution of the bedrock and the development of integrated groundwater flow routes can still provide for hydrologically significant lateral water transport. Much of the data in Aley (1997) is from glaciated limestone and dolomite areas.

Vulnerability Mapping

We have conducted vulnerability mapping for most of the recharge areas delineated during the last 25 years. Vulnerability mapping is designed as an aid for land management decisions and is based on hydrogeologic settings with attention to current and likely near-term land uses. Vulnerability mapping is a qualitative assessment of how vulnerable particular portions of a recharge area are to the introduction and transport of pollutants that could impact known habitats for listed species. Areas where inputs of water into the groundwater system are highly localized (such as losing-stream segments and sinkholes) have greater vulnerability than lands where the water inputs are more dispersed (such as uplands and hillslopes). Areas closer to the habitat sites have greater vulnerability than lands that are more remote. Losing-stream valley segments downstream of major highways or railroads where catastrophic spills could occur have higher vulnerability rankings than lands that would not be affected by such disasters. Urbanizing areas have higher vulnerability rankings than lands that are maintaining their rural characteristics.

We have typically used three, occasionally four, vulnerability classes. They are routinely High, Moderate, and Low Vulnerability lands. In a few cases we have expanded the classes to include an Extremely High Vulnerability category. The nature of the landscapes and the existing and near-future land uses are such that not all recharge areas have all vulnerability classes. Many recharge areas have no identified Low or Extremely High Vulnerability lands. The standard descriptions we have used for the four vulnerability classes are as follows:

1. Low Vulnerability Lands. These are lands where the hydrogeological setting and existing and anticipated land uses pose low risks of groundwater impacts likely to adversely affect species of conservation concern or associated biological communities. These are often upland areas remote from sinkholes or losing streams where land use does not include hazards such as urban or suburban development or confined animal feeding operations (known as CAFOs, which include commercial poultry operations).

2. Moderate Vulnerability Lands. As above, but land uses pose moderate risks of groundwater impacts.

3. High Vulnerability Lands. There are high risks of groundwater impacts. Examples of high risks are losing-stream segments downstream of a major highway, waste-disposal facilities, and losing-stream valleys in which land application of animal wastes from CAFOs is, or might become, common.

4. Extremely High Vulnerability Lands. As above, but these lands appear to have extremely high risks of groundwater impacts. Land uses and very close proximity to critical habitat areas are factors.

Table 2 summarizes vulnerability mapping of recharge areas for sites providing habitat for one or more of the listed species. The table makes it clear that most of the recharge areas for the species studied currently pose significant threats to water quality at the habitat sites. Seventy five percent or more of the lands in the recharge areas for the Tumbling Creek Cavesnail, Illinois Cave Amphipod, Hell Creek Cave Crayfish, and Grotto Sculpin are ranked as having High or Extremely High Vulnerability. Only the Ozark Cavefish and fens providing known or potential habitat for Hine's Emerald Dragonfly had less than 50% of their recharge areas in High or Extremely High Vulnerability classes. Vulnerability mapping was not conducted for the Spring Cavefish site.

Table 2 *Results of vulnerability mapping of recharge areas for sites providing habitat for federally listed threatened and endangered species and one other species of conservation concern. See text for descriptions of vulnerability classes.*

Species	High or Extremely High	Moderate	Low	Number of Studied Sites
Ozark Cavefish	46	46	8	24
Tumbling Creek Cavesnail	83	17	0	1
Benton Cave Crayfish	57	42	1	4
Hell Creek Cave Crayfish	75	25	0	1
Illinois Cave Amphipod	93	7	0	7
Grotto Sculpin	91*	9*	0	5
Hine's Emerald Dragonfly	13	87	0	3

* Estimated; delineation and mapping in progress.

Localized Land Use Impacts

Localized land use activities likely to create significant, adverse impacts in delineated recharge areas were located by field reconnaissance and aerial photography. Activities mapped include: (a) agricultural and forestry, (b) sewage disposal facilities or concentrated housing served by on-site sewage systems, (c) landfills, dumps, and salvage yards, (d) industrial sites, (e) transportation routes, including pipelines, (f) petroleum storage sites, (g) other chemical storage sites, (h) other types of sites or facilities.

The extent and diversity of land uses that can impact aquatic fauna is frankly amazing and will be summarized for six species.

Ozark Cavefish Sites

The 24 delineated recharge areas for the Ozark Cavefish in Missouri, Arkansas, and Oklahoma incorporate a total of 548.8 km^2 (211.9 $mi.^2$). Numerous federal, state, and county highways cross these lands, including a segment of Interstate 540 in Arkansas and 16.5 km (10.25 mi.) of Interstate 44 west of Springfield, Missouri. This segment of Interstate 44 crosses the recharge area for four known cavefish populations. About 18.2 km (11.3 mi.) of heavily-used rail lines and 9.0 km (5.6 mi.) of petroleum pipelines also cross Ozark Cavefish recharge areas. A pipeline transporting ammonium nitrate and urea fertilizer crossed recharge areas for Ozark Cavefish populations in Oklahoma and Missouri, but is no longer used for liquid transport. While the pipeline was being used for liquid fertilizer transport a major break occurred in 1981 (Vandike 1985). This break resulted in a massive kill of aquatic life at Maramec Spring 20.6 km (12.8 mi.) from the spill site. The dead aquatic life discharged from the spring included Southern Cavefish, Salem cave crayfish (*Cambarus hubrichti*), and Grotto salamander (*Eurycea spelaea*).

Urbanization has been identified as a water quality hazard in 14 of the 24 Ozark Cavefish recharge areas. Urbanization is a very major issue at Cave Springs, Arkansas, which has the largest known population of the Ozark Cavefish. Domestic sewage disposal practices for communities are a problem affecting 42% of the cavefish sites. Sewage treatment plants (both public and private) and their associated discharges are within the recharge areas for six Ozark Cavefish sites, and six sites have communities depending upon septic systems within their recharge areas. Two sites have both treatment plants and communities served by septic systems within their recharge areas. One site is located beneath a community that has public wastewater treatment but where leaky public and private sewers undoubtedly impact groundwater quality.

Both the Northwest Regional Airport and the Springfield-Branson National Airport are located within the recharge areas for Ozark Cavefish populations. An airport at Neosho is also within the recharge area for a cavefish population. Both the Northwest Regional and Springfield-Branson Airport have given substantial attention to minimizing groundwater impacts that could adversely impact cave fauna. Both airports have substantial amounts of green space where development is not planned. These areas can serve to introduce good-quality runoff water into the karst groundwater systems. On September 20, 2001 a fuel truck overturned at the Springfield-Branson airport and spilled 6,098 L (1,611 gal.) of jet aircraft fuel into a sinkhole. Good weather, rapid response, and the removal of 483,600 kg (532 tons) of contaminated soil prevented any detectable offsite migration of the fuel. Also in 2001 a smaller spill occurred at the Northwest Arkansas Regional Airport; it was all captured in a spill control structure installed in recognition of the fact that the airport was in the recharge area for an Ozark Cavefish population.

There are numerous CAFOs in the Ozarks. At the time that recharge areas were being delineated there were 169 commercial poultry houses plus 42 CAFOs for dairy, beef, or hogs in the recharge areas for Ozark Cavefish populations. The current number is undoubtedly larger than this. Land disposal of wastes from these operations is the common approach, and much of this disposal is within delineated recharge areas for populations of Ozark Cavefish. Land application followed by precipitation producing surface runoff into losing streams is a major problem especially during cold weather conditions when wastes are not rapidly trapped in the soil and vegetation.

At least 65 dumps, salvage yards, and one closed municipal landfill lie within delineated recharge areas for Ozark Cavefish populations. This number is undoubtedly an underestimate since many dumps are not readily visible from public roads. As will be discussed below, dump density was about 1.2/km² (3/mi.²) in a recharge area where a thorough search was made for these features. Using this value and the total size of delineated recharge areas for Ozark Cavefish populations (548.8 km², 211.9 mi.²) the total number of dumps in recharge areas for Ozark Cavefish could be about 660. While some caving organizations have conducted dump cleanup projects in sinkholes and losing-stream valleys, most of the dumps have received no cleanup efforts. Dumps commonly include small amounts of petroleum products, asphalt roofing shingles, some pesticides and inadequately cleaned pesticide containers, and a wide range of undesirable materials. Dumps are commonly located in or near drainageways upstream of losing-stream segments. The one closed municipal landfill pre-dated requirements for reasonably effective liners and leachate collection systems and thus will be a long-term source of groundwater contamination.

Tumbling Creek Cavesnail Site

Figure 1 is a map showing the delineated recharge area for Tumbling Creek Cave. The recharge area encompasses 23.36 km² (9.02 mi.²) and lies

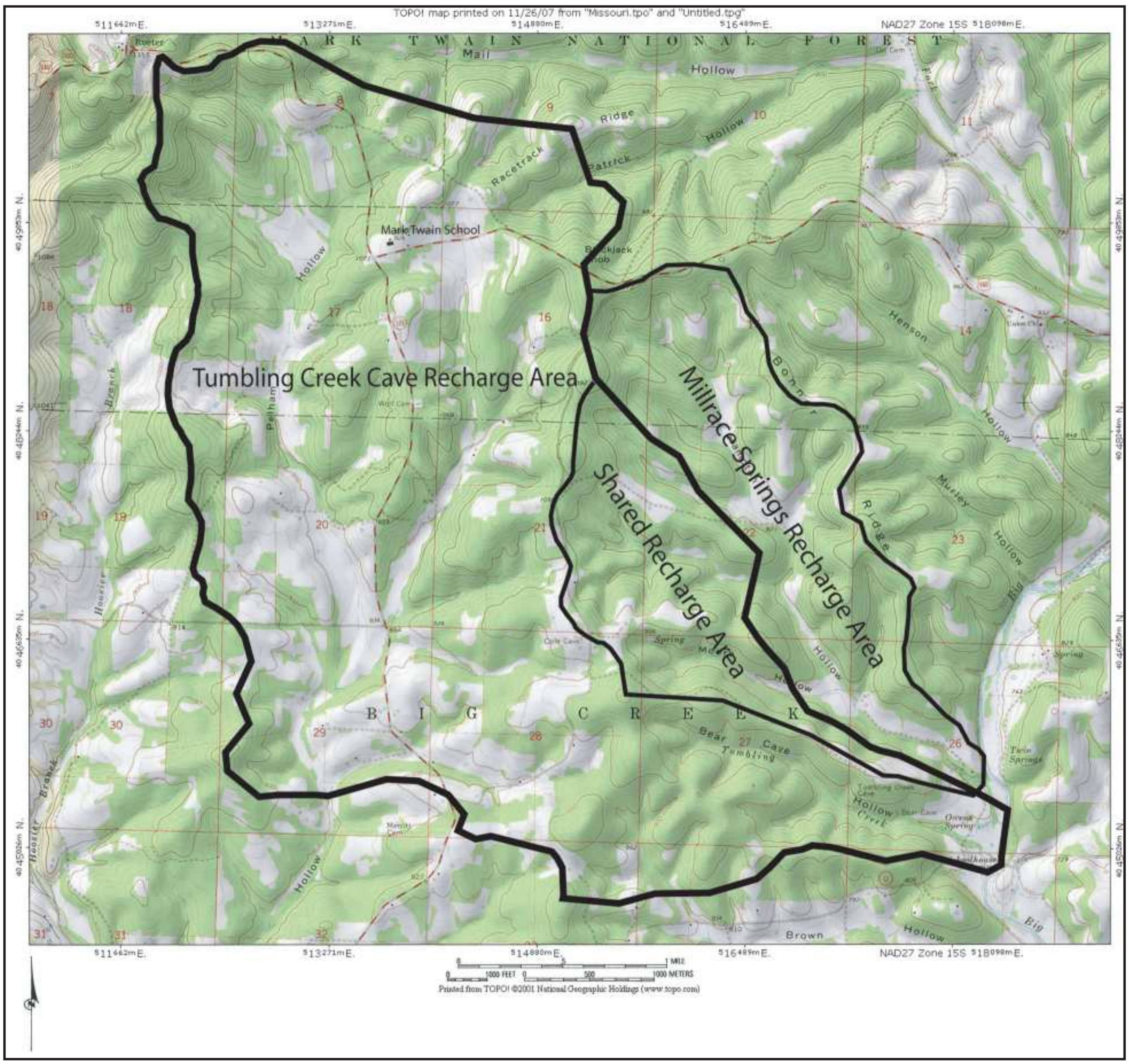

Figure 1 *Delineated recharge area for Tumbling Creek Cave. Note that the recharge area lies in several topographic basins. A portion of the recharge area is shared with another system of springs. The data are based on 62 groundwater traces.*

in several topographic basins. The map illustrates that a portion of the recharge area is shared with another system of springs. A total of 29 dumps (about 1.2/km^2 or 3/mi^2) have been discovered in this recharge area as a result of a cost-share project to discover and assess the dumps. Major funded efforts have been made to cleanup these dumps and dispose of all materials outside of the recharge area for Tumbling Creek Cave. This work should be completed by December 2008.

About 4.57 km (15,000 feet) of U.S. Highway 160 and 4.51 km (14,800 feet) of Missouri 125 cross the recharge area for the Tumbling Creek Cavesnail population. These roads are lightly traveled and are not major trucking routes. However, over the last 40 years there have been several accidents where fuels were spilled. A large tanker load of road oil wrecked in a ditch on Missouri 125 about 2002 but did not lose any appreciable amount of cargo. A beer truck rolled over on U.S. 160 in 1970 and a substantial amount of liquid was spilled. Local residents rapidly responded and removed much of the cargo, thereby protecting groundwater quality.

A rural school using a badly leaking sewage lagoon system was a major problem source in the Tumbling Creek Cave recharge area. A number of entities and individuals contributed funds to design and construct an advanced wastewater treatment plant that now serves the school and protects groundwater quality (Elliott et al. 2007). Several sewage system upgrades have been made at privately owned critical sites in the recharge area and a major effort is underway to expand this program. There are no communities or urbanizing areas in this recharge area.

There is one, small, beef–cattle CAFO in the Tumbling Creek Cave recharge area. It is about 122 m (400 ft.) from a major losing stream that rapidly contributes much of its flow to the cave. Owners of the land between the stream and the CAFO are maintaining an ungrazed and uncut vegetative cover on this land to function as a filter strip, and thereby reduce impacts from this facility.

Sediment from eroding pastureland has been identified as the most likely factor causing a drastic decline in the Tumbling Cavesnail population in Tumbling Creek Cave (McKenzie 2003, Elliott et al 2007, 2008). New owners of the involved properties assisted by funding from U.S. Fish and Wildlife Service and U.S. Department of Agriculture have corrected this problem, yet the cavesnail population has not shown an appreciable increase as of November 2007.

Benton Cave Crayfish Sites

The four known sites for the Benton Cave Crayfish are all in Benton County, Arkansas. One of the sites extends a few feet into Missouri and a cave crayfish reportedly discharged from an estavelle on the Missouri side of the border during a storm period. The combined recharge areas for the four sites encompass 97.9 km^2 (37.8 mi.^{2}). One of these sites, with a recharge area of 30.0 km^2 (11.6 mi.^{2}), also provides habitat for the Ozark Cavefish.

A total of 21.3 km (13.2 mi.) of Arkansas state highways and 6.1 km (3.8 mi.) of U.S. highways cross delineated recharge areas for the Benton Cave Crayfish. All four of the recharge areas are experiencing urbanization and all have communities dependent upon on-site sewage disposal. There are a total of at least 73 commercial poultry houses or CAFOs for other animals in one of the two recharge areas that still contain an appreciable amount of rural land. There are about 15 poultry houses and one hog CAFO in the other recharge area with appreciable rural land. Land application of animal wastes from these operations is the common approach, and much of this land application occurs in delineated recharge areas for listed species.

Hell Creek Cave Crayfish Site

Hell Creek Cave is one of two known sites for this species and is the only site for this species that we have delineated. Our work here was conducted in 1984-85, and land use conditions have changed somewhat since that investigation. Additional tracing work in the region is envisioned, and may add substantially to our knowledge of the hydrogeology of this system. The delineated recharge area encompasses 12.2 km^2 (4.7 mi.^{2}).

The recharge area for this site is crossed by 2.5 km (1.6 mi.) of an Arkansas state highway. There is an industrial site that yields sediments and potentially other materials located in the upper end of the major losing stream, which supplies much of the water to the cave system. In 1985 there were five petroleum storage sites, one chemical storage location, and three dumps and salvage yards in the delineated recharge area. Urbanization is occurring in parts of the recharge area and these developments rely upon on-site sewage systems.

Illinois Cave Amphipod Sites

We have delineated the recharge areas for seven sites for this southwestern Illinois species. The total size of delineated recharge areas for this species is 108.8 km^2 (42.0 mi.^{2}). There are 6.0 km (3.7 mi.) of state highways crossing recharge areas for this species.

Urban expansion is the major water quality threat in the region since it is within commuting distance of the greater St. Louis area. Expanding suburbs exist on 9.8% of the lands in the delineated recharge areas, and many of the new homes rely upon on-site sewage systems. Soils in the area are largely derived from loess, and row crop agriculture now occurs on 58.1% of the lands in the seven recharge areas. Most of the expanding suburbs are located on lands that were formerly used for row-crop agriculture. Pesticides are a concern with row-crop agriculture, but in our opinion suburban development presents more water quality problems to karst groundwater systems than are presented by the agriculture of this region.

Hine's Emerald Dragonfly Sites

The total size of the three delineated recharge areas for this species is 1.6 km^2 (0.6 mi.^{2}). All of these sites were studied because of planned highway improvements that would cross the recharge areas for the sites. The total length of highway corridors in these three recharge areas is 1.42 km (0.88 mi.). None of these recharge areas had other land uses likely to adversely impact water quality and habitat conditions for the dragonfly.

Sites for Other Species

We are currently delineating the recharge areas for five sites in Perry County, Missouri that provide habitat for the Grotto Sculpin, and at this time we do not have sufficient information to warrant a detailed discussion. We have also delineated the recharge-area for one cluster of springs that provide habitat for the Spring Cavefish. Vulnerability mapping was not conducted in this recharge area. Finally, we have conducted recharge-area delineation work for populations of cavefish and cave crayfish that are not federally listed. This work is mentioned here to illustrate that there are other aquatic species dependent upon springs and cave waters that have recharge areas warranting delineation and vulnerability mapping.

Defensibility of the Delineated Sites

The delineated recharge areas for Ozark Cavefish, Tumbling Creek Cavesnail, Hell Creek Cave and Benton Cave Crayfish, Illinois Amphipod, and Hine's Emerald Dragonfly encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. It is estimated that the lands encumbered by right-of-ways for county, state, and federal roads in the delineated recharge areas almost equal the acreage owned by conservation agencies, not-for-profit conservation entities, or that are included in conservation easements. Good resource management practices on private lands are clearly essential to the continued existence of these species and the number of habitat sites that presently exist.

Under present conditions and anticipated near-term changes in land use, many of the habitat sites cannot be effectively defended against land use activities or accidents that could seriously damage or destroy some of the populations discussed in this report. Based upon conditions in the studied recharge areas we have qualitatively ranked the defensibility of the sites over the next thirty years. Poorly defensible sites are those where land use and hydrologic conditions are such that it is more likely than not that the population of the species of concern will be seriously damaged or destroyed within the next 30 years. Moderately defensible sites are those where some damage to the population of the species of concern is likely within the next 30 years, but where the population is likely to continue to exist. Highly defensible sites are those where little or no damage to the population of the species of concern is likely within the next 30 years. These sites are generally remote from most disturbances and have landowners or some conservation entity that is capable of providing some protection for the sites and for water quality in the recharge areas. While the credibility of our assessments can be questioned, they represent the best estimates of people familiar with the sites. Table 3 summarizes our assessment of site defensibilities for habitats for the listed species. We have not made an assessment

Table 3 Defensibility of federally threatened and endangered cave and spring species. See text for a description of the categories. Values are number of sites.

Species	Poorly Defensible	Moderately Defensible	Highly Defensible	Total Studied Sites
Ozark Cavefish	10	8	6	24
Tumbling Creek Cavesnail	0	0	1	1
Benton Cave Crayfish	0	4	0	4
Hell Creek Cave Crayfish	0	1	0	1
Illinois Cave Amphipod	7	0	0	7

for Hine's Emerald Dragonfly since our sample is only a small portion of total known sites and the sites investigated were not reflective of typical sites for this species.

Summary

Perennially saturated epikarstic zones with "likely habitat" are associated with 79% of the delineated cavefish sites, all of the Benton Cave Crayfish sites, and at the only known site for the Tumbling Creek Cavesnail. Five hand-dug wells bottom in the epikarst support populations of Ozark Cavefish, and attest to the significance of epikarstic habitat beneath valley floors.

Fens underlain by limestone and dolomite units are usually associated with populations of Hine's Emerald Dragonfly. All three of the delineated fen recharge areas receive groundwater supplies from the epikarstic zone. It is likely that other fens, both in glaciated and unglaciated areas, are dependent upon epikarstic groundwater flow.

Protecting water quality entering karst groundwater systems through sinkholes and losing streams poses substantial challenges. Problems associated with sinkholes are typically confined to very localized areas with relatively few landowners. In contrast, some of the losing-stream segments contributing flow to important cave faunas drain hundreds to thousands of hectares and water quality is impacted by numerous property owners who may be located far from the habitats that they are affecting.

With the exception of fens, travel rates for waters moving into and through the groundwater systems providing "likely habitat" are in the range of hundreds to thousands of meters per day. Travel rates are greatest under storm-flow conditions and slowest under low-flow conditions when there has not been significant precipitation for a week or longer. Travel rates through epikarstic aquifers to the studied fens are in the range of 3 to 30 m/day (10 to 100 ft./day) or more.

Vulnerability mapping is a qualitative assessment of how vulnerable particular portions of recharge areas are to the introduction and transport of pollutants that could impact sensitive habitats. Most of the recharge areas for the species studied currently have significant threats to water quality in the habitat sites. Seventy-five percent or more of the lands in the recharge areas for the Tumbling Creek cavesnail, the Benton Cave crayfish, the Hell Creek Cave crayfish and the Grotto sculpin are ranked as having High or Extremely High Vulnerability. Only the Ozark Cavefish and fens providing "likely habitat" for Hine's Emerald Dragonfly had less than 50% of their recharge areas in High or Extremely High Vulnerability classes.

The 24 delineated recharge areas for the Ozark Cavefish are crossed by numerous federal, state, and county highways; five of the recharge areas are crossed by interstate highways. Significant segments of heavily used rail lines and petroleum pipelines cross some of the recharge areas. Sewage treatment plants and communities with on-site sewage systems are found in many of the Ozark Cavefish recharge areas. Fuel spills have occurred at two of the three airports located in recharge areas for the Ozark Cavefish; both of these spills were rapidly contained and recovered.

Disposal of CAFO wastes is a major concern in many of the Ozark Cavefish recharge areas since there are at least 211 CAFOs in the delineated recharge areas. Land disposal of wastes from these operations is the common approach, and much of this disposal is within delineated recharge areas for populations of Ozark Cavefish. A major problem is land application followed by precipitation yielding surface runoff into losing streams, is especially during cold weather conditions when wastes are not rapidly trapped in the soil and vegetation.

The recharge area for the Tumbling Creek Cavesnail encompasses 29 dumps, but all of these should be cleaned up and the trash exported out of the recharge area by December 2008. The recharge area for the cavesnail population is crossed by U.S. Highway 160 and Missouri 125. These roads are lightly traveled and are not major trucking routes, but some spills have occurred. Several sewage system upgrades have been made at a school and privately owned sites in the recharge areas and this program is being expanded. There are no communities or urbanizing areas in this recharge area. Sediment from eroding pastureland was identified as the most likely factor causing a drastic decline in the Tumbling Cavesnail population in Tumbling Creek Cave. New land owners have corrected this problem, but the cavesnail has not increased.

There are four known sites for the Benton Cave Crayfish in Benton County, Arkansas. One site also provides habitat for the Ozark Cavefish. A total of 21.3 km (13.2 mi.) of Arkansas state highways and this species. Urbanization is increasing in along with all four of the recharge areas on-site sewage disposal. At least 89 CAFOs, and associated waste-disposal problems are a major concern.

Hell Creek Cave is one of two known sites for *C. zophonastes* and is its only site that we have delineated. The delineated recharge area is crossed by 2.6 km (1.6 mi.) of an Arkansas state highway. An industrial site that yields sediments and potentially other materials located in the upper end of the major losing stream supplies much of the water to the cave system. Urbanization increases in parts of the recharge area, and these developments have on-site sewage systems.

We have delineated the recharge areas for seven Illinois Cave Amphipod sites in southwestern Illinois. Urban expansion is the major threat to water quality in these recharge areas. Expanding suburbs exist on 9.8% of the lands in the delineated recharge areas, and many new homes have on-site sewage systems. Row-crop agriculture now occurs on 58.1% of the lands in the seven recharge areas, and most of the expanding suburbs are located on former farm lands. Pesticides are a concern with row-crop agriculture, but in our opinion suburban development presents more water-quality problems to karst groundwater in this case.

The total size of the three delineated recharge areas for Hines Emerald Dragonfly is only 1.6 km^2 (0.6 mi.^{2}). All of these sites were studied because of planned highway improvements that would cross the recharge areas for the sites. The total length of highway corridors in these three recharge areas is 1.42 km (0.88 mi.). No other land uses are likely to adversely impact water quality and habitat conditions for the dragonfly.

We are currently delineating the recharge areas for five sites in Perry County, Missouri that provide habitat for the Grotto Sculpin, so that is a work in progress.

The delineated recharge areas for Ozark Cavefish, Tumbling Creek Cavesnail, Hell Creek Cave and Benton Cave Crayfish, Illinois Amphipod, and Hine's Emerald Dragonfly encompass a total area of 764 km^2 (295 mi.^{2}). About 95% of this land is in private ownership. Lands encumbered by right-of-ways for county, state, and federal roads in the delineated recharge areas are estimated to almost equal the size of the area owned by conservation agencies, nonprofit conservation entities, or that are included in conservation easements. We qualitatively ranked the defensibility of the sites over the next thirty years. All seven of the delineated sites for the Illinois Cave Amphipod are poorly defensible. There are no highly defensible sites for either the Benton Cave Crayfish or the Hell Creek Cave Crayfish. Seventy-five percent of the Ozark Cavefish sites are poorly or moderately defensible. The only known site for the Tumbling Creek Cavesnail is ranked as highly defensible because of restoration actions during the past seven years. In the absence of such aggressive efforts in other recharge areas it is our conclusion that many population sites and perhaps some species will be lost within the next 30 years or sooner.

Acknowledgments

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STRUCTURAL CONTROLS ON EPIKARST AND SURFACE WATER DRAINAGES IN THE OZARKS

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Abstract

Recent studies substantiate the importance of structural controls (joints, lineaments, faults, dips) on the surface and groundwater hydrology of the Ozarks. Structural controls tend to dominate in the upper, weathered bedrock (epikarst), which affect both shallow groundwater and surface water hydrology.

Several Ozark studies show a correlation between joint (fracture) orientation and straight stream segments, indicating that the fractures provide zones of enhanced weathering that can be highly susceptible to pollution. High groundwater yields along lineaments (fracture traces) indicate their influence on bedrock permeability. Fracture and bedding plane controls in Ozark caves are well documented.

Most of the Ozarks is characterized by mantled karst, which is covered with residuum/soil, and may have no readily observable karst features. Groundwater flow in most Ozark aquifers is dominated by fractures and conduits. Solution enlarged, vertical fractures can reach high densities in the epikarst, representing potential discrete recharge points across the landscape. Ozark residuum can have high permeability, providing little protection. In many cases, karst influences on hydrology can only be observed after rainfall events.

Mantled karst systems may have similar susceptibility to pollution as the more recognizable (geomorphic) karst, especially if the soil cover is disturbed. Land surface impacts along structural features can have a disproportionably high impact to groundwater quality. Ozark water resources can be better protected if the nature and extent of structural/karst influences on surface water and groundwater hydrology are better understood.

Key words: karst structural geology, hydrology, Ozarks

Introduction

The Ozark Plateaus Physiographic Province (Ozarks) consists of a broad, asymmetrical geologic dome that rises above surrounding lowlands (Figure 1). The Province covers approximately 65,000 square miles mostly in Missouri and Arkansas, but also includes parts of Oklahoma, Kansas and Illinois. Erosion of the dome has exposed a sequence of older rock at the center and progressively younger bedrock toward the edge. The Province consists of four sub-sections: Salem Plateau, Springfield Plateau, St.Francois Mountains, and the Boston Mountains (Imes and Emmett 1994). The St.Francois Mountains are the exhumed igneous (Precambrian) core of the Ozark dome, consisting of igneous peaks surrounded by carbonates and clastics. The Salem Plateau roughly coincides with the outcrop of Cambrian and Ordovician bedrock, composed primarily of carbonates with minor clastics. The Springfield Plateau consists of an irregular shaped band of resistant Mississippian carbonates.

Both the Salem and Springfield Plateaus include broad upland plains, which are highly dissected in proximity to large streams. The Boston Mountains are capped by resistant Pennsylvanian sandstone, underlain by Mississippian strata.

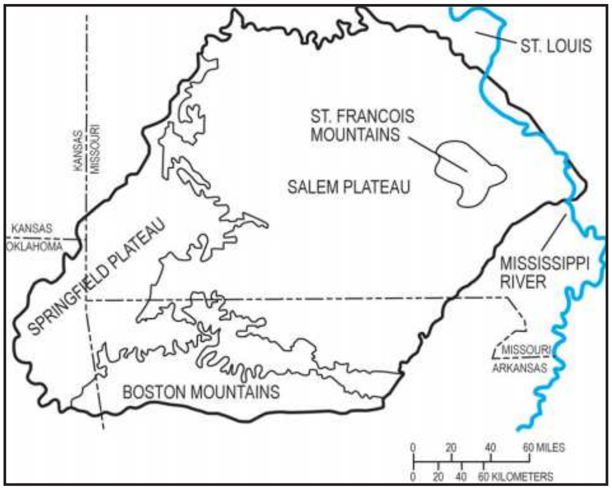

Figure 1 Ozark Plateaus physiographic province and subsections (modified from Imes and Emmett 1994).

The regional bedrock dips are generally low (<5 degrees), away from the center of the dome, with higher dips on the east side of the Province. Thousands of smaller scale structures (faults, anticlines, synclines, etc.) overlie the regional trends. The Missouri Environmental Geology Atlas (MEGA 2007) has over 5,600 "Geo-Structures" documented in an ArcGIS database. The Ozarks have undergone at least six episodes of structural deformation: Precambrian, Upper Ordovician, Pre-Mississippian, Post-Mississippian, Post-Pennsylvanian, and Tertiary (McCracken 1971). The entrenched streams and current seismic activity reflect a continuing uplift of the Ozark dome.

A fractured and faulted igneous basement complex, composed of extrusives (mostly rhyolite) and intrusives (mostly granite), underlies the Ozarks, similar to the St. Francois Mountains. This provided an uneven surface for the subsequent deposition of Paleozoic sediments. The differential compaction across this terrain and reactivation of Precambrian faults may be responsible for some of the structural features exposed in the Ozarks today (McCracken 1971, Harrison et al. 2002).

The Ozarks are noted for well developed karst, with thousands of springs, caves, sinkholes and losing streams. The predominantly carbonate Paleozoic bedrock ranges from hundreds of meters thick to less than 100 meters in proximity to the igneous knobs. Good overviews of Ozark hydrogeology are presented by Imes and Emmett (1994), and Miller and Vandike (1997).

Lineaments and Fracture Traces

Lineaments (>1.6 km or 1 mi. long) and fracture traces (<1.6 km) are mapped based upon tonal patterns that reflect changes in soil, bedrock and vegetation, and the alignment of straight stream/valley segments, and sinkholes. Lineaments are considered (Palmer 2007) to represent zones of intense fracturing (facture swarms), which enhance both surface weathering, and permeability/dissolution in karst aquifers. These features have long been used to locate water wells in karst areas (Ford and Williams 1989).

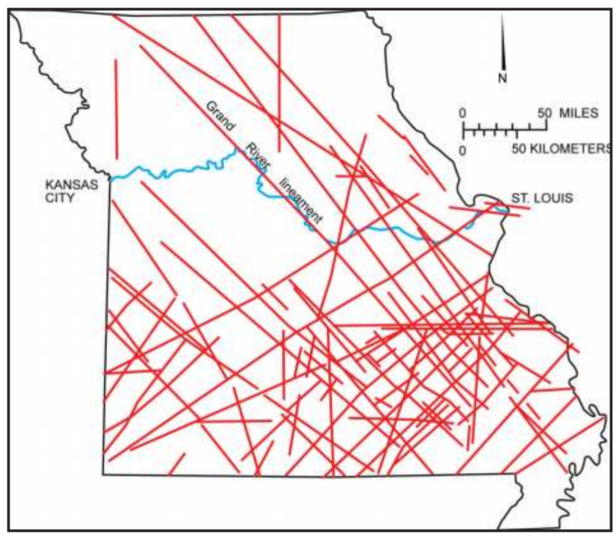

Figure 2 Missouri lineament map (after Kisvarsanyi and Kisvarsanyi 1976).

Missouri has a distinct pattern of roughly orthogonal lineaments (Figure 2), which correlates with the major structural features of Missouri (McCracken 1971). The highest density of lineaments is centered on the St. Francois Mountains, where the basement complex is shallow or exposed. The St Francois Mountains have numerous examples of structurally controlled streams. One of the best examples is the approximately 16-km-long (~10 mi.) segment of the St. Francis River that flows along a prominent lineament (Figure 3).

A correlation between lineaments and faulting has also been noted in the Arkansas Ozarks (Miller and Appel 1997). Lineaments in northern Arkansas were found to correlate with high-yield water wells, especially in the Roubidoux Formation and the Gunter Sandstone member of the Van Buren Formation (Miller and Appel 1997).

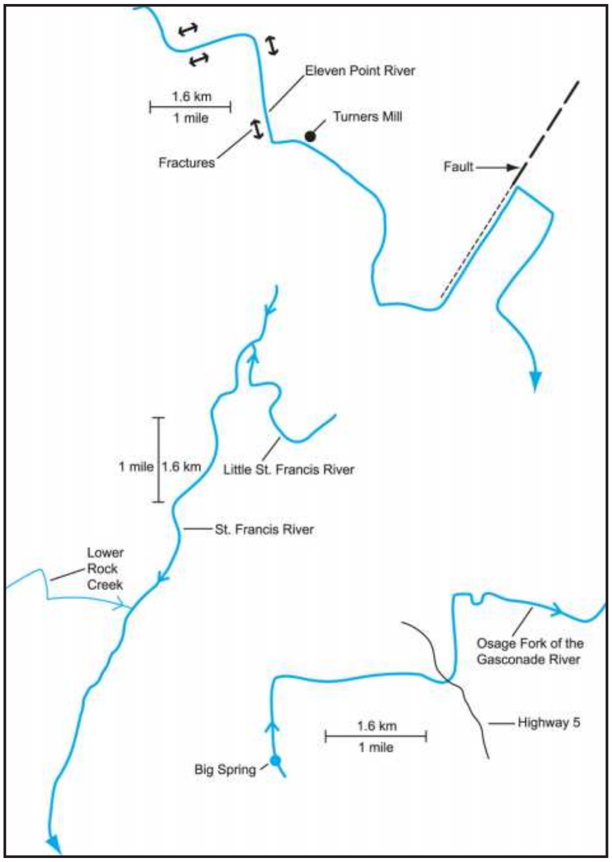

Figure 3 *Examples of structurally controlled rivers in the Missouri Ozarks: St. Francis River, Madison County; Eleven Point River, Oregon County; and the Osage Fork of the Gasconade River, in Laclede County*

Regional Studies

The surface water and groundwater hydrology for parts of the Osage and Gasconade River watersheds was characterized with detailed geologic mapping, stream gauging, stream profiles, groundwater potentiometric maps, and dye tracing (Figure 4) (Harvey et al. 1983). This study concluded that, "The most important controlling factor on the hydrology of Ozark basins is the amount and type of structural deformation. Faulting and jointing deflects streams, alters stream flows, and deflects the underground movement of water". Several of the tributaries studied have a modified dendritic drainage patterns with numerous straight stream segments and abrupt (90°) stream bends, which are attributed to structural controls. A prominent set of northwest trending faults is apparently responsible for the inter-basin flow of groundwater from Dry Auglaize Creek to the Niangua River (Figure 4).

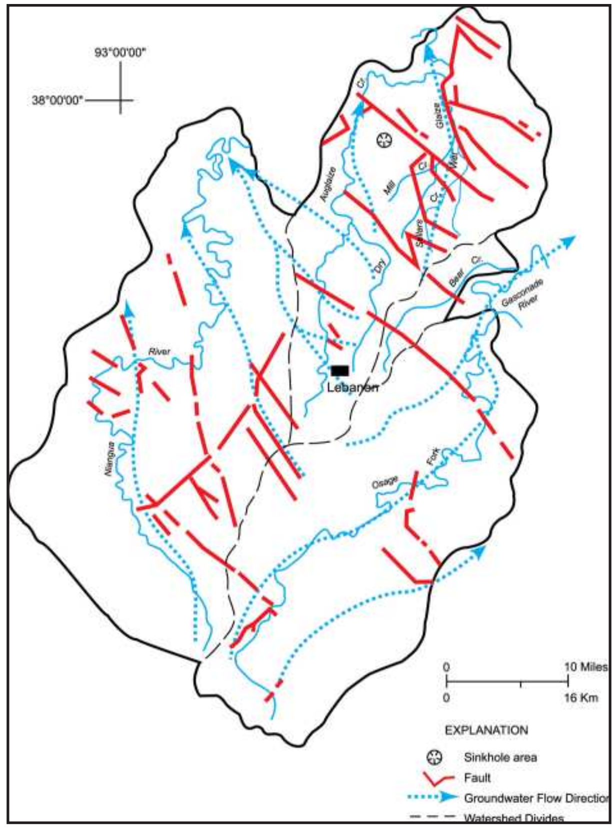

Figure 4 *Structural influences on groundwater flow directions in Osage and Gasconade River tributaries (modified from Harvey et al.1983).*

In his hydrogeologic studies in the Salem Plateau, Aley (1978) and Aley and Aley (1982) found a correlation between lineaments, and both large springs and losing streams. The two largest springs in the Missouri Ozarks (Big and Greer Springs) are located at the intersections of lineaments (Figure 5). Mammoth Spring, the largest spring in the Arkansas Ozarks, is associated with intensely faulted bedrock (Hedden 1968).

In a study on the North Fork basin, Vandike (1979) looked at the relationship of "photo-geologic linear features" (lineaments and fracture traces) and hydrogeology, karst features, and surface drain-

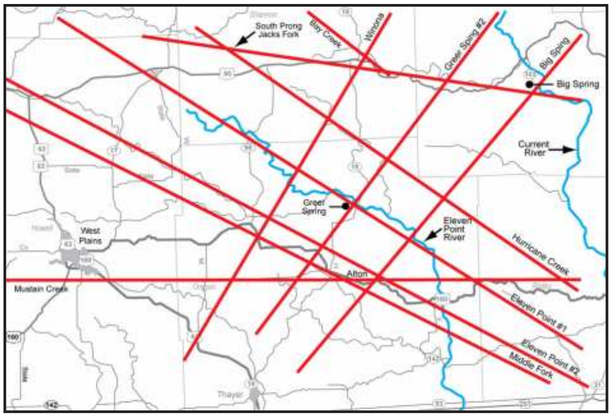

Figure 5 Lineaments in the Eleven Point River and Current River areas (modified from Aley 1978).

age systems. All of the large springs in the watershed were found to occur at or near the intersection of lineaments. The study found a correlation between bedrock fracture orientations and straight stream segments. Lineaments were also found to correlate with losing streams, faults and the long axis of sinkholes. In addition, several perennial streams lose flow into the subsurface at the intersection of lineaments (Vandike 1979).

In the Turner's Mills section of the Eleven Point River this deeply entrenched river makes several abrupt turns that follow prominent fracture orientations (Figure 3) (McDowell 1998). Just downstream, the River again makes abrupt bends, and in one case matches a fault line (Harrison and McDowell 2003).

Several tributaries of the Current River (Rocky Creek, Mill Creek) form a modified (angular) dendritic drainage pattern that roughly matches fracture and fault orientations (Harrison et. al. 2002). At the Mill Creek Fault crossing of Mill Creek, the perennial surface flow is lost into the subsurface (Harrison et. al. 2002).

The Brickey Hills along the Mississippi River are noted for a series of very deep, straight streams that are roughly parallel to anticlines and synclines, indicating possible structural control (Baker 2001a and 2001b). Dominant fracture orientations were also shown to correlate with these straight streams (Figure 6).

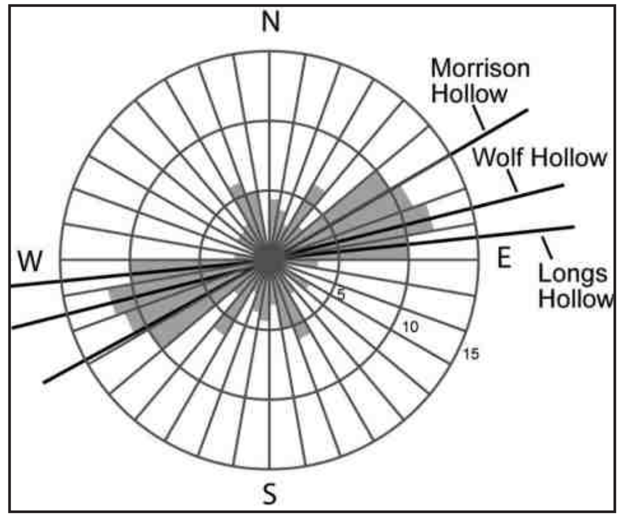

Figure 6 Compass-rose diagram of bedrock fractures in the Brickey Hills along the Mississippi River, and comparison to straight streams.

Epikarst

Several studies have documented the intensity

Figure 7 Fractured epikarst, Johnsons Shut-Ins State Park, Missouri.

of fracturing in Pre-Pennsylvanian bedrock of the Ozarks (McCracken 1971, Unklesbay and Vineyard 1992). In the Stegall Mountain Quadrangle fracture densities were classified as follows: widely spaced (>1.8 m, 6 ft.), medium spaced (0.6 to 1.8 m, 2 to 6 ft.) and closely spaced (<0.6 m, 2 ft.) (Harrison et. al 2002). This intense fracturing is one of the key components of the Ozark epikarst. Fracture intensity typically decreases with depth as groundwater flow coalesces into master conduits that may be controlled by bedding planes as observed in many Ozark caves. An excellent example of fractured epikarst was recently (2005) exposed in Johnson's Shut-Ins State Park, Missouri (Figure 7). These steeply dipping beds of the Bonneterre Formation show the influences of fracturing and bedding planes on the flow of water through the epikarst. Upon encountering bedrock, water moves laterally along bedding planes until reaching vertical fractures that allow water to descend to lower levels. The fracture orientation may create preferential groundwater flow pathways. Also evident is enhanced dissolution near bedding planes due to the higher groundwater flow (note arrow in Figure 7).

Caves

Geologic structure has also been shown to affect Ozark cave development (Bretz 1956, Taylor 1997). In a study of the hydrogeologic controls on carbonates in Christian County, Missouri, Dreiss (1976) found a correlation between joint orientation and cave passage trends. Brod (1990) identified 22 Missouri caves that may have been influenced by faulting. Brod (1964) also discussed possible structural control in the formation of fissure caves in eastern Missouri. Further discussion of Ozark cave speleogenesis is beyond the scope of this paper (see Elfrink, this volume).

Residuum

Most of the Ozark karst is covered with a thick mantle of overburden, composed predominantly of decomposition and solution residuum (Richman and Weide 1993). The residuum can inherit structures (fractures, clay seams, etc.) from the underlying bedrock (Madole et. al 1991). Ozark residuum typically contains a high percentage of coarse-grained material and can be highly permeable (Aley 1978, Madole et. al 1991). The selective removal of fines in the more porous zones can result in discrete recharge points through the residuum with no surface expressions (Aley 1978). Thus, the overburden can provide little protection to a karst aquifer from surface degradation.

Precipitation Events

In addition to the overburden concealing karst features, the Ozarks have many karst features that are not, under normal conditions, visible at the surface. Examples include gaining and losing streams that may not show either function except after significant precipitation events. In order to understand local hydrogeology, streams must be observed during both dry and wet conditions.

Vulnerability Assessments

The vulnerability assessments of karst aquifers to water degradation have long identified sinkholes and losing streams as high-risk areas because of the direct (unattenuated) entry of surface water (Figure 8). It has become apparent that additional factors need to be considered in assessing vulnerability:

1. The high permeability zones associated with lineaments/fracture traces may be more susceptible to degradation and may have a disproportionately high impact to groundwater quality,
2. Bedrock structure (faults, anticlines, synclines, etc.) can influence surface water and groundwater interactions and flow directions,
3. Fracture density and orientation controls the entry and flow of water and contaminates in the epikarst, and
4. The structure and permeability of Ozark residuum may allow the relatively un-attenuated entry of surface water into karst aquifers.

As more detailed hydrogeologic information becomes available to natural resource managers, it will allow a better assessment of land use risks. Examples include limiting certain activities along lineaments because of enhanced permeability, and more accurate predictions of contaminant migration based upon fracture orientations and geologic structures.

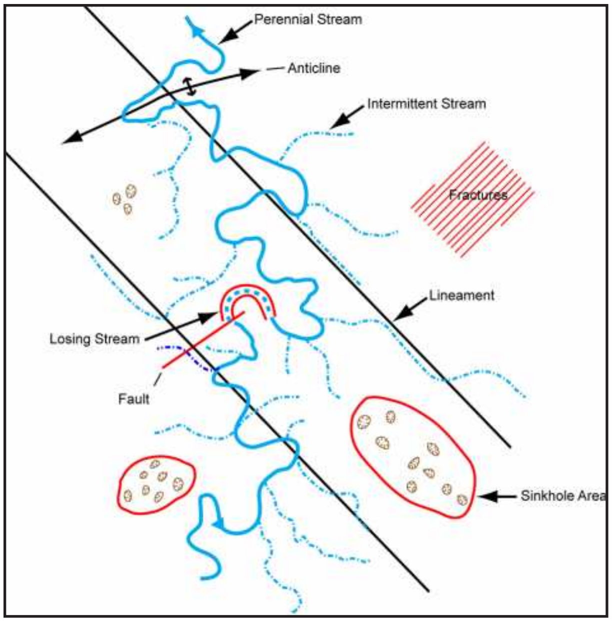

Figure 8 *Vulnerability assessment of a theoretical Ozark watershed.*

Acknowledgments

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SOIL-COVER KARST COLLAPSE: A GEOLOGIC HAZARD IN MISSOURI

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Abstract

Soil-cover karst collapses often may be seen as small local nuisances, but large collapses pose a significant threat to public health, safety and welfare. In May of 1978 a catastrophic soil-cover karst collapse occurred within the basin of the 15-ha (37-ac.) City of West Plains, Missouri, sewage lagoon, rapidly draining 284 million L^3 (75 million gal.) of sewage into the regional unconfined Ozark aquifer, forming a series of new sinkholes. This type of collapse represents one of several large, soil-cover collapses that have threatened infrastructure and groundwater supplies in Missouri. Catastrophic collapses have also occurred in Farmington, rural southwest Missouri, and in St. Louis County. The roots of many collapses are large karst conduits that may have little or no surface expression, such as visible sinkholes, yet these "blind karst" features can form abruptly, surprising landowners and municipalities.

Many of the environmental geology sites undertaken by geologists with the Division of Geology and Land Survey (DGLS) involve assessing the potential for soil-cover karst collapse in areas underlain by limestone or dolomite bedrock. These assessments are based on geologic and geohydrologic characteristics observed at known soil-cover collapses. These are, (1) groundwater greater than 15 m (50 ft.) below the surface, (2) thick and porous residual soils, (3) weathered limestone or dolomite bedrock terrane and, (4) sinkholes or losing streams in the area. Some collapses may be feasibly repaired, but at potentially high capital and environmental cost. The high potential for damage to groundwater supplies and infrastructure warrants care when evaluating proposed waste disposal or construction sites in soil-cover, karst-collapse settings.

Key words: epikarst, Missouri, sinkhole collapse, soil-cover karst collapse, geologic hazard

Hazards of Soil-Cover Karst Collapse

Soil-cover karst collapses in Missouri are not uncommon in areas of dolomite and limestone bedrock, and have occurred in a number of southern Missouri locations. Collapses most often occur in regions that have active karst features (Figure 1), but may also occur in areas that locally have little or no surface evidence of subsurface karst features. The early stages of a soil-cover karst collapse may appear as a soil-piping feature, but can rapidly grow to proportions that threaten urban infrastructure (Figure 2). Since the pre-collapse field conditions may reveal little evidence of subsurface karst, the collapses could be considered "blind karst." There are, however, geologic characteristics that are common to most collapse locations. These are:

1. Groundwater >15 m (50 ft.) below the surface,
2. Soil materials dominated by permeable, thick (≥9m or 30 ft. thick) residual silty-clay soils of-

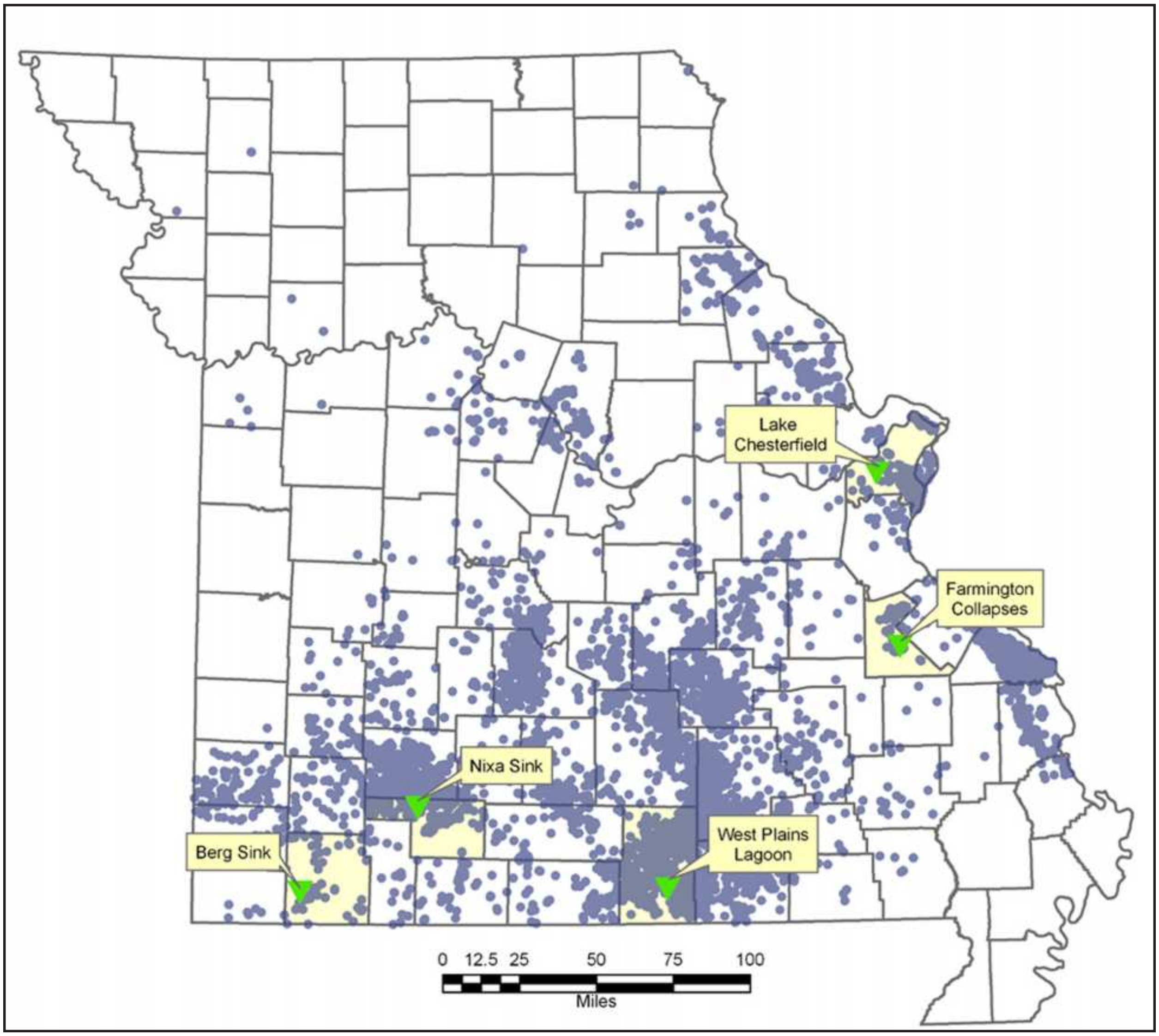
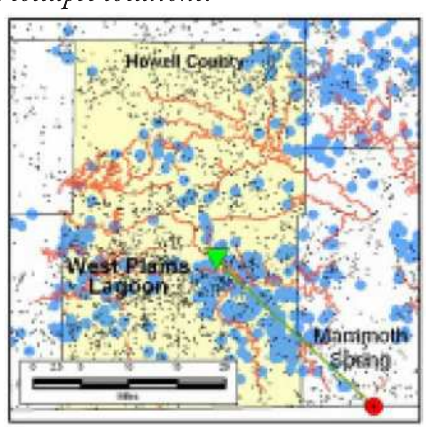


Figure 1 *Missouri karst hazard potential areas. Karst-related geologic hazards, such as groundwater pollution or sinkhole collapse, are obvious in areas with abundant, large sinkholes. The map above shows the locations of sinkhole areas (dots) and collapse locations.*

Soil-cover karst collapse beneath the West Plains Lagoon in Howell County (right), affected groundwater in a large area. The line represents a water trace from the West Plains Lagoon to Mammoth Spring in Arkansas (bullseye). Small squares are drinking water supply wells.



Well data, losing streams, sinkhole and water trace data are from the Missouri Environmental Geology Atlas (2007). Only streams that have been classified previously by DGLS are shown.

ten with relict bedrock structure,
3. Highly weathered underlying limestone or dolomite bedrock,
4. Nearby active sinkholes, or within a losing stream valley.

Large collapses have occurred in valleys that appear ordinary except that they lack perennial streams. Groundwater no longer discharges to the surface in these valleys, but instead has been pirated to subsurface flow paths that may cross multiple drainage basins (Williams and Vineyard, 1976, Harvey et al., 1983). These so-called "losing streams" are widespread in southern Missouri (Figure 1). Valleys with losing streams typically have poorly developed channels, and are often completely dry except during high rainfall periods. Geologists at DGLS have applied the field characteristics observed at known collapse sites to evaluate the "collapse potential" at proposed waste sites for over 30 years. Areas of Missouri that have these collapse characteristics include portions of the outcrop regions of Cambrian, Ordovician, and Mississippian limestone and dolomite bedrock formations.

Cases of Soil-Cover Karst Collapse

The five collapses described here are in slightly

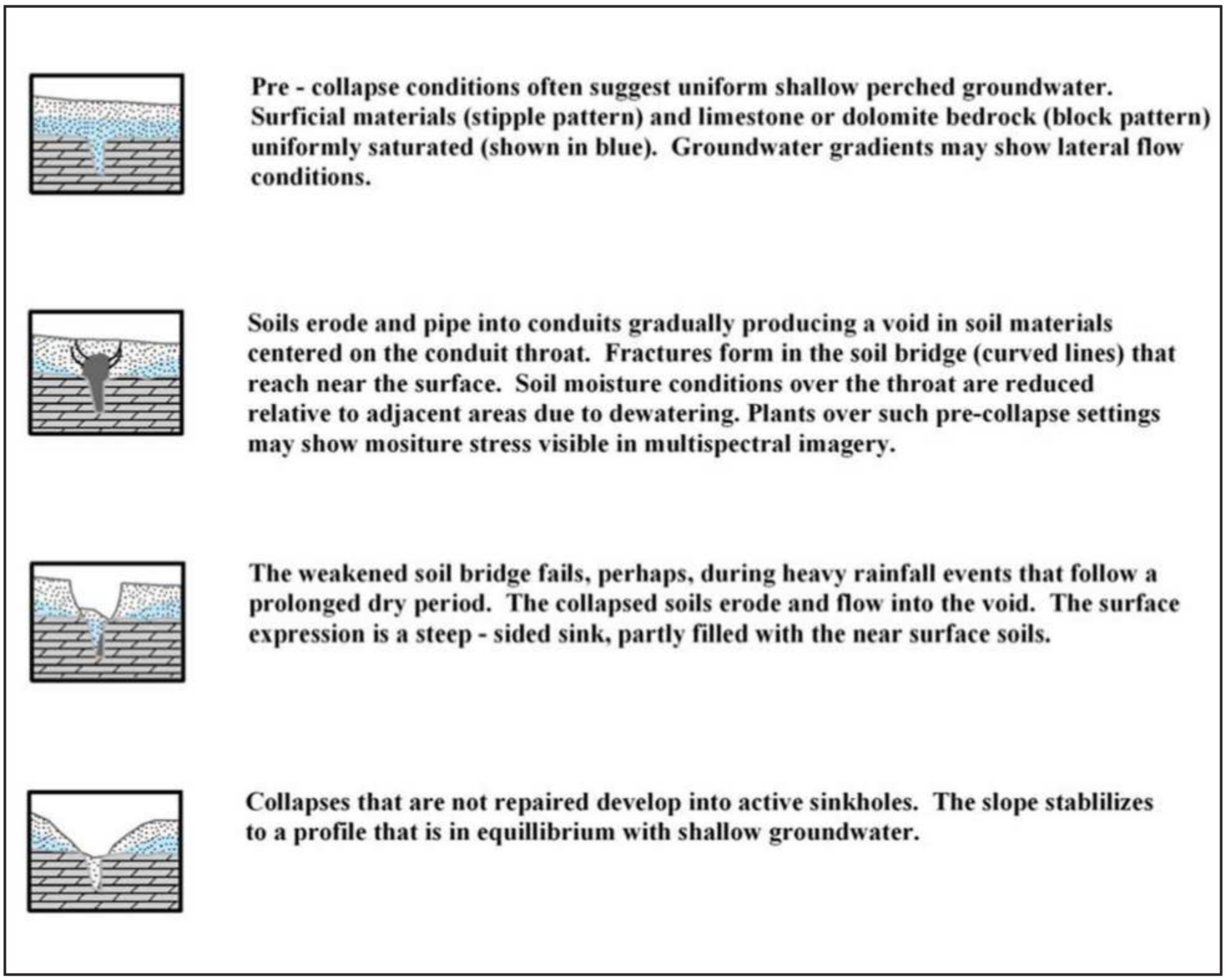


Figure 2 *Geologic model of soil-cover karst collapses resulting in typical sinkhole shapes if they are not repaired. Collapses near sinkholes are not uncommon in losing stream valleys that have thick, residual, bedrock soils over weathered, carbonate bedrock, and steep, vertical groundwater gradients. DGLS geologists use these field characterisitcs to assess collapse potential in carbonate bedrock areas. Vegetation over pre-collapse areas may show differential moisture conditions visible in infrared wavelengths. Satellite imagery, as resolution improves, may provide additional tools to predict locations prone to soil-cover collapse.*

different local settings, but have similar site characteristics as described above.

Figure 3 *This post-collapse view of the West Plains Lagoon shows two sinkholes that developed as the lagoon drained.*

West Plains Lagoon Collapse

The city of West Plains is located within the Ozark Plateau. The surrounding region has numerous sinkholes and losing-stream segments (Figure 1). The West Plains lagoon was located in the valley of Howell Creek, which had been previously classified as a losing stream. The valley has a poorly developed channel, and borings for the site encountered silty and clay-rich gravelly soils >9 m (30 ft.) thick. Shallow bedrock at the site is weathered and porous lower Ordovician-age Jefferson City Dolomite that locally exhibits karst features. The Jefferson City Dolomite is in the upper part of the unconfined Ozark aquifer and serves as a major water supply for southern Missouri. Water traces from the site before and after the collapse shows flow to the southeast into Arkansas and discharge at Mammoth Spring (USEPA 1978, Duley 1997).

On or about May 5, 1978, the lagoon basin floor collapsed (Figure 3). Following the collapse more than 800 people living near West Plains reported illnesses ranging from flu-like symptoms, including severe nausea and diarrhea (DGLS unpublished files). Since the initial construction of the lagoon, small collapses had occurred at the site in 1964 and again in 1966 (Aley et al. 1972), providing evidence of active recurrence of collapse in these settings. In each instance the collapse features were repaired using cement, clay and bentonite, and then put back into active service.

DGLS geologists had noted the potential for groundwater contamination at this location in a site evaluation in 1964. Investigations prior to May 1978 concluded that a catastrophic failure could occur in Howell Creek valley, and that groundwater in the region would

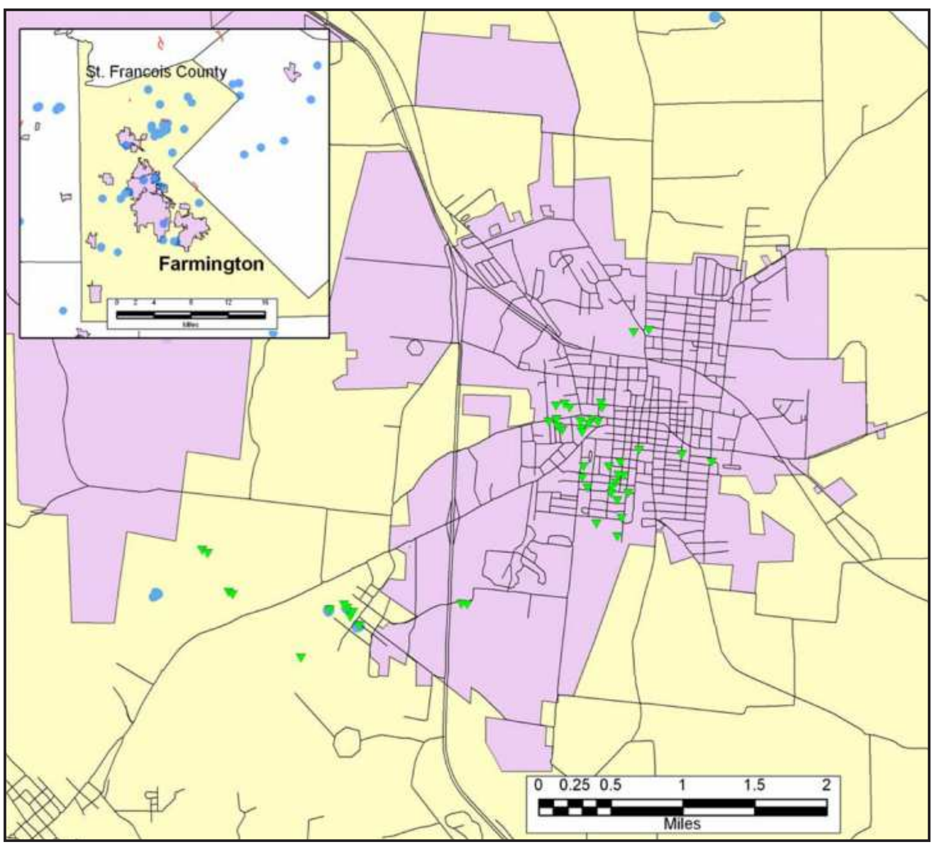


Figure 4 *Forty-eight soil-cover karst collapses were reported in Farmington, Missouri. The bedrock in the shallow subsurface consists of fine to medium-crystalline dolomite of the later, upper Cambrian Bonneterre Formation. Little karst development had been recorded in either the Bonneterre Formation or in* **continued**

the Farmington area, but fractures and open joints were observed in outcrops and in the collapses themselves. Small dolines were observed near the city. Groundwater draining into bedrock joints erodes and pipes the soils, creating cavities. As the draining progresses, shallow water table conditions reflect soil dewatering near the joints. Most reported collapses were in urban areas, many occurring in residential yards, others forming near or under streets. One formed at a street intersection along a joint in dolomite, over 25 m (80 ft.) deep and nearly 19 m (60 ft.) in diameter, severing utilities and swallowing pavement and sidewalk.

be threatened. The 1978 catastrophic failure led to the construction of a mechanical treatment plant for West Plains, which could meet applicable discharge standards for losing streams. These non-earthen structures, while expensive, are less likely to induce soil piping into bedrock conduits and are not as susceptible to damage from a catastrophic, soil-cover collapse. The series of collapses at the West Plains lagoon demonstrates that these soil-cover type collapses can and do recur, even when mitigating strategies are employed.

Farmington Collapses

For more than 50 years soil-cover karst collapses have been reported in the city of Farmington, Missouri. Surface expressions of karst features are not common in this area (Figure 4). However, soil-cover collapses have damaged residential building foundations and collapsed sections of city streets resulting in broken municipal water, sewage, and gas lines. Known collapses have a diameter up to 9 m (30 ft.), and are rooted in karst joints as deep as 19 m (63 ft.). Poorly designed urban drainage may contribute to soil piping in these areas, but the karst joints were present prior to collapse (Figures 5a and 5B). Small soil pipes were observed at the surface at some locations prior to collapse, but no other surface expressions have been recognized. These collapses are not known to hold water after failure, demonstrating that near-surface groundwater is drained rapidly into the bedrock karst joints. The collapses that have been excavated and repaired show partial to complete piping of soils from the karst bedrock joints.

Figure 5A *Collapse in residential neighborhood, Farmington, Missouri. This collapse had been repaired with soil fill only, but it reactivated.*

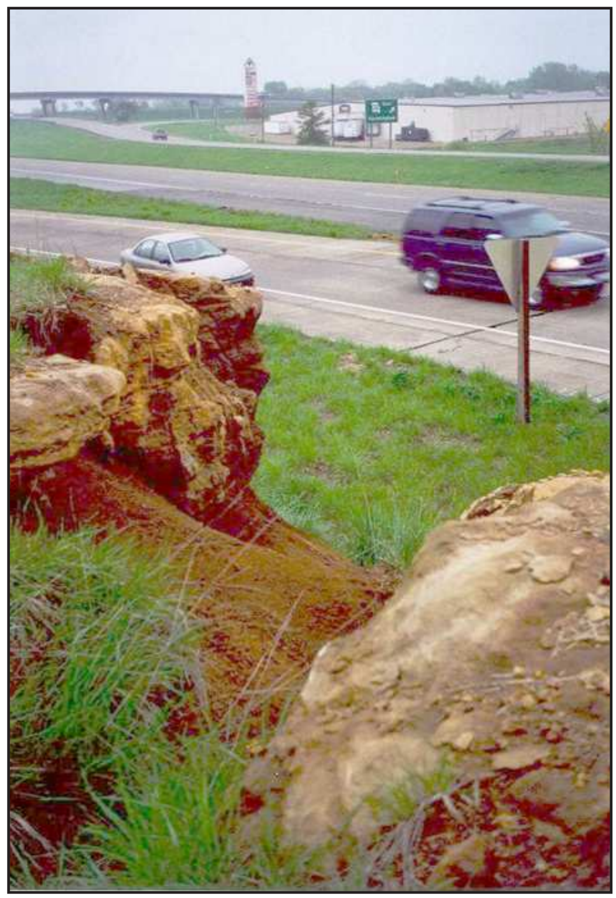


Figure 5B *Karst joint in Bonneterre Formation dolomite in Farmington, Missouri. Red soils are clay-rich silt. Joint walls have irregular, scalloped surfaces typical of karst conduits in carbonate rocks.*

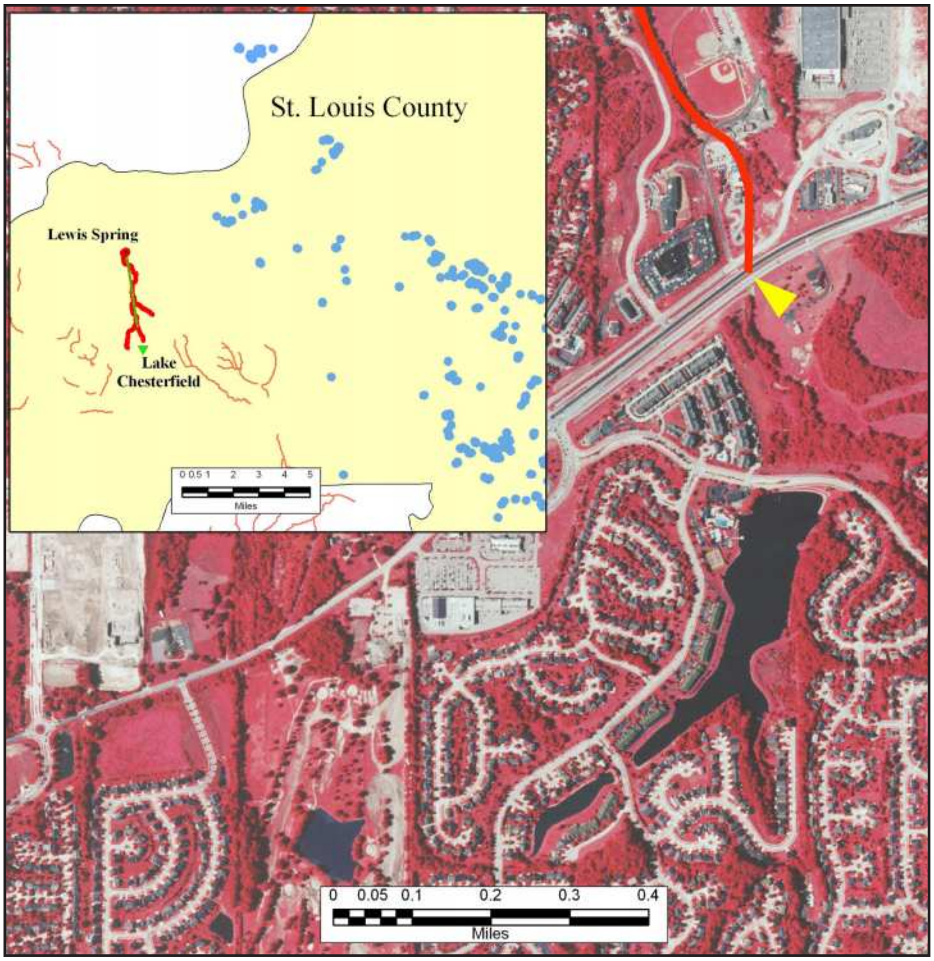


Figure 6A *Infrared aerial photograph showing the location of the Lake Chesterfield Collapse. The nearest mapped sinkholes (inset, dots) are more than 11 km (7 mi.) from Lake Chesterfield, but the lake site is within 400 m (¼ mi.) of a previously mapped losing stream (bold line at upper right, marked by pointer). A water trace from near the site (inset) indicates water lost to the ground near lake site flows to Lewis Spring (dot).*

Lake Chesterfield Collapse

Built in 1987 to control storm water runoff from a large residential development, Lake Chesterfield was a 9-ha (23-ac.) recreational lake for a community in west St. Louis County (Figures 6A–6C). The lake was formed by construction of an earthen dam across a portion of Caulks Creek. Shallow bedrock at the site consists of the Mississippian-age limestone. Although this unit is highly weathered and contains solution features indicative of karst, the nearest mapped sinkhole is over seven miles from the lake site.

In a 1978 engineering geology report, DGLS staff geologists noted a severe collapse potential for earthen wastewater storage facilities and lake sites constructed in this general location. Studies of waste disposal issues along Caulks Creek revealed that the stream was a losing drainage and did not support a surface flow during normal hydrologieriods. Water tracing was conducted in order to gain further understanding of subsurface groundwater flow. Analysis of the water trace data indicated that surface waters were rapidly infiltrating the subsurface and emerging at Lewis Spring nearly 6.4 km (4 mi.) to the north.

In June 2004, a large sinkhole formed in the lake bottom and completely drained the impoundment (Figures 6B and 6C). Reportedly, repairs of small collapses and excessive leakage had been made to the lake several times in the preceding years.

Figure 6B *Post-collapse aerial view of Lake Chesterfield showing sinks that formed at the cave beneath the lake.*

Figure 6C Soil cover collapsed beneath Lake Chesterfield into a well-developed cave.

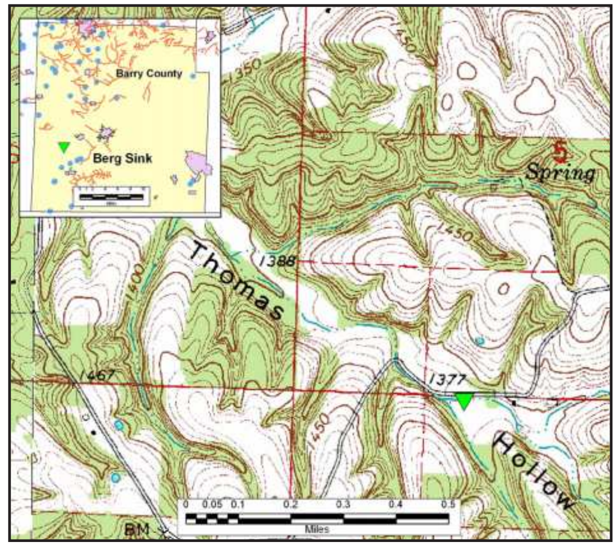


Figure 7 Berg Sink, Barry County. The bedrock in the shallow subsurface is the variably cherty limestones of the Mississippian Elsey Formation. Streams in the vicinity of the collapse (triangle) had not been classified, but investigations since the collapse showed losing flow above the collapse and within 60 m (200 ft.) downstream. Surficial materials in the valley floor appear to be greater than 9 m (30 ft.) thick based on electrical resistivity. During the first week of March 2005, the collapse flowed to the adjacent losing stream. If the collapse is about 45 m (150 ft.) deep, the conduit would be in the Ozark Aquifer. The nearest sinkholes are approximately 4.3 km (2.7 mi.) from the collapse. Base map: USGS Exeter 7.5' Quadrangle.

However, there was no physical evidence that a collapse of this magnitude was imminent. In an effort to repair the catastrophic collapse, an extensive drilling and grouting program was undertaken. To date, the small lakeside community has expended over $650,000 in an attempt to remedy the situation.

Berg (Exeter) Collapse

Located in Barry County near Cassville (Figures 7–10), this collapse is also within a losing stream valley, in an area of cherty limestones of the Mississippian-age Elsey and Reeds Spring formation, and has residual soils that are from 9 to >18 m (30 to >60 ft.) thick. The collapse was first observed by the landowners during the third week of February 2005 as a 3-m-diameter (10-ft.), water-filled depression in an open pasture. The owners indicated that the depth of this first opening was about 12 m (40 ft.). By the second week in March of 2005, the collapse had expanded to nearly 76 m (250 ft.) wide by 30 m (100 ft.) long (Figure 8A and 8B), and at one stage appeared to be greater than 46 m (150 ft.) deep. At this depth, the feature would breech the lower Ordovician bedrock and recharge the Ozark Aquifer.

At one time in early March 2005, the collapse behaved as a spring discharging to the adjacent small channel. Since that time the water level reportedly fell below the level of the adjacent dry stream channel, as the collapse became a sinkhole. One end of the sink is within a few feet of a county road, which has been closed to all traffic. It seems likely that the road will be impacted by the formation of the sinkhole.

Figure 8A *Berg Sink, last week of February 2005. The collapse margin has a well-defined scarp. The near background tree line is along a county road.*

Figure 8B *Berg Sink, second week of March 2005. The collapse had developed to a water-filled "spring" and had dimensions of 76 by 30 m (250 by 100 ft.).*

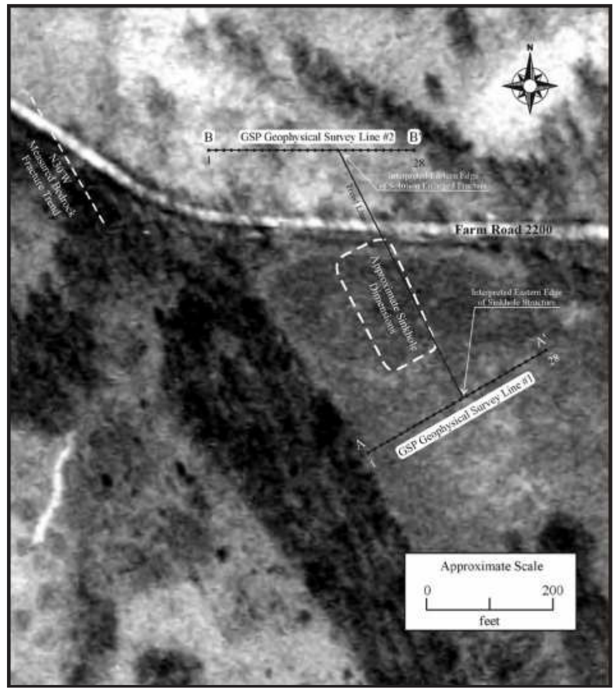


Figure 9 *Site Map of Berg Sink showing the approximate locations of the geophysical survey lines and the surface expression of the sink structure.*

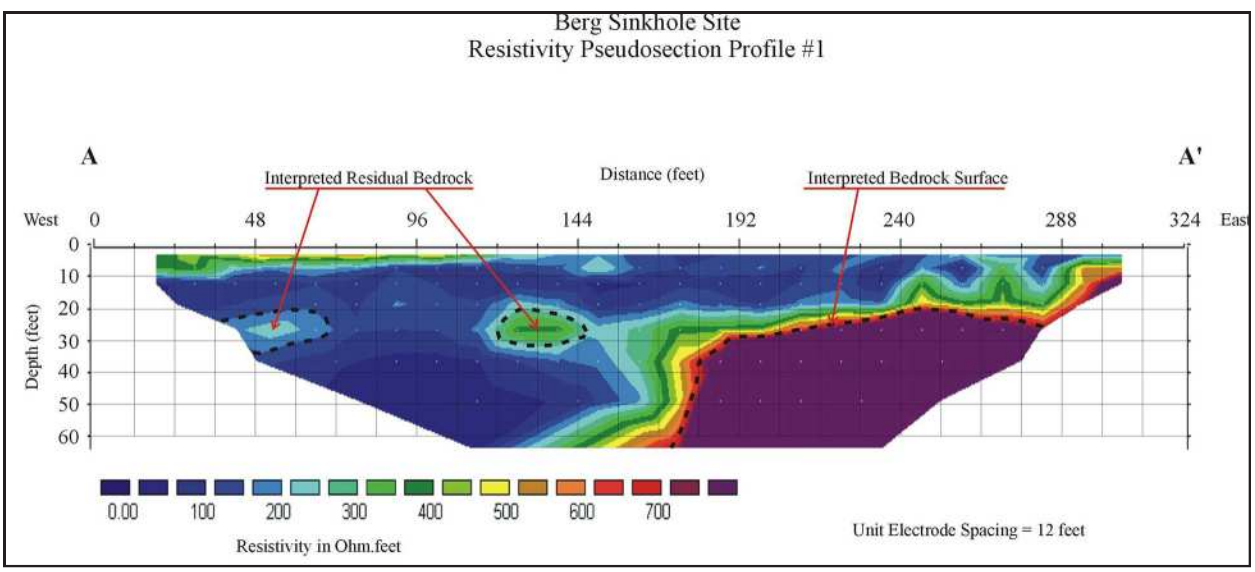


Figure 10A *Electrical resistivity pseudosection profile on the south side of Berg Sink.*

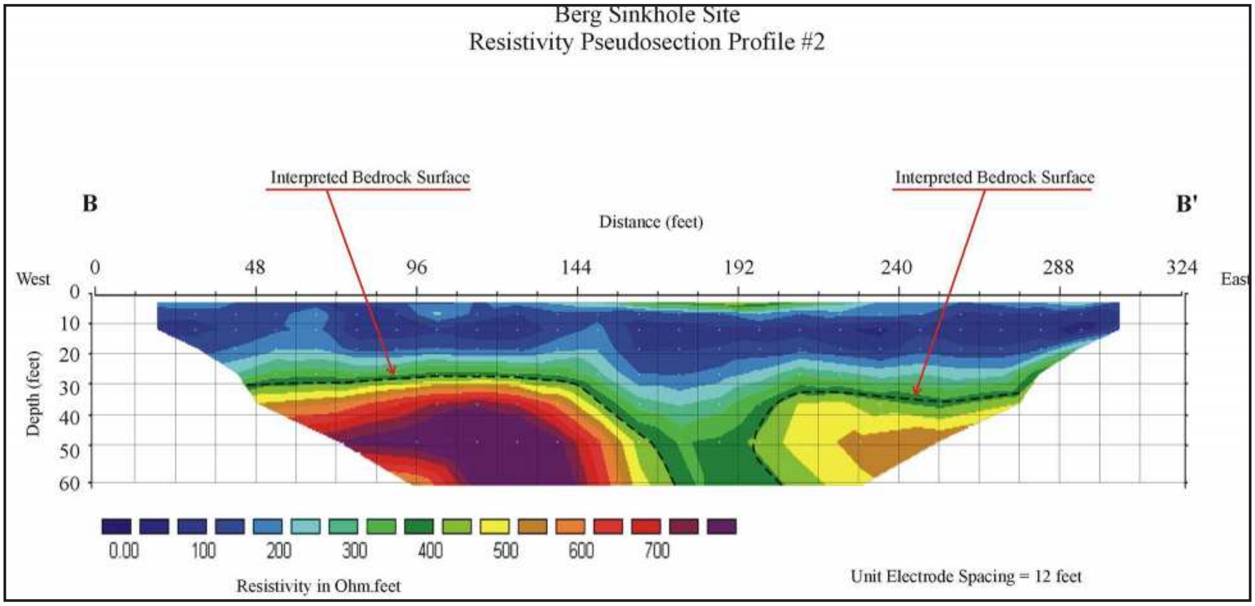


Figure 10B *Electrical resistivity pseudosection profile on the north side of Berg Sink.*

Nixa Collapse

On the morning of August 13, 2006 a collapse occurred at 327 N. Delaware Avenue in the City of Nixa (Christian County) beneath part of a house owned by Mr. Norman Scrivener. On that day the depth of the structure was reportedly measured at about 25 m (75 ft.) (Figure 11). This was after engulfing the garage, which included a medium-sized sedan. Neither groundwater nor bedrock was ever observed in the collapse. Bedrock beneath the structure is the Mississippian-age Burlington Limestone. The Burlington Limestone typically weathers severely along fracture traces to create a very irregular (cutter and pinnacle) bedrock surface. The collapse structure developed in a structured reddish-brown, cherty, and clayey residuum (Figure 12).

The Nixa area is well known for the development of sinkholes. Forty sinkholes have been

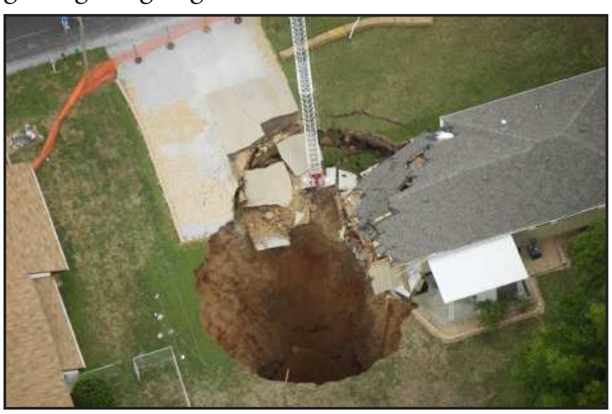


Figure 11 *Aerial view of the a collapse at 327 N. Delaware Avenue, Nixa, Christian County, Missouri, beneath part of a house owned by Mr. Norman Scrivener. The depth of the structure was measured at about 25 m (75 ft.). This was after engulfing the garage, which included a medium-sized sedan.*

Figure 12 *The collapse structure developed in a structured reddish-brown, cherty, and clayey residuum as can be seen from this view. From the angle of this picture the lack of subsidence of the area is apparent. Also visible is an abandoned steel septic tank.*

mapped within the Nixa municipality using USGS 1:24,000 scale topographic maps. The highest concentration in the general area is just to the north of the city limits. The closest mapped sinkhole to the Nixa collapse is about 400 m (¼ mi.) to the south. Considering the concentrated development of sinkholes in this area, it is interesting to note that no signs of subsidence were observed at the site prior to the collapse.

Evaluation of Collapse Potential

Sites that have potential for soil-cover collapse, as described above, are not always in areas of obvious karst development. Collapses have occurred at sites that are quite remote from active sinkholes, but are commonly within valleys that lose surface water flow to dolomite or limestone bedrock. Since the 1978 collapse of the West Plains Lagoon, geologists at DGLS have evaluated collapse potential of proposed lagoon sites, with the goal of avoiding future catastrophic collapse and widespread groundwater contamination. A high collapse potential, based on these geologic evaluations, requires the construction of a structurally reinforced treatment system. No similar collapses have been reported at a state-regulated waste treatment facility constructed after 1978.

DGLS has also worked with local governments and individuals to better define and locate soil-cover karst collapse hazards. The recent Berg Collapse did not immediately threaten groundwater, but there was a need to address the potential threat to an adjacent county road. DGLS geologists completed a geophysical survey of the site using electrical resistivity methods to determine the depth of bedrock and locate possible extensions of karst conduits on either end of the collapse (Figure 10). These surveys suggest the road may be damaged through natural equilibration of the sinkhole walls, or through renewed collapse and expansion of the current sink margin.

Techniques for Future Site Assessment

Shallow groundwater in soils and its effect on plants near pre-collapse locations, may play an important role in the future detection of soil-cover collapses. If soil groundwater levels are depressed in the vicinity of active soil-cover collapses, the vegetation in these areas may be stressed compared to adjacent areas. Satellite imagery in appropriate spectral bands can detect small differences in color and moisture content in vegetation. These data, when combined with geologic data in a geographic information system, can identify targets for ground truth investigations (Rouse et al., 2004). Currently, the available imagery resolution is too low to identify small pre-collapse targets. Other ground factors such as urban development can also impede target identification. As satellite imagery resolution and availability improves, this type of analysis may lead to more efficient site investigations and regional analyses for soil-cover karst collapse hazards.

Conclusions

Catastrophic soil-cover karst collapses have been costly in Missouri, causing groundwater contamination and damage to municipal and private property. The geologic settings in which collapses occur are well understood, and pre-construction site evaluations can reduce the risk of possible, future soil-cover collapse. Collapse-prone areas are commonly in losing stream settings, regardless of the proximity to active sinkholes or other indicators of subsurface karst. Therefore, pre-construction investigations are often necessary to determine collapse potential in the area.

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THE BERMUDA CAVE AND KARST INFORMATION SYSTEM: A GIS DECISION-SUPPORT TOOL FOR CAVE AND KARST MANAGEMENT AND CONSERVATION

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Abstract

Bermuda is a densely populated island with approximately 65,000 inhabitants and 200 caves. These caves began forming about 1 million years ago, and many include passages with deep anchialine pools and extensive underwater networks. Bermuda's caves are significant for their numerous and delicate speleothems, as well as their large variety of cave-adapted life, making them globally recognized as a biodiversity hotspot. Many of these species were previously unknown, and 21 are currently listed as critically endangered under the Bermuda Protected Species Act in accordance with IUCN (International Union for the Conservation of Nature) criteria. Their importance as a part of Bermuda's natural heritage, the fact that they support approximately 25% of Bermuda's endemic fauna and that they contain the best-preserved archives of Bermuda's entire previous natural history (including biological, geological and palaeontological history) adds to their local significance. Unfortunately the rapid pace of development, which continues to escalate, as well as vandalism, pollution and other factors have significantly impacted and continue to threaten Bermuda's unique cave resources.

In 2002, the multidisciplinary Bermuda Cave and Karst Information System (BeCKIS) project was established, leveraging the efforts of professionals and volunteers alike into a common GIS database. BeCKIS has been used to establish baseline information from past observations, determine change over time, gain insight to the effects of development and landuse practices, and to create supporting documents and maps to increase public and governmental awareness. It is available and used by key resource managers to assist them in decision-making, with goals to continue evolving the GIS program further as an integral component of the decision-making process to yield policies and regulations that will preserve these unique cave resources.

Key words: island karst management, databases, GIS, karst hydrology, cave geology, cave history, cave biology, contaminants, law, Bermuda

Introduction

Bermuda is located in the western Atlantic Ocean 960 kilometers off the coast of North Carolina, United States. It is the second-most densely populated island in the world, with approximately 65,000 inhabitants in a land area of 53.7 km^2. Approximately 200 caves have been discovered in Bermuda, many of which are profusely decorated with delicate and unique speleothems. Many caves include passages which extend to sea level and contain deep anchialine pools and extensive underwater networks.

A large variety of cave-adapted life, including previously unknown species, has been found in these underwater caves. Of the species identified in Bermuda's caves, 21 are currently on the Bermuda Protected Species Act critically endangered species list. The high population density and resultant development pressures, vandalism, pollution and other negative factors have significantly impacted and continue to threaten Bermuda's unique cave resources.

While observation and explorations of Bermuda's caves date from the earliest days of human settlement, the fact that most of the caves form part of an extensive network of submerged passages has meant that cave research is limited to the skills of a select group of cave experts.

In early 2002 the Bermuda Cave and Karst Information System (BeCKIS) project was established with the primary goals of increasing public awareness of Bermuda's caves and cave life, increasing awareness of negative impacts on these resources, and promoting the scientific study of Bermuda caves. BeCKIS utilizes GIS software from ESRI, one of the early project sponsors, to maintain a database and inventory of cave locations and field observations.

The GIS is being used to establish baseline information from past observations, to query and analyze the data and to understand relationships with other geographic and hydrologic factors. The development of a GIS database also facilitates the production of high quality cartographic maps invaluable to record these features, understand their significance and relationships, and effectively communicate with others. The system has increasingly leveraged the efforts of professionals and volunteers alike, and represents a multi-national effort with partner organizations on both sides of the Atlantic including the Departments of Conservation Services and Planning and Environmental Protection in Bermuda.

BeCKIS is facilitated through the Bermuda Biodiversity Project (BBP) at the Bermuda Aquarium, Museum and Zoo. Established in 1997, the aims of the BBP are three fold: to collect and collate information on Bermuda's natural history, to identify gaps in the information and encourage collaborations to fill these gaps and to ensure that all the information is made available and widely disseminated.

Geology

Bermuda sits atop an extinct, volcanic seamount capped by limestone. During the Pleistocene approximately 1 million years ago, Bermuda's limestone caves began forming during glacial periods when sea level was as much as 120 m lower than present (Palmer et al. 1977) and the land mass was about 1,000 km^2 or 20 times larger than present. At this time, there would have been a sizeable, fresh, groundwater body, which resulted in the formation of the caves. Post glacial sea level rises subsequently led to large portions of these caves becoming drowned with seawater, which displaced the freshwater. This is evident by the presence of submerged stalactites and stalagmites, features in today's submerged caves. Sea levels have reportedly been as much as 22 m above present (Hearty et al. 1999).

Speleological History

Referenced in the writings of Bermuda's earliest explorers (Forney 1973, Iliffe 1993) the Island's caves have long been a feature of interest, a subject of scientific study, a place of refuge and of worship, an important natural resource for tourism and more recently a biodiversity hotspot and habitat of global significance.

In 1983 Dr. Tom Iliffe completed a two-year survey of cave features on the island, identifying 166 caves. The caves were evaluated and rated regarding specific factors, including vandalism, pollution, dumping, biological significance, threat, speleothems and others. Each cave was rated on a scale of one to five in each category. This information provided the valuable baseline data for developing the digital basemap of caves, and has also served as a basis for continuing exploration, mapping and research activities.

Establishment of the Cave GIS

In 2001, several contacts were made that catalyzed a project trip in January, 2002, which brought together a small, but multi-national group of volunteers and professionals— cavers, cave divers, researchers, and students—to map caves and collect data to establish a baseline of information to date. The use of a Geographic Information System (GIS) was proposed to develop a Cave and Karst Information System to store cave location information, cave survey data and biological and other inventory data that had been collected.

The GIS would be used to store, manage, query, and analyze the data to understand relationships of these features to other geographic and hydrologic factors. Perhaps more importantly, it was hoped that this GIS information would be incorporated into the country's GIS, and become part of the policy and decision-making process to help preserve and protect these valuable resources. This system was named the Bermuda Cave and Karst Information System, or BeCKIS.

The initial step was to develop a GIS data layer from the information that Tom Iliffe had completed in 1983. Cave locations where obtained from derived XY coordinates that had been collected. These were imported into a GIS data layer, and attribute fields were added to store the evaluation ratings for the observed factors. Additional layers were obtained from the Bermuda Planning Department, or derived from available information. These layers included several layers of high-resolution imagery obtained at different times, geology, elevation models, parish boundaries, building footprints and others.

With the GIS foundation established, the

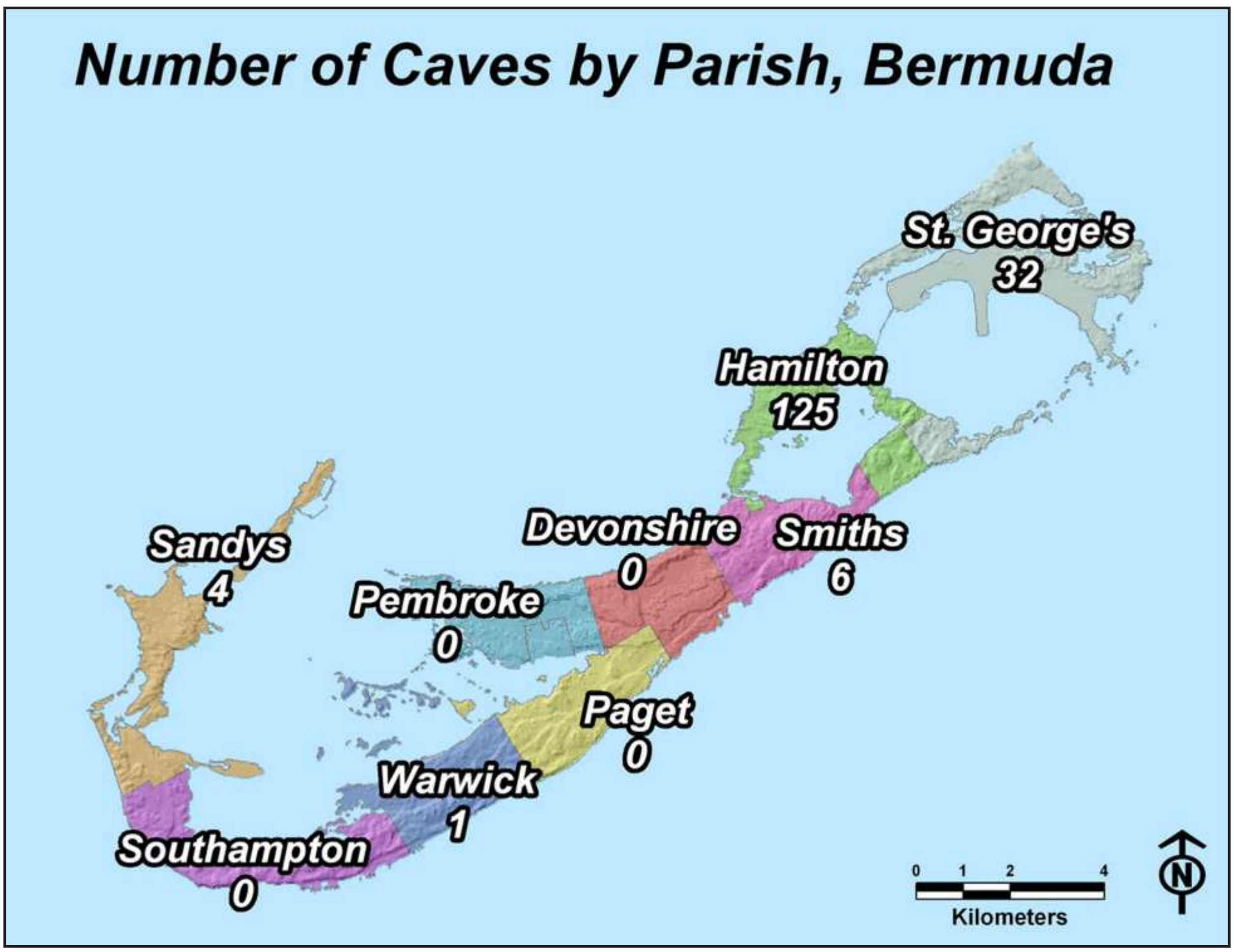

Figure 1 GIS map showing the number of caves per parish based on the 1983 cave inventory. Note the high number of caves in Hamilton Parish, where the Walsingham limestone is found.

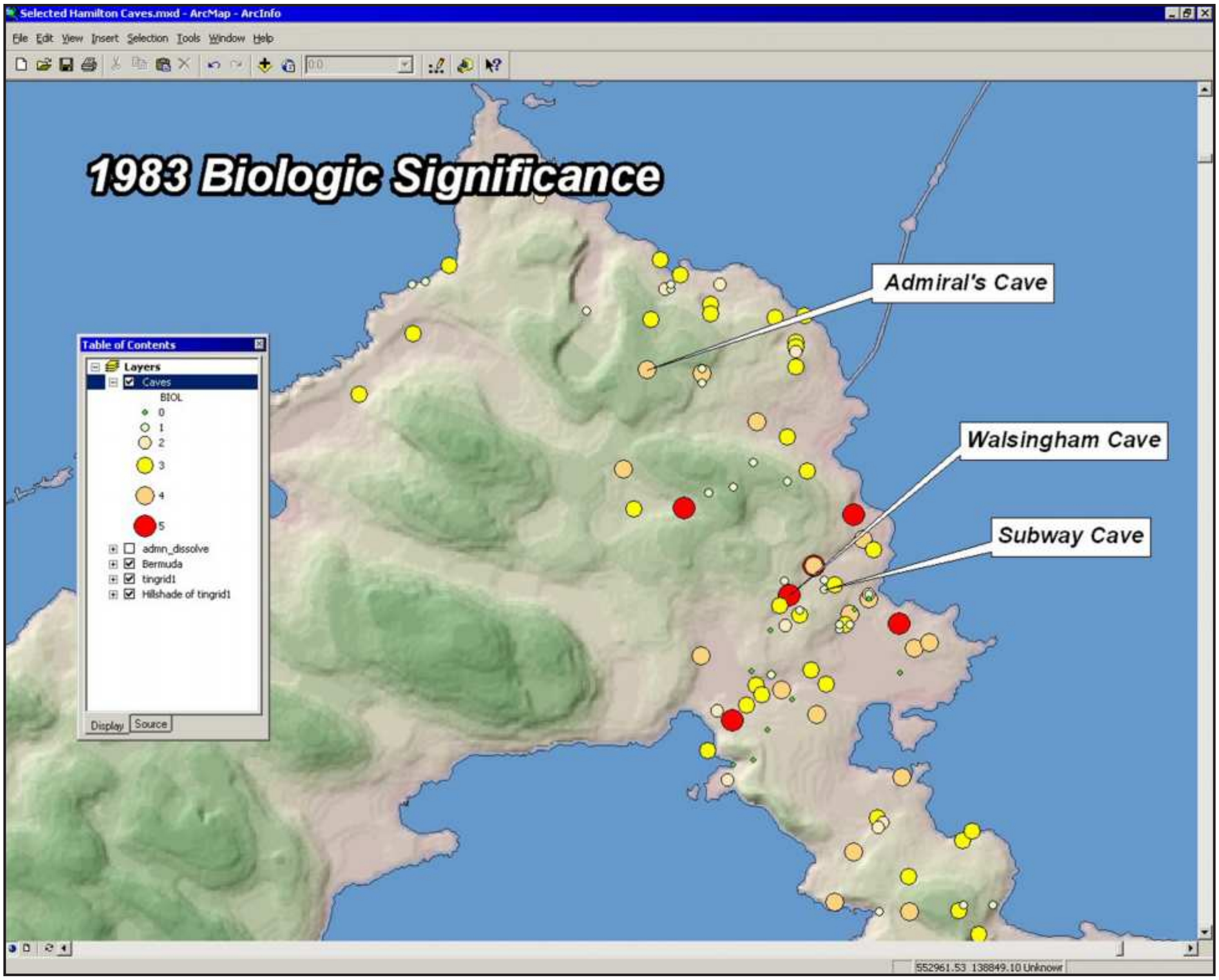

Figure 2 *Screen shot of GIS map of the northeastern portion of Hamilton Parish showing cave locations with graduated symbols indicating biological significance, based Iliffe's 1983 database.*

database was used in the production of a variety of high-quality cartographic maps. These maps included those showing the density of caves by parish, the relationships of caves to island geology, the proximity to housing and roads and thematic maps showing the inventoried cave factors (Figures 1 and 2). A variety of digital and hardcopy maps were authored and supported a variety of publications, public presentations, and inter- and intra-organization communications (Figure 3). These have played a key role in increasing the awareness of Bermuda's caves, and gaining an appreciation of their vulnerability.

BeCKIS Evolves

The BeCKIS has been leveraged for ongoing research and other activities, and has benefited as new information has been incorporated. In 2003, Darcy Gibbons completed her Master's thesis titled *An Environmental Assessment of Bermuda Cave Health* (Gibbons, 2003). Gibbons built upon the 1983 baseline evaluation with her own observations 20 years later. These provided insight to change and impacts over time, and added updated information including new GPS coordinates, elevation at each entrance, and new entries. Other graduate students are also building upon this information, and will in turn contribute to it.

But many challenges still remain. The intermittent nature of cave survey and study make it difficult to maintain continuity and pick up where previous work has left off. Definitive protocols for collection of cave survey and inventory information still need to be established, and ancillary information and content, such as photographs and cave maps still need to be integrated into the system. Some of this work has been prototyped with the georefer-

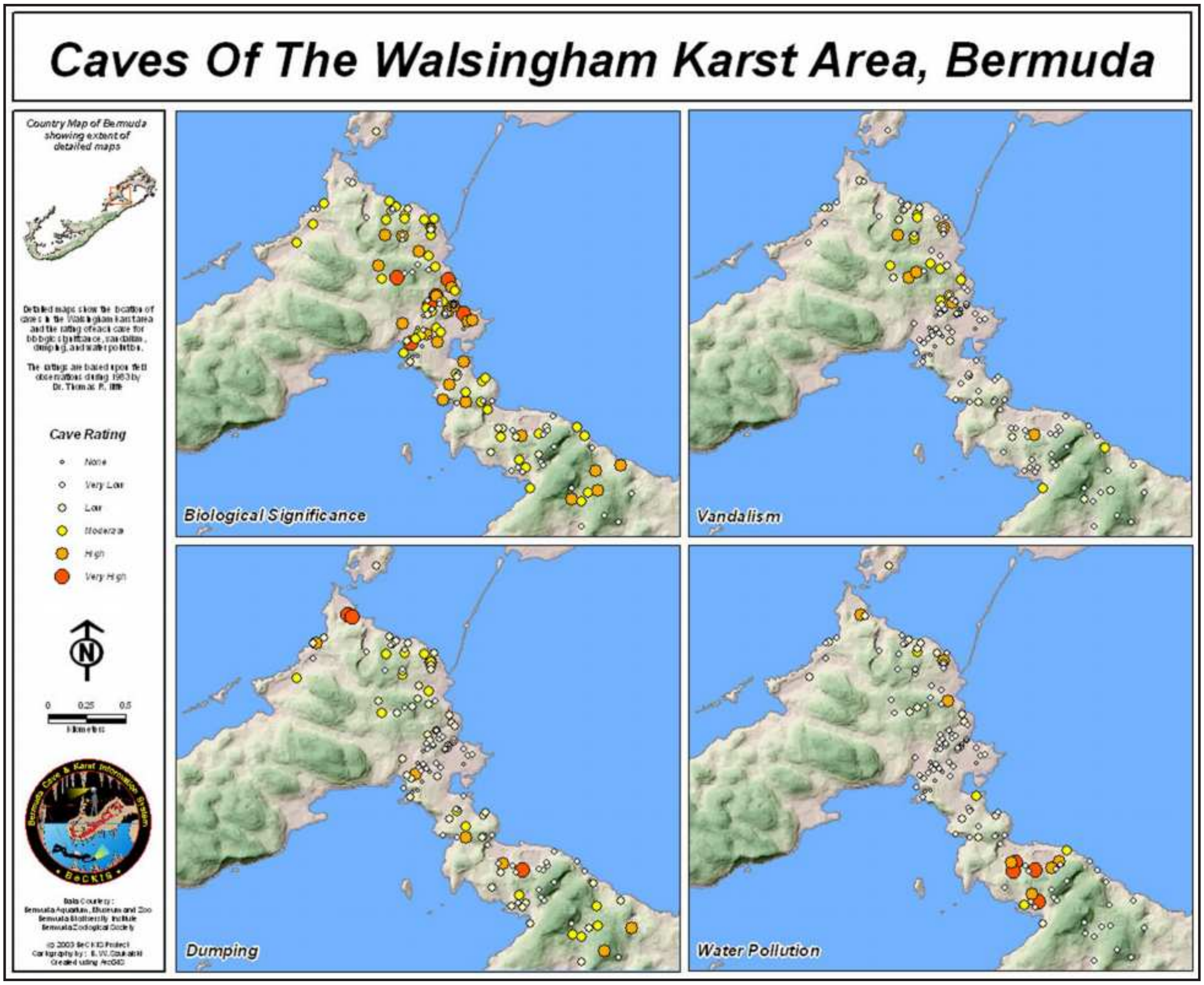

Figure 3 *A poster created from the GIS database showing cave locations and various evaluated parameters based on Iliffe's 1983 database.*

encing of the detailed plan maps of the surveyed caves, and the digitization of "cave footprints" from these maps showing in detail the proximity of caves to quarries, constructions, and injection wells, and providing additional information that can contribute to management and preservation (Figure 4). Despite the need for additional work, the BeCKIS provides a valuable foundation which should increase in value and use as additional information becomes incorporated.

Use within the Government and Policy

Under Bermuda's legislative framework, the Island's caves are afforded the highest level of protection through the Bermuda Planning Act 1999. Further protection has been afforded through the Protected Species Act 2003, which lists 23 of Bermuda's stygiobitic fauna and requires a cave fauna recovery plan to be implemented for these species. While this legislation provides a solid foundation for conservation, local resource managers have historically been challenged to ensure effective management, primarily because of a lack of information, or at least access to it. Clearly one of the most significant of these challenges relates to the extensive, submerged nature of the underwater passages.

Through BeCKIS, this information gap is being bridged. A key constraint at present is that there is no clearly defined understanding of what baseline conditions in the caves should be. It is challenging in the absence of this data, to accurately assess or predict human impacts. Further, without accurate mapping of the caves, implementation of policy is also compromised.

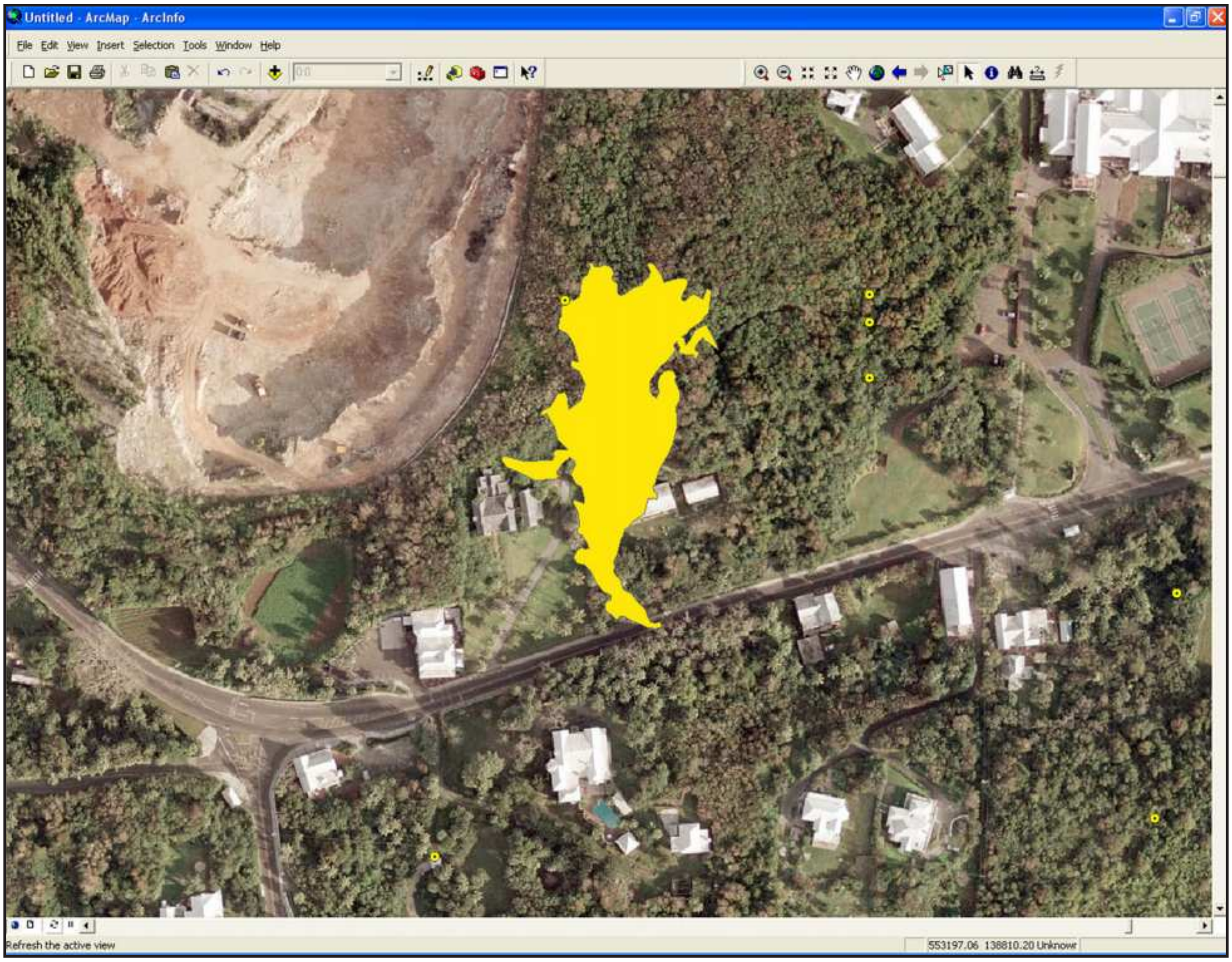

Figure 4 *The outline of Admiral's Cave, Hamilton Parish, derived from the final cave map. The map was scanned, georeferenced and digitized to create an overlay on the high-resolution aerial imagery.*

Through BeCKIS, ongoing research, targeted mapping expeditions and increased public awareness are all key activities that are strengthening our understanding of, and ability to manage Bermuda's unique cave systems. Integral to this is the use of a map-based system through which all the data being collated is made available to resource managers so that they are better able to make informed decisions that relate to planning zonings and construction activity, location of cesspits, drilling of freshwater wells, development of show caves for tourism, development of specific recovery plans and establishment of monitoring activities.

In 1990 the Geospatial Information Systems Committee was formed in Bermuda, initially as an interest group seeking support for GIS development within the Bermuda Government. Their focus has been the coordination of activities across the government to reduce duplication of effort and develop GIS resources. It is intended that through BeCKIS, we will continue to help evolve the GIS program further as an integral component of the decision-making process to yield policies and regulations that will preserve Bermuda's unique cave resources.

Summary

Bermuda's cave resources remain in the balance between human needs and preservation. The BeCKIS system has proven a valuable system for storing and managing cave and karst information, and has proven an effective tool for developing maps and for analysis that contribute to the decision-making process to yield policies and regulations that will preserve these unique cave resources.

Acknowledgments

This project was supported by ESRI (Environmental Systems Research Institute, Inc.), the Bermuda Departments of Conservation Services, Planning and Environmental Protection, and the Geospatial Information Systems Committee in Bermuda. BeCKIS is facilitated through the Bermuda Biodiversity Project (BBP) at the Bermuda Aquarium, Museum and Zoo.

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MAPPING FLOODED CAVES FROM ABOVE: SURFACE KARST INVENTORY OF THE YUCATAN PENINSULA

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Abstract

More than 700 km of flooded cave have been documented along the 200 km of coastline south of Cancún, Yucatán Peninsula, México. Development projections include a 40-fold increase in population in the coming 20 years. Access to the caves is through collapse sinkholes called cenotes, which may serve as surface proxies for the underlying cave systems. Cenote mapping will likely expedite exploration and ultimately contribute to water and waste management. However, all data on cenotes remains limited. Modest efforts began in 2006 to establish a standardized cenote data collection methodology bridging geological, biological, archeological, and land use aspects for use by local persons, explorers, and visiting interested persons. Therefore the methodology needed to be usable by persons with no specific background in karst or the local area. A three-page data collection form is supported by a 10-page orientation guide including instructions for field sketching, and a field picture guide. In 2006-2007, volunteers spent a total of four months collecting data on 80 sites. In 2008 the project will include more volunteers, data entry into a GIS, and initial interpretations of cenote geospatial data with structural and topographic features in this subtle, low relief karst platform. The greatest long term challenge in this effort remains legal issues surrounding information management and ultimately transfer to government decision makers.

Key words: mapping, karst, cenotes, Mexico, hydrology, contaminants, ecology, land use

Introduction

The Yucatan peninsula is the ~150,000 km^2 emergent portion of the Yucatán Platform that divides the Gulf of Mexico from the Caribbean Sea. The aquifer is density stratified, with a lens of freshwater overlying naturally intruding saline water. The aquifer system remains the only natural source of potable water for the whole peninsula, while it is also widely used under government directives as a sink for treated and untreated effluent. Mexican government plans include the establishment of several new urban centers with target populations of 200,000 each along the Caribbean coast, which will result in a nearly contiguous urban strip from ~50 km south of Cancún, to the northern border of the Sian Ka'an Biosphere Reserve. These development plans aim to increase the local population 40-fold in the coming 20 years.

The whole peninsula is highly karstified. However, there is a notable concentration of more than 700 km of explored caves along the 200-km, north-central portion of the Caribbean coast and cave density reaches >4/km^2 in well-explored areas (Beddows, 2004). Collapse sinkholes, locally called cenotes, are abundant throughout the region, and these provide access to the underlying cave networks. Most of these caves explored so far are water-filled, and exploration is therefore by cave diving. The geomorphology and speleogenesis of the flooded caves shows that these develop principally in relation to sea level and the depth of the fresh-saline mixing zone where the phenomenon of mixing corrosion generates waters undersaturated with respect to calcium carbonate *in situ* (Smart et al., 2006; Smith et al., in preparation).

The cenotes overlie the phreatic cave networks, and they form principally by mechanical collapse of the cave roofs during low sea levels when buoyant support is lost. The vast majority of cenotes along the Caribbean coast do not have exposed water pools and remain invisible from the air under the closed forest canopy. Mapping all of them aerially remains a serious challenge. Nonetheless, the cenotes remain excellent surface proxies for the underlying caves which function as the river networks through this large region. Mapping of cenotes will not only expedite direct exploration of the subterranean rivers but may also provide the basis for a quantified ecological signature based on the distinct vegetation often growing in the cenotes. Mapping will equally contribute to water and waste management by generating the ability to test questions of structural and geological controls on speleogenesis at the regional scale . This project aims to establish a georeferenced surface karst inventory of features situated principally within the proposed urban footprints with data generated by a wide range of "stakeholders."

Data Collection Methodology

Beginning in 2006, the efforts began to establish a standardized methodology for collecting data on cenotes, bridging geological, biological, archeological, and land use aspects for use by local persons, explorers, and visiting interested persons. The methodology needed to be used by persons with no specific background in karst or the local area. The surface karst inventory (SKI) package presently consists of:

- Instruction Booklet of ~10 pages: This booklet has a brief introduction to karst in the local context, scientific terms needed for collecting data, instructions on how to collect correct GPS points, and exercises to build field sketching and mapping skills.
- Picture guide of features of interest.
- Data collection sheets which presently fill three pages, mostly with tick-boxes to facilitate easy and rapid data entry (See Table 1).
- Grid paper for sketching the site to scale.
- Data inventory sheets to track the sites visited and the photographs taken.

Discussion

Field Sketches – When photos will not do

It is a common temptation to document sites using only digital photographs. However the information on location, scale, and orientation of the field of view are rarely adequately documented, and therefore these photos fail to show the site dimensions, orientation of features within the image, depth profiles, etc.

Most often digital images taken quickly only show the undergrowth vegetation. At a minimum

Table 1 Information sections currently included in the Surface Karst Inventory data collection sheets.

1.1 Name of Inventory person(s):	5.1 Site Type
1.2 Position (Volunteer, resident, tourist, other.):	5.2 Site Usage
	5.3 Floor Covering
2.1 Date of site visit	5.4 Vegetation
2.2 Date form filled out	5.5 Formations – Karst and Cave related
2.3 Your familiarity with the site	5.6 Geology
	5.7 Archaeology
3.1 common name of site (if exists)	5.8 Water
3.2 Directions to site (sketch of how you got there)	5.9 Critters
3.3 General location (nearest settlement)	
3.4 GPS Coordinates	6.1 Dimensions – aerial perspective
3.5 GPS Make, Model, Projection used:	+ SKETCH TO SCALE
	6.2 Dimensions – vertical development
4.1 Landowner name + contact information	+ SKETCH TO SCALE
4.2 Who showed you/told you about the site?	Entrance dimensions and details

this project requires low-resolution, quantitative data of the long and short axis in both the plane and cross-section orientations notably to address questions of fracture and structural controls on cenote collapse formation, and how these factors may relate on a larger scale to regional speleogenesis.

We assume a low level of prior knowledge of the target workers, and so far a significant challenge has been providing instructions on how to draw simple, but adequate plan and cross-section field sketches with key measurements. We believe that providing limited written instructions, but with numerous examples of good field sketches followed by exercises on estimating distances, will result in adequate quality site sketches. Distance estimation exercises and methods include: calibration of paces, calibration of visual estimates inside a room analogous to inside a cave and outdoors (e.g. distance between trees), and use of a knotted string for horizontal measurements, combined with a plumb weight for vertical measurements inside actual sites.

While we are not trying to enforce standardized and codified symbology for the maps, the foundation of good field map and sketching is required, including the listing of symbols and shading marks used, drawing to scale (1 square on the grid paper equals a stated measure such as 1 m), north arrow, and metadata including site name and date.

We think that new data collectors with no prior experience may be trained in less than one day. Figure 1 (a & b) provides examples of sketches generated by volunteers with no prior experience in karst shortly after their involvement in the project. While the more accurate and computer-enhanced surveys generated by experienced cave mapping volunteers provide some advantages (Figure 1c), in all cases the simpler scale sketches equally serve the purpose of documenting the fundamental aspects of the feature, which may be of particular value when significant cenote modification has occurred (Figure 2).

Characteristics of Target Participants

This effort aims ultimately to include the participation of local landowners, staff of nongovernmental organizations, and municipal government agencies, scientifically knowledgeable volunteers recruited for the project, cave explorers and cave divers visiting and living in the area, and university

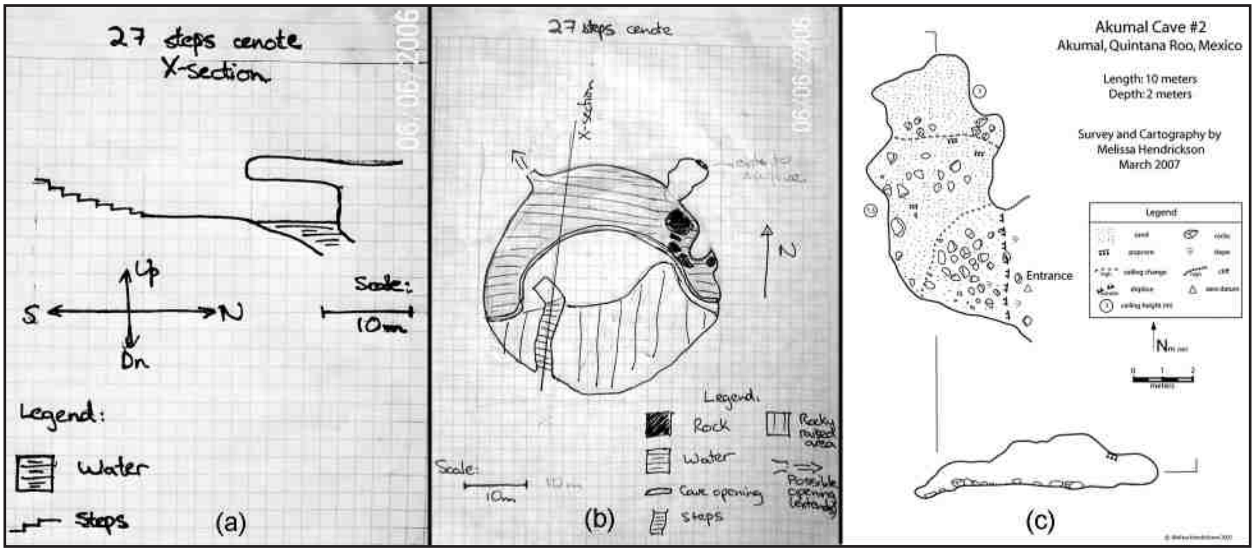

Figure 1 *Examples of cenote field sketches in cross section (a) and plan form (b) generated by volunteers with no previous knowledge of karst, and comparison with that generated by an experienced cave surveyor (c)*

Figure 2 *Recent example of cenote enlargement using heavy machinery. The landowner created an open water pool to attract paying snorkelers. (Photo by Robbie Schmittner)*

and high-school groups on field trips.

Of the five volunteers who have so far employed the existing methodology, the ability to speak Spanish and explain the goals of the work to the local persons and landowners has proven most valuable in generating leads and access to new and previously unidentified cenotes. Even without the ability to speak Spanish, there remains a large number of known and publicly accessible sites that have never been documented, which would keep a willing volunteer occupied.

With the number of cenotes being modified, it is also becoming increasingly obvious that return site visits perhaps every two years will prove valuable in documenting changes to the surface karst features, notably in relation to tourism and waste disposal activities.

Future of the Surface Karst Inventory

In 2006-07, three volunteers spent a total of four months dedicated to collecting data on 80 sites, with a smaller number of contributions coming from two of the local cave divers. In 2008, the goals include

- upgrading the data collection sheets with the input of the dedicated volunteers of this project,
- additional data collection by more volunteers,
- entry of all data collected to date into a GIS framework which includes the significant geopolitical features of coastline and proposed urban footprints,
- initial attempts at interpretations of cenote geospatial data with structural and topographic features in this subtle, low-relief karst platform.

Effort so far has been concentrated in the area of the village of Akumal located 105 km south of Cancún, slated to be the city of Akumal with a population of 200,000 by 2036. Akumal and the neighboring village of Puerto Aventuras, also slated to become urbanized, are likely to remain the focal points of efforts in 2008, in part because of the local support available through the Centro Ecologico Akumal (www.ceakumal.org). Other significant collaborations include financial support from the Quintana Roo Speleological Society, and data sharing with Amigos de Sian Ka'an. Most recently, the establishment of the GIS aspects are beginning through coordination with Aaron Addison of Washington University in St. Louis. The greatest long term challenge in this effort remains the legal issues surrounding information management and ultimately transfer to government decision makers, and these will remain to be addressed beyond 2008.

Acknowledgments

We would like to thank the growing number of people who have supported this project so far and in particular the landowners who have been kind enough to grant access to their properties. We thank the Centro Ecological Akumal for acting as a safe home base for volunteers within their cost sharing research scheme; Cave Exploration for the use of field safety equipment, on- site orientation of volunteers, and GPS equipment; and the Quintana Roo Speleological Society (QRSS) for a grant supporting basic field expenses.

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WHEN THE SURVEY IS NOT ENOUGH: TEMPERATURE, SALINITY, AND DYE TRACING REVEAL FLOW PATHS

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Abstract

Tourism-driven development along the Caribbean coast of the Yucatán Peninsula is resulting in a nearly continuous 200 km urban corridor stretching from Cancún to south of Tulum. There is an urgent demand for hydrogeological knowledge in this area, where cave diving exploration is revealing a dense network of more than 700 km of flooded cave passages. The widespread speleothem deposits below the water table indicate that the caves are polygenetic, having been drained and re-flooded. The distinct depth levels of passages are tied to speleogenesis at past sea levels and climate conditions. Where older sections of cave have been re-flooded, these often show varying degrees of hydrodynamic disequilibrium with modern boundary conditions. Consequently not all explored caves are necessarily hydrologically active. Temperature and salinity profiles along a major trunk passage in Sistema Aktun Ha, upstream of Cenote Car Wash, have helped map out distinct water masses. Dye releases in two locations confirm two distinct hydrological regimes, and that the water does not flow along the biggest apparent flow path. These results show the value of cost-effective physico-chemical mapping of water masses and modified dye tracing techniques in translating cave surveys and maps into valuable hydrological knowledge.

Key words: hydrology, cave diving, Mexico, dye tracing, water chemistry, mapping

Introduction

Sistema Aktun Ha is a water filled complex of two caves located ~8.6 km inland from the Caribbean coast on the Tulum-Coba highway (Figure 1a). The system is comprised of a "spring side" explored to a length of 1467m, extending NW from the central entrance sinkhole, called Cenote Car Wash, while on the coastward "siphon side" there is a water-filled cave explored for 1342 m. Cenote Car Wash is an open basin of water while the other two cenotes are naturally small and sediment choked. All three are post-genetic offset collapses, such that the actual point of entry into the water is offset from the apparent principal flow path. This cave system was one of the first explored and mapped in detail in the region, with a published survey in 1990 by J.G. Coke and T.M. Yong (1990). No exploration or survey data have been compiled for this cave since 1999, despite this having been one of the more popular cave dives in the whole region.

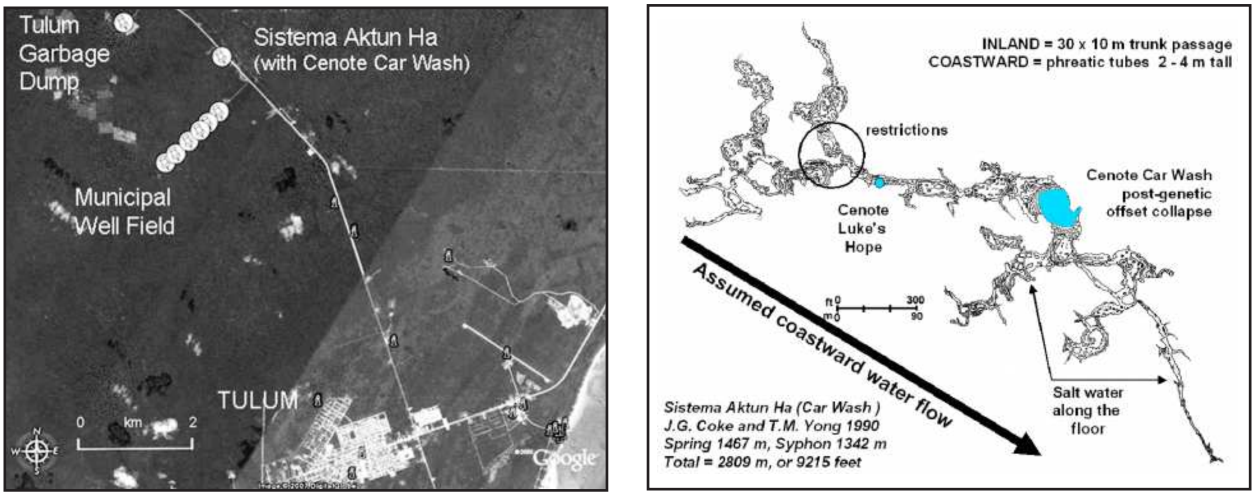

Figure 1(a) *Location of Cenote Car Wash within the Sistema Aktun Ha at 8.6 km straight line distance inland from the Caribbean Sea on the Tulum-Coba highway. The locations of the individual wells of the Tulum municipal well field, as well as the Tulum garbage dump are indicated.*
(b) *Survey of Sistema Aktun Ha with annotations (Coke and Yonge 1990).*

The cave system is flanked within 2 km by the Tulum municipal well field, while inland is the municipal unregulated garbage dump (however, it is reported by word of mouth that the dump has been closed in the last two years; Figure 1b). The dominant orientation of the cave complex is NW-SE, consistent with the dominant direction of most cave development in the region (Smart et al., 2006), and suggesting that the cave acts as a conduit for groundwater from the area of the dump and coastward to the well field. This is further supported by the orientation along the hydraulic gradient of the region, although this is exceptionally low at 10^{-5} (Beddows 2004).

Discrimination of Distinct Water Masses

From 2000 through 2007, a number of vertical physico-chemical profiles have been obtained in most areas of the cave using multi-parameter probes (Hydrolab M5, or YSI600XLM). These profiles are collected at discrete locations by a cave diver extending the probe out horizontally and descending slowly and smoothly from the ceiling to the floor, all while moving slowly forward into undisturbed water mass (Figure 2a). The data pertaining to the profile is extracted from the whole dive data, and then plotted in relation to depth. At shallow depths (< 7 m) in Sistema Aktun Ha, like other cave systems of the region, pockets of isolated water are often encountered within the cenotes with distinct temperatures from rapid recharge of storm water or from direct insolation, and coloration due to algal blooms or organic acids (tannins). These surface waters are affected by top-down processes, and are not part of the active circulation of groundwater through the cave. The mixing zone between the fresh and saline water in this density stratified aquifer is encountered at ~20 m in Sistema Aktun Ha and below that is saline water which can only be accessed in the coastward sections of this cave.

Distinct water masses are shown by temperature and specific electrical conductivity (SpC) profile data from 2007 at depths of 9-12 m below the water table (Figure 2b) from five locations on the inland side of Cenote Car Wash (as indicated

Figure 2(a). *Collection of multi-parameterprofile data by a cave diver (Photo by A. Kuecha).*

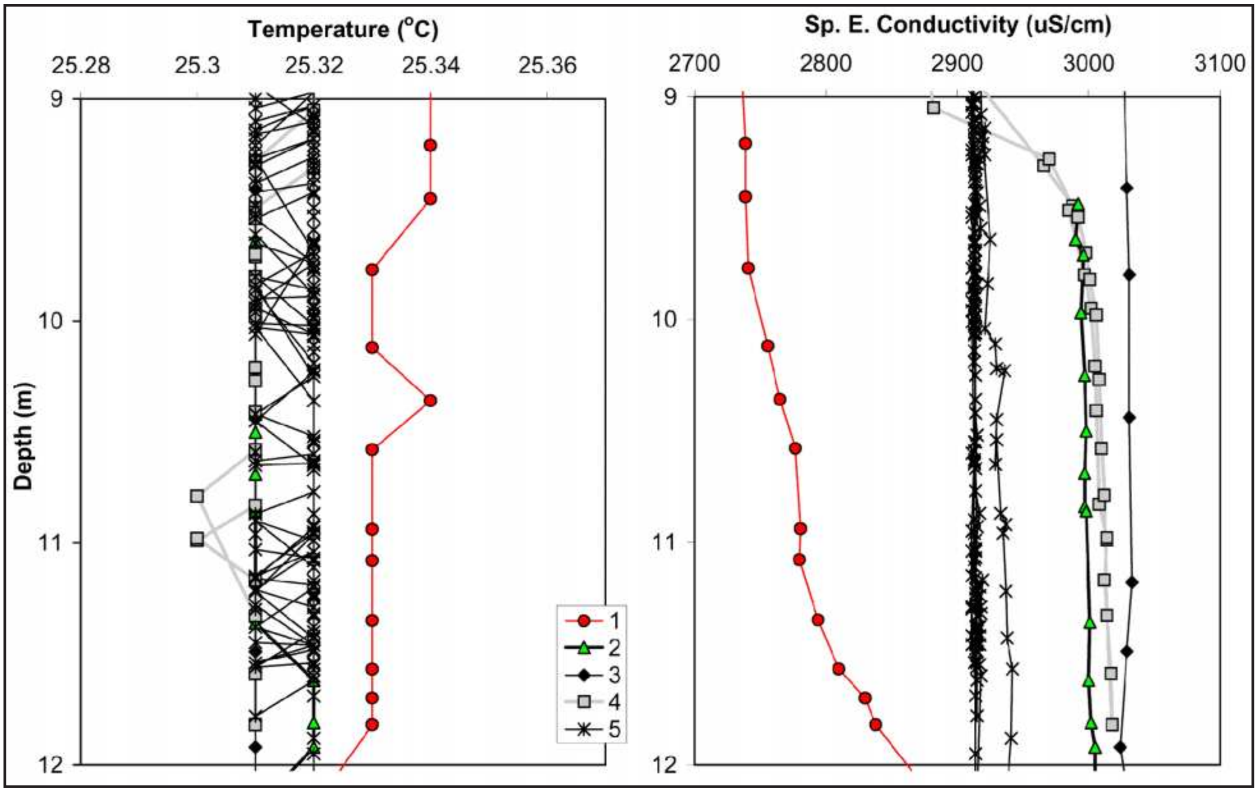

Figure 2(b) *Temperature and specific electrical conductance (SpC) between 9 and 12 m depth below the water table from five locations in Sistema Aktun Ha as identified in Figure 2(c).*

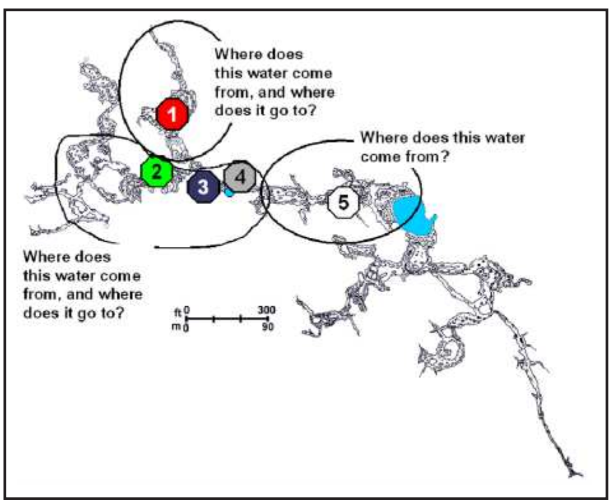

Figure 2(c)

in Figure 2c). This depth increment is selected here since it is within the principal depth of conduit development in this cave system along which the fresh water may flow. Almost all of the water throughout the cave is at the same temperature (25.31-25.32 °C) except for Profile 1 from the inland NE section of the cave (Adriana's Room) where the temperature is slightly cooler. However the distinctness of this water is clearly discriminated by looking at the SpC, which is significantly lower than elsewhere in the cave with a value of ~2750 µS/cm (minimum 2900 µS/cm). A second type of water is discriminated by looking at Profiles 2, 3, and 4 from the inland northwest and central portion of the cave around Cenote Luke's Hope. Here the waters are all 25.31-25.32 °C, but with generally higher SpC of ~3000 µS/cm. Profile 5 data is a compilation from along the whole of the passage inland from Cenote Car Wash and approaching, but not reaching, Cenote Luke's Hope. Here the water is of intermediate SpC with values of 2900 µS/cm.

In the inland section of this cave system, the common idea amongst cave divers is that the water flows simply from the northwest and northeast segments, along the large trunk passage measuring 30 x 10 m, around and through Cenote Car Wash, and then on into the coastward sections of the cave. However, the physico-chemical data from temperature and SpC clearly show three distinct water masses, and these cannot be explained by the hypothesized hydrology. There is no likely process for the water in the northeast branch (Profile 1) to be cooled before merging into the water flowing into

Cenote Car Wash. Equally there is no likely process for the removal of solutes and salts from the second water mass in the northwest segment and near Luke's Hope, such that it arrives more dilute should it flow coastward directly through Cenote Car Wash.

Dye Tracing to Test for Hydraulic Connectivity

Fluorescent dye tracing was used to test the hydrological connectivity between the different zones of the cave identified to have different water masses by physico-chemical profiles (Figure 2c). A single sampling location in Cenote Car Wash was used with water samples pumped manually from ~11 m water depth through a tube anchored in the middle of the NW inland side of the debris-collapse pile within Cenote Car Wash (Figure 3a, 3b). On April 19, 2007, water soluble and food/domestic product grade dyes were released within the flooded cave by cave divers with Rhodamine WT released in the NE inland segment (FL on Figure 3b), and Uranine (sodium Fluorescein) released immediately downstream of Cenote Luke's Hope. Background water samples were collected before dye release, and then at intervals of 1/10th the time elapsed since the first dye release rounded to the closest 10 minutes. The internal volume of the sample tubing was calculated, and voided into a bucket before each sample. No adjustments to the time series have been made to account for the 2–5 minutes spent voiding the tube volume. Water samples were analyzed for relative fluorescent intensity at the University of Western Ontario using a PTI QM-1 spectrofluorometer with a xenon arc source. Both emission and excitation variations were accounted for with real-time corrections. Synchronous-scan spectra were produced at delta lambda = 20 from excitation range 250 to 600 nm and emission of 270-600 nm.

The breakthrough of Uranine dye was rapidly observed in the water samples from Cenote Car Wash with a recession curve spanning 13 hours, and returned to near background levels afterwards, although a possible secondary pulse is evident through the last sample taken 21.5 hours after initial appearance (Figure 4). In contrast, the fluorescent intensity at 578 nm for Rhodamine WT showed little variation over the course of sampling, which may simply result from natural variations in

Figure 3.(a) Cave divers handling two lengths of the sample tubing at the cenote surface.

Figure 3(b) Pre-dive briefing on the dye-release protocol showing the two heat-sealed, impermeable cloth pouches containing masses of dye. These are cut open with utility shears underwater.

the background fluorescence, such as from organic acids, or may indicate some minor dye leakage beginning at 1:00 on April 20. Cave divers provided additional visual observations of the dye distribution in the system. A "vivid green algae colour" along the ceiling in NW section was observed three months after injection (E. Reinhardt, pers. com.). Previous experience of the principal author in that section of the cave suggests that this likely was dye, as water discoloration has never been previously observed there. Furthermore, the only locations regionally with vivid green coloration are those with open water pools experiencing algal blooms, and there are no exposed water surfaces in that section of the cave. In the NE section, observation by

Figure 3(c) *Manual pumping of water samples from a fixed point in the water-filled cave. The internal volume of the tubing is voided into the bucket before each sample.*

the primary author the day after the dye release indicated a significant red color consistent with the RhWT dye that had been released there, with no obvious displacement of the water. A further unsolicited report arrived three weeks later, reporting that red discoloration remained in the NE section of the cave (B. Phillips, pers. com.).

Conclusions and Implications

Physico-chemical profiles of temperature and specific electrical conductivity have effectively identified three distinct water masses in the inland portion of Sistema Aktun Ha. A dual dye release indicated that water in the inland NE section of the cave (Adriana's Room) is near stagnant over weeks and months, with little, if any, water flowing coastward via the large diameter (30x10 m) flooded

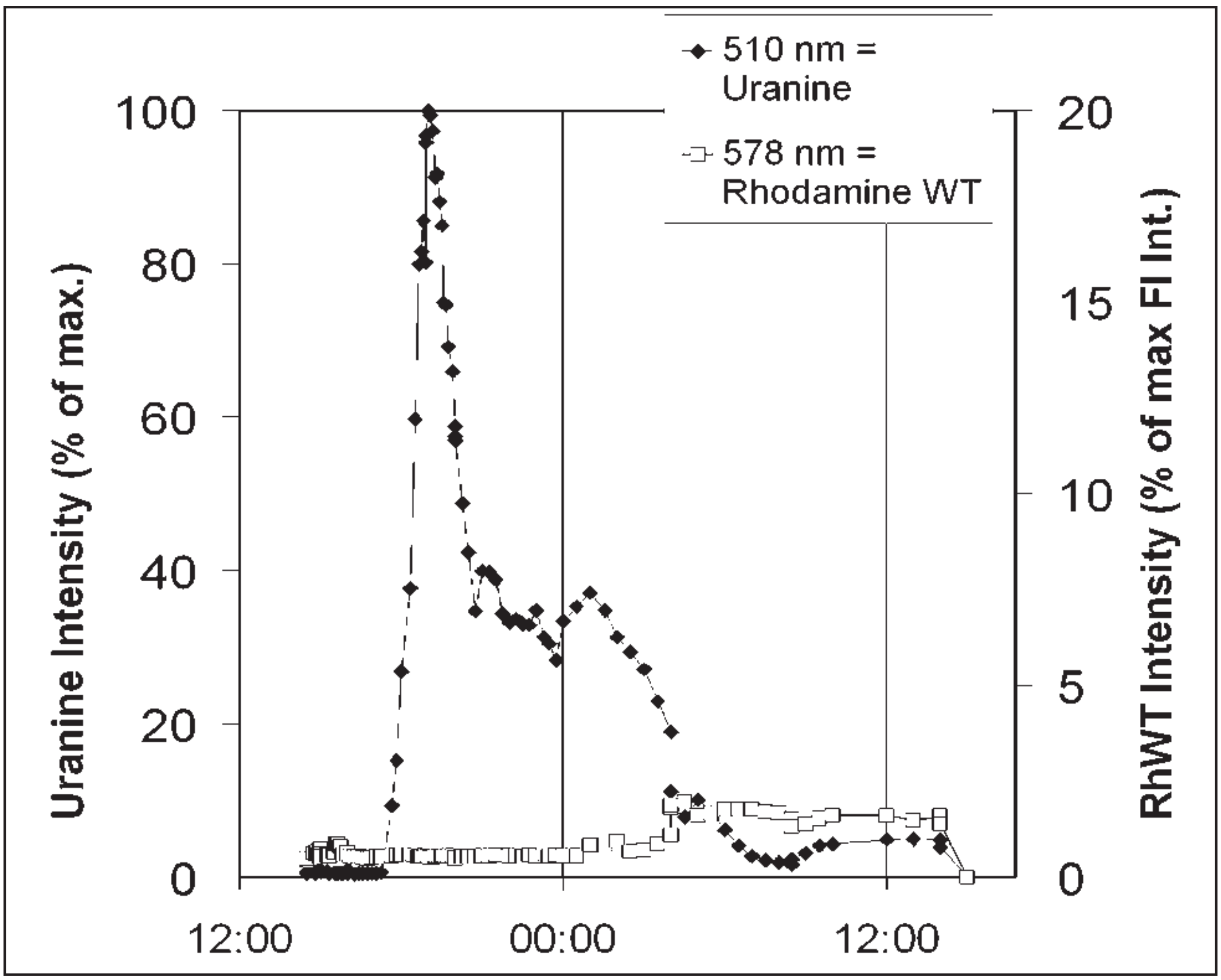

Figure 4(a) *Relative intensity (three-point moving average) of fluorescence at 510 nm for Uranine (Sodium Fluorescein) and at 578 nm for Rhodamine WT in water samples pumped from ~11 m water depth on the inland NW side of Cenote Car Wash, Sistema Aktun Ha.*

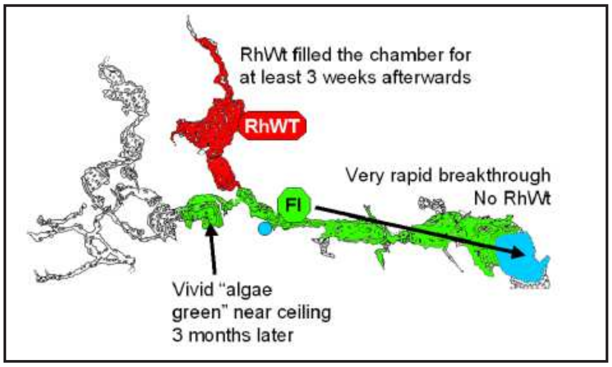

Figure 4(b) Schematic showing the regions of the inland cave affected by the two dyes released based on dye-tracing and divers' observations.

cave towards Cenote Car Wash. The water within this large passage inland of Cenote Car Wash has a dominant rapid flow coastward but with a relatively extended flushing time spanning more than 12 hours over this relatively short distance of ~220 m. Furthermore, some inland flow of water from this principal trunk passage into the NW section of the cave is indicated by divers' observations of water discoloration three months after dye release, while residence time in the NE section is very long.

The complex flow paths within Sistema Aktun observed here are inconsistent with the simple model of coastward flow of water through the largest available and continuous cave passage. Furthermore, the source of the water flowing through the principal trunk passage immediately inland of Cenote Car Wash cannot be either the NE or NW sections of the cave, posing the challenge of locating the inflow of such large volumes of water, which then flows through Cenote Car Wash. Close examination of the NE wall at and just coastward of Cenote Luke's Hope is warranted.

The complex flow paths of water through Sistema Aktun Ha demonstrated here suggest that contaminants from the municipal garbage dump may follow equally complex flow paths through the aquifer, and therefore may not traverse this particular cave even though the cave is located nearby and coastward of the site. Similarly complex flow paths on the coastward side of the explored cave may further mediate the direct arrival of contaminants from the dump to the municipal water supply wells. Conversely, other point and diffuse sources of contamination in the broader area may instead pose a more direct threat to the municipal well field of Tulum and the cave system, but it would be very difficult to identify such sources since they are not necessarily located along obvious inland-coastward locations.

Using multi-parameter probes while cave diving may be a cost-effective and efficient means of identifying distinct water masses. Characterizing physico-chemical properties of cave waters throughout the Yucatán Peninsula could elucidate the locations of complex, obscure flow paths. Where the observed physico-chemical properties of the water throughout the cave are inconsistent with the simplest hypothesized flow path, the actual hydrology through the cave system may be revealed using well-constrained (one-day, <500 m) dye traces.

Acknowledgments

We thank the Quintana Roo Speleological Society (QRSS) for a grant in support of basic field expenses, the Centro Ecological Akumal for acting as a safe home base within their cost sharing research scheme, Simon Richards and Cave Exploration for the use of cave diving and field safety equipment and Kevin Casey for his contribution to the overnight manual pumping.

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CAVE-DRIP MONITORING AS A FOUNDATION FOR BETTER PALEOCLIMATE RECONSTRUCTION

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Abstract

Many caves preserve high-resolution palaeoenvironmental records within stalagmites, from which an increasing number of records are being published. The dating of speleothem calcite and the analysis of stable isotopes is now routine and decreasing in cost. However there remains a need for greater confidence in how representative each stalagmite may be of environmental conditions on the local to regional scale. It is recommended that when studying younger and actively growing samples, that a suitable cave-drip-water monitoring program be undertaken to assess representativeness of key variables compared to adjacent and distant drips, and specifically to identify seasonality in the hydrological flows. Where drips become seasonally inactive, the corresponding stalagmite record will be seasonally biased, therefore requiring more careful interpretation. Drip monitoring results from 18 drips in six caves across North America will be used to illustrate the variability of drip waters within a cave passage, between caves in the same region, and across the continent. Study of modern cave-drip waters is very valuable in ensuring that only the most suitable speleothem samples form the basis of palaeoenvironmental reconstruction, in support of the unique role that speleothem-proxy records may play on a global scale.

Key words: speleothem dating, cave-drip water, paleoclimate, water chemistry

Introduction

The secular variations of isotopic and trace element compositions of speleothem calcite provide valuable continental based indices of paleoclimate change, with a spatial distribution complimentary to that of polar ice cap and marine core records. Paleoclimate studies often assume that the isotopic chemistry of the calcite broadly reflects that of the local meteoric precipitation. However, the epikarst and vadose zone above the cave is complex because of storage and mixing of fast and slow-flowing waters along different-sized fractures and conduits. Qualitative observations indicate that drip-water hydrochemistry may differ between closely spaced adjacent drips as shown by the distinct ability of some drips to form soda straws and corresponding stalagmites (Figure 1). Similarly, observations show seasonal variation in seepage rates, which suggests potential for seasonal variations in "upstream" calcite deposition and deposition on the speleothem itself, bias in the chemical and isotope composition of the water reaching the cave, and significant differences between adjacent drips and corresponding speleothem. A key research challenge presently at the forefront of paleoclimate reconstruction from speleothem records is developing an advanced understanding of hydrological processes in the karst vadose zone that control the surface climate components captured in individual speleothems, and how representative each speleothem is of the regional climate signal. The broader focus of this research effort is progress towards an integrated trans-North American study of the calcite-cave drip-climate system. Study sites include six caves, including three on the Pacific coast of Vancouver Island and one each in the Bow Valley of the Rocky Mountains, the Midwest (southern Indiana) and the northeastern U.S. (upstate New York; Figure 2).

A specific advantage of monitoring closely spaced drip points is the potential to quantify the common elements of the drip hydrology and hydrochemistry independent of confounding environmental factors such as infiltration through distinct geological units above the cave, differences in surface land cover and vegetation units, vadose zone thickness, and distance from the cave entrance. These environmental factors may give rise to complexities that are often suggested as explanations of significant inter-drip differences observed between monitored drips where longitudinal monitoring of distinct drip types along caves have been undertaken (Tooth & Fairchild, 2003; Vokal et al. 1999).

Figure 1 *Distinct hydrochemical characteristics of adjacent drips showing that only a limited number of drip points are competent at forming stalagmites.*

Methods

Custom drip monitoring stations were deployed late in 2004 through 2006 to provide high frequency 15-minute records of temperature, electrical conductivity as a proxy of total dissolved solids, and drip rate at three adjacent drips (<30 m distant) in each of the six caves, while monthly bulk water samples were captured for isotopic and chemical analysis (Figure 3). Water samples were isotopically analyzed at McMaster University using a Finnigan Delta XP^{PLUS} isotope-ratio mass-spectrometer coupled with a Thermo TCEA that was set at 1450°C. A redesigned glassy carbon reactor column combined with a redirected helium carrier gas flow system was employed to improve sample flush-

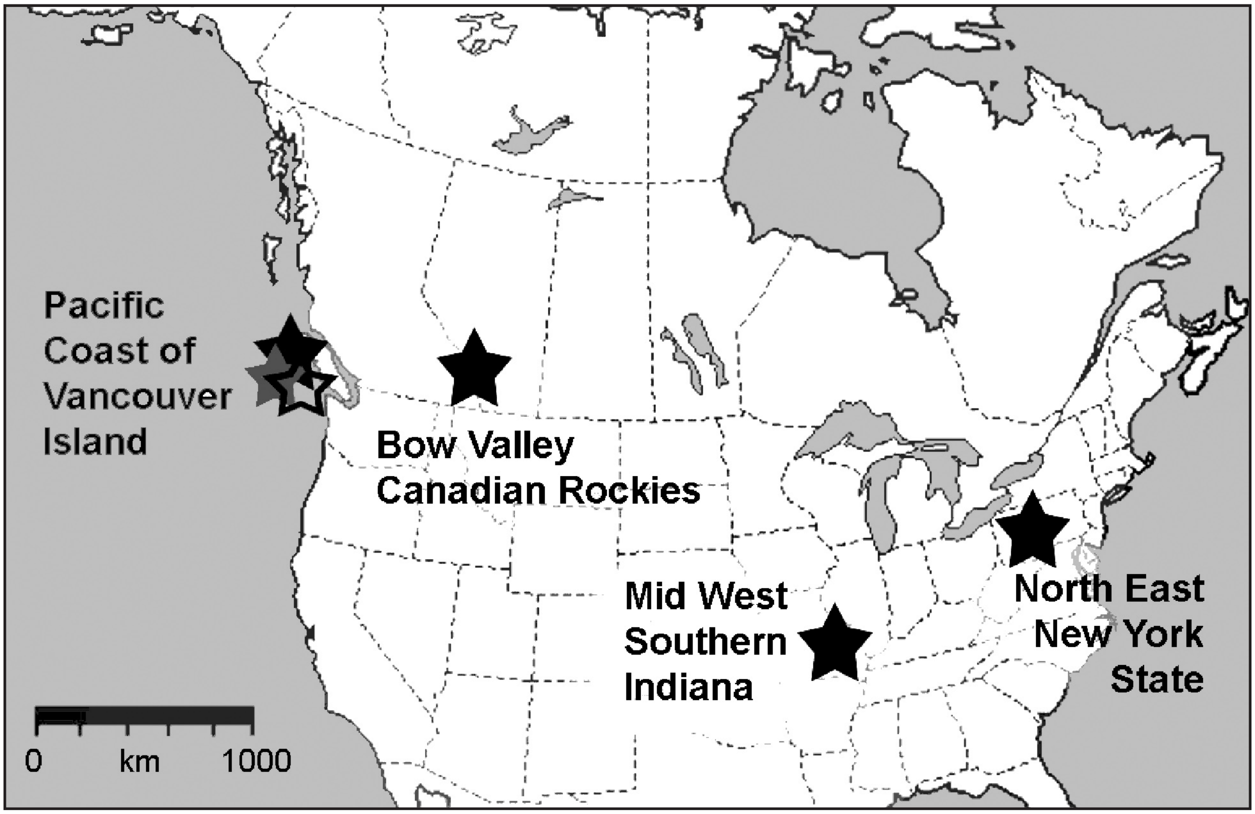

Figure 2 Location map for 6 caves across North America with drip monitoring networks.

ing through the system as described by Gehre et al. (2004). In each analysis, 0.8 µL of sample was manually injected via a septum into the top of the glassy carbon column. The data was normalized to the VSMOW scale in ‰ using bracketed initial and final runs of DTAP (internal lab standard) and IAEA accepted standard (VSMOW, GISP, or SLAP) on each analysis day.

Upon decommissioning of the drip monitoring sites in 2006, pre-weighed, acid-cleaned, frosted glass plates were positioned under each drip site on which calcite was growing. These glass plates will be returned to the lab where the modern calcite will be micro milled and analyzed for $\delta^{18}O$ and $\delta^{13}C$, with the resulting data interpreted within the context of the broad chemical and isotopic characteristics of the drip site.

Results and Discussion

The drips selected for monitoring all appeared to be actively precipitating calcite. Within the classification scheme for karst waters of Smart and Friedrich (1987) all had very low drip rates, with many plotting below the minimum boundary of the original classification scheme, while the coefficient of variation (COV = average / standard deviation, also known as RSD) spanned several orders of magnitude, but for most sites was relatively low (Figure 4). Previous studies on karst waters focused on larger scale hydrogeology with implications for water supplies and contaminant transport through karst aquifers. In comparison we have focused on year-round, active, cave-drip waters and more specifically, those that are apparently forming stalagmites. We found that calcite deposition is associated with slower drip rates in general. This observation is consistent with the conceptualization of slow-flowing seepage waters being sourced principally by longer-residence-time storage water in the smaller flow paths of the vadose zone. The physic0-chemical aspects of these waters should therefore be decoupled from the day-to-day weather components affecting the surface, and instead be modulated, and damped, reflecting broad climatological aspects.

Qualitative observations in caves indicate that many drips are indeed responsive, with increased drip rates during surface recharge events such as rainfall or snow melt. In the high resolution elec-

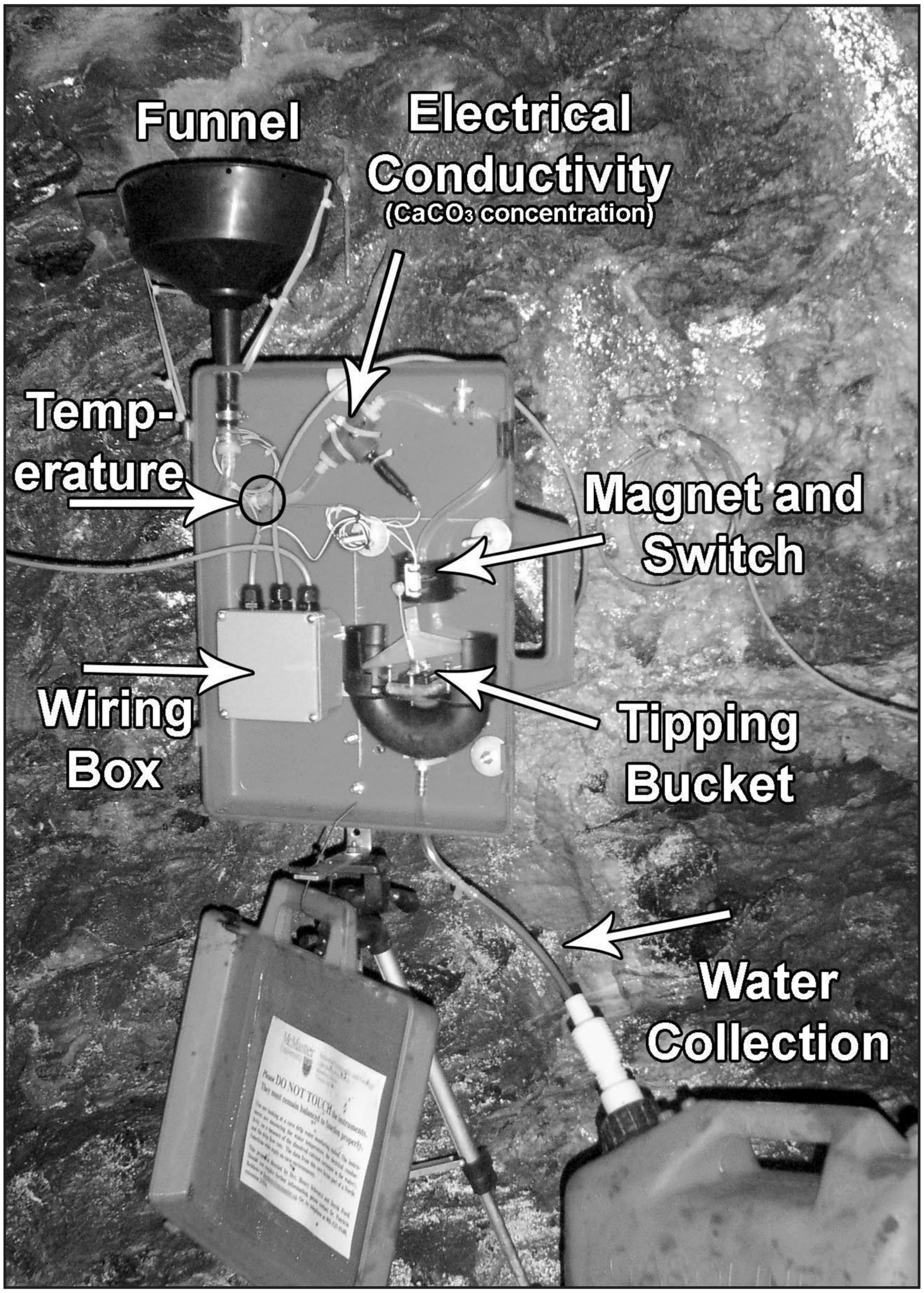

Figure 3 *Custom cave-drip-water monitoring station.*

tronic data, hydrological events are evident (Figure 5) even though, as noted, the month-to-month bulk water rate is low and relatively constant (COV<50) for most drips. Perhaps the constancy in drip rate observed in this study is a function of targeted monitoring of drips forming speleothem calcite, while adjacent drips without calcite formation may be the ones observed qualitatively to respond most dramatically to recharge. Furthermore, the hydrological data show that temporal variations in hydrological parameters are sometimes concurrent between drip sources located tens of meters apart in the same cave, while at other times each drip may display independent hydrological characteristics.

A paradoxical relationship exists between the isotopic and chemical responses of drips to seasonal driving forces, and the observed hydrological response. Drips with nonseasonal hydrology, such as the nine monitored drips in the three caves on Vancouver Island, may have equally nonseasonal response in the specific electrical conductivity and the solute flux through the system (Figure 6). However, the hydrogen and oxygen isotopes are clearly seasonal for these drips (Figure 7). In contrast, drips with seasonal hydrological cycles, such as at Marengo Cave, may also have corresponding seasonality in specific electrical conductivity, yet the isotope chemistry of these drips is temporally invariate over the course of the year (not shown). In Howe Caverns, New York, the three monitored drips have parallel patterns in specific electrical conductivity, however the hydrological response is varied and clearly inverse between the two drips with higher drip rates (Figure 7). For Howe Caverns, similar to Marengo Cave, which is the other mid-continent site in this study, the drips are isotopically nonseasonal, although the drip with the lowest drip rate has a step-wise change in isotopic values.

Some of the assumptions made in palaeoenvi-

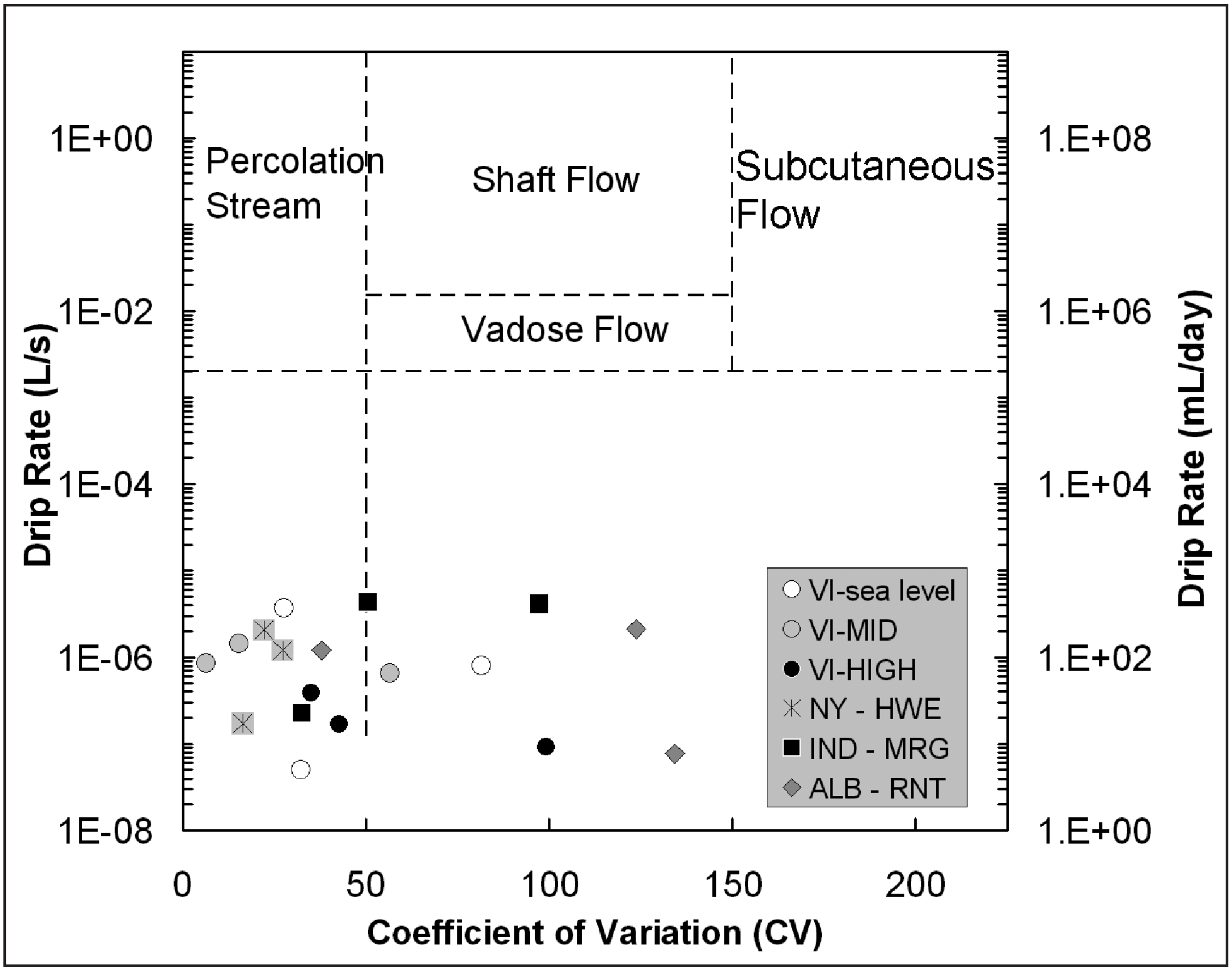

Figure 4 *Plot of drip rate based on daily average from monthly bulk water collected versus the inter-monthly variability measured as the coefficient of variation (standard deviation divided by mean value, expressed as a percentage) within the Smart and Friedrich karst water classification scheme (1987).*

ronmental reconstruction from speleothems is that the calcite is precipitated continuously throughout the year so that there is no seasonal bias, and that the isotopes in the speleothem calcite will broadly reflect that of the mean annual precipitation and temperature above the cave, and that each speleothem is equally good at recording conditions above the cave. Within this dataset, drips with seasonal drip rates tend not to have isotopic seasonality, while hydrologically stationary drips exhibit significant isotopic seasonality, thereby undermining some of the assumptions. This result is consistent with the general knowledge that some speleothems have annual bands because of seasonality in aspects of the drip waters, while other speleothems are not banded at all, potentially because of a constant drip water chemistry and supply. Also, there are examples of significant differences between adjacent drips in the monitored caves in all variables examined, and this is consistent with other recent reports of differences between coeval speleothem records from the same cave: two coeval and adjacent speleothems from South Dakota were found to have a 4‰ offset in $\delta^{18}O$ although their secular variations still revealed the same important climate events (Serefiddin et al. 2004).

Cave-drip monitoring is a valuable method in characterizing the hydrochemical response to seasonal climate forcing at individual drip points. Ultimately, cave-drip monitoring will help determine which corresponding speleothems may provide intra-annually unbiased records of long-term change, as opposed to those speleothems with signals dominated by responses to sub-annual events.

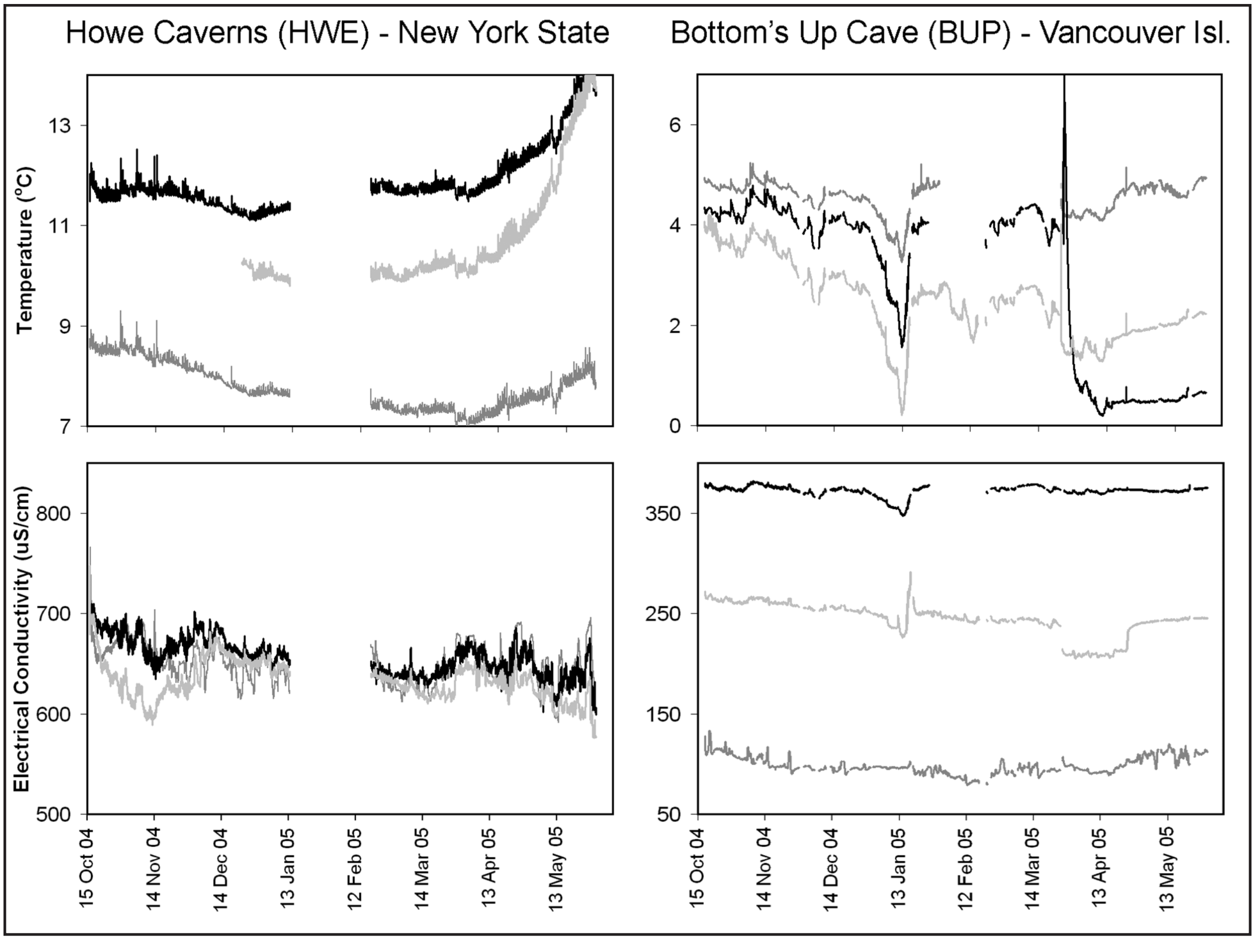

Figure 5 *Cave-drip water specific electrical conductivity (top row) and temperature (bottom row) in Bottom's Up Cave at 550 m ASL mid elevation on Vancouver Island (left) and Howe Caverns in upstate New York (right).*

This study focuses on drips actively forming calcite, and therefore this approach is inherently limited to palaeoenvironmental studies focused on the Holocene, since the drip points of older speleothems are often now inactive. Given the distinct hydrochemical response observed at individual drip points, the sampling of more than one coeval speleothems may be required to provide robust palaeoenvironmental records.

Acknowledgments

This study was supported by a grant from the Canadian Foundation for Climate and Atmosphere Sciences (CFCAS Grant No. GR-421) to HPS and DCF and a grant to HPS from the Natural Sciences and Engineering Research Council of Canada (NSERC). Site access and logistical support for the monthly drip monitoring was provided by Gordon Smith and Steve Calhoun at Marengo Caverns (Indiana), John Sagendorf of Howe Caverns and Art and Peggy Palmer (New York), Chas Yonge at Rats Nest Cave (Alberta), and Brian Bischoff and Paul Griffiths for three caves in Tahsis Inlet, Vancouver Island, and coordination of the research effort with the British Columbia Ministry of Forests. Invaluable technical support was received from Kenrick Chin of the Nuclear Reactor Facility, McMaster University

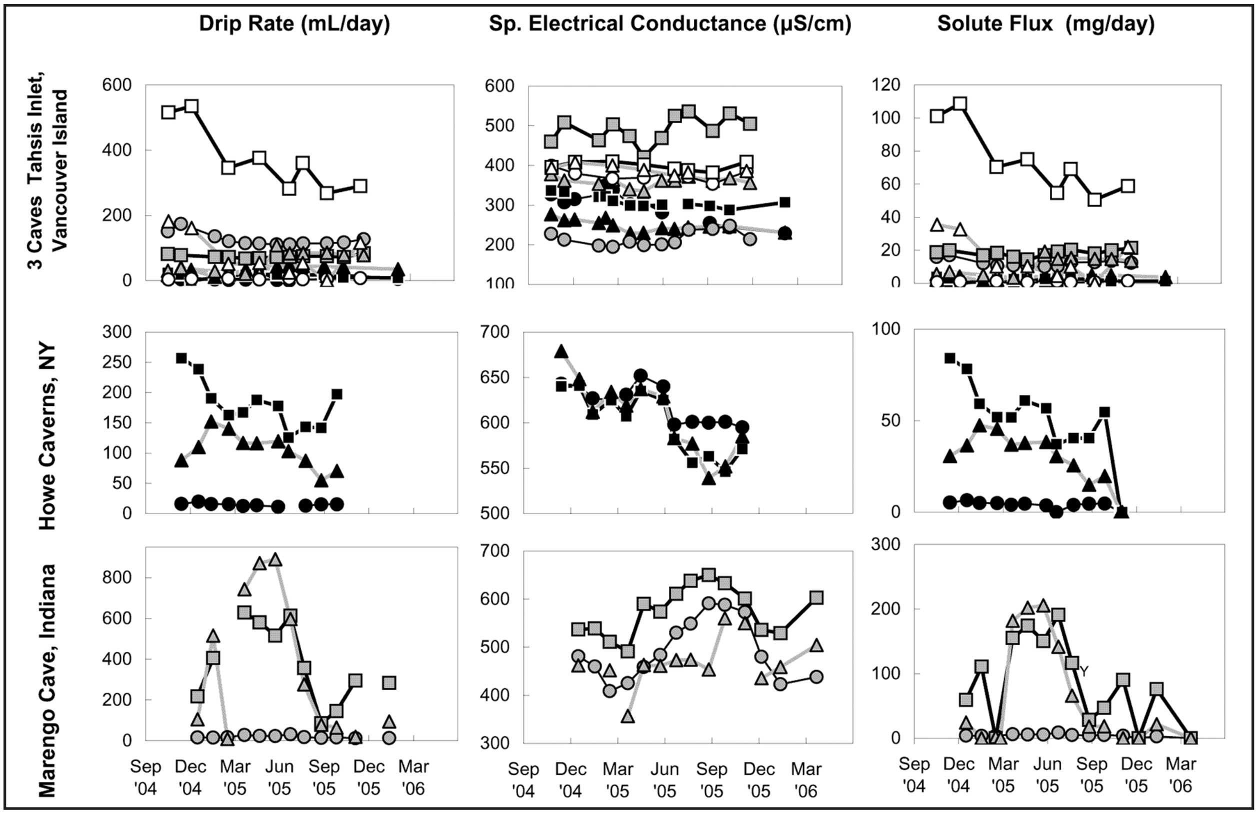

Figure 6 *Data matrix for drip water data from different cave regions (each row) for the three parameters of drip rate (left), specific electrical conductivity (SpC; middle), and solute flux (right) which was calculated by using Equation 19 of Krawczyk and Ford (2006) for nonpolluted karst waters.*

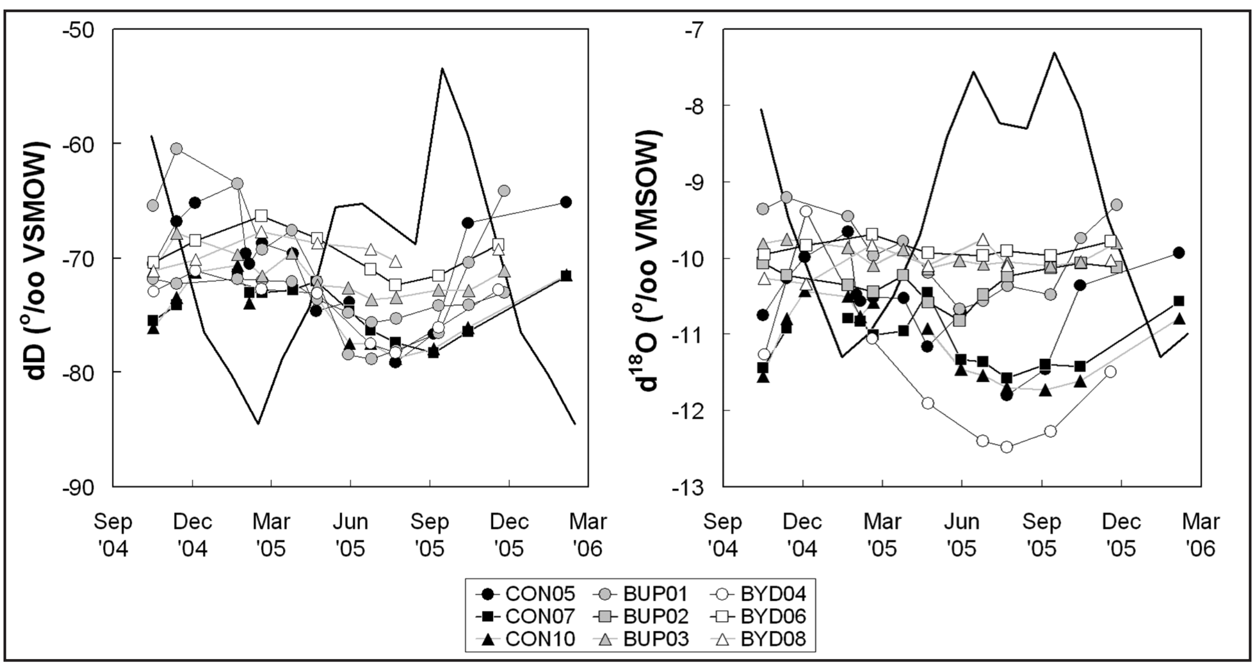

Figure 7 *Deuterium (∂D) and oxygen (∂^{18}O) isotopic values of drip waters from 3 caves, Tahsis Inlet, Vancouver Island.*

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GROUNDWATER MONITORING IN KARST TERRAIN: A PILOT STUDY OF OIL-AND-GAS DEVELOPMENT IN SOUTHEAST NEW MEXICO

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Abstract

Rapid oil-and-gas exploration, drilling, and production in karst terrains in southeast New Mexico are posing increased potential for contamination of groundwater sources. There has not been a systematic analysis of karst groundwater in this region. Gathering baseline data on groundwater quality and determining its flow paths and resurgences is crucial in understanding, detecting, and mitigating undesirable incidents in the oil-and-gas drilling and production industry. A pilot study was initiated by the Bureau of Land Management in the summer of 2005 to begin gathering field data to help fill some of the voids in our understanding of karst groundwater flow in the study area referred to as the Southern Guadalupe Escarpment.

Key words: oil and gas, karst groundwater, dye tracing, contaminants, New Mexico

The Setting

The primary area of concern is the Capitan Reef aquifer near Carlsbad, New Mexico, south of Sheep Draw down to Big Canyon and the gypsum karst lands of the Delaware Basin extending eastward to the middle of Range 26 East (Figure 1). Within the boundaries of this study area are critical groundwater-recharge zones and numerous springs and resurgences. The aquifers in this area supply drinking water to the City of Carlsbad, Carlsbad Caverns National Park, White's City, Carlsbad Area Retarded Citizens (CARC) Farm (Washington Ranch operation), several ranching families, and water wells for domestic livestock in the area. These aquifers also are the source of water for numerous springs in the area that provide the basis for critical riparian areas and wildlife habitat, including Rattlesnake Springs, Preservation Spring, Cottonwood Spring, Owl Spring, Ben Slaughter Spring, Chosa Spring, and the largest, Blue Springs with an outflow of 0.3-0.4 m^3/sec(10-15 $ft.^3$/sec). Also included are the numerous springs that give rise to the Black River. These freshwater sources are critical in sustaining life along the northern edge of the Chihuahuan Desert ecosystem.

Groundwater research conducted by Hendrickson and Jones (1952) for Eddy County, New Mexico, indicates that recharge of the groundwater associated with the Capitan and Carlsbad limestones is largely through the joints and fractures in the bottom of gravel filled arroyos. Water that enters the gravel and boulders in the arroyo bottoms moves downward into the underlying bedrock. The amount of water that enters the underlying rock and into the aquifer depends on the permeability of those rocks. All the water probably enters the limestone where the gravels are underlain by cavernous limestones. Movement of groundwater after it reaches the bedrock is controlled chiefly by fractures and bedding planes, more or less enlarged by solution in limestone and dolomite.

They further state that the flow of the Black River, Rattlesnake Springs and Blue Springs is sustained chiefly by discharge near the base of the Capitan reef escarpment. The principal source of these springs is almost certainly discharged from the Guadalupe Mountains area, as the recharge in the area between the reef escarpment and the springs is not enough to provide their flow. In addition to the water discharged by the springs, groundwater probably moves from the Capitan limestone and other underlying limestones into the alluvium and underlying Castile formations, and it may supply water to several of the other springs located in the gypsum karst lands of the Delaware Basin. Perched aquifers may be present in the Quaternary piedmont alluvial deposits and the Quaternary alluvial deposits which are underlain by the Castile formation.

Potential Oil-and-Gas Impacts

The reasonable foreseeable development of the study area has yet to be determined. There have been several geophysical studies conducted in the area that indicate the potential for oil-and-gas exploration is high. The 1997 Carlsbad Resource Management Plan Amendment for Oil and Gas shows the area as having a high potential for oil and gas occurrence. To date there have been 263 oil or gas wells drilled in the area on 171 existing oil-and-gas leases. Based on the maximum allowable number of wells per section (16 oil wells and 4 gas wells) the maximum number of wells that could be located in the study area is 4,600 wells if maximum production were achieved.

Drilling in the study area could affect both the perched aquifers and the underlying Capitan aquifer. Potential groundwater impacts from drilling can be divided into those caused:

- During drilling and cementing. Drilling and

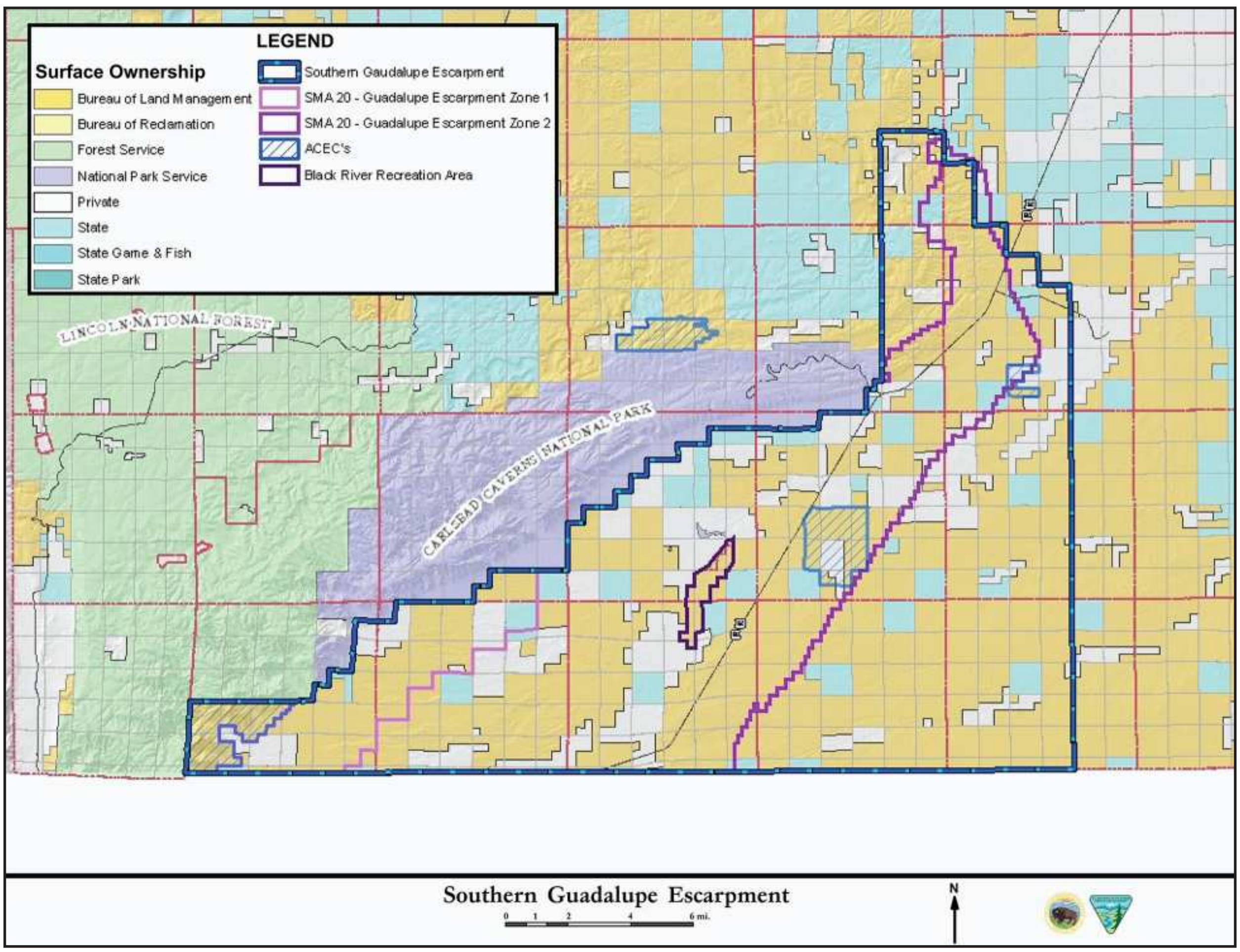

Figure 1 *Recent studies by Snow and Goodbar (2007) indicate the critical recharge areas of the Capitan Reef aquifer are within 1-2 km (1 mi.) of the reef front and along the contact zones of theYates and Seven Rivers formations in addition to the recharge into fractures in the alleviated canyon bottoms.*

cementing fluids will spill or leak into formation at any lost circulation zones.

- During testing and production. If the inner and intermediate casing strings fail following installation due to inadequate cementing or long term (≥50 years) corrosion, drilling fluids, brine, or gas could be released directly to the subsurface anywhere along the casing string.
- Following plugging and abandonment of the well. Because the atmosphere in the unsaturated part of the aquifers contain elevated concentrations of carbon dioxide and trace amounts of sulfur compounds as well as oxygen, the steel well casing could slowly become corroded and eventually fail in zones not protected by cement (U.S. Department of the Interior 1993)

A more complete description of oil-and-gas impacts on caves and karst can be found in U.S. Department of Interior (1993).

The Pilot Study

Identification and monitoring of karst areas includes gaining a better understanding of the underlying groundwater flow paths and their associated erosional features. A monitoring program needed to be established to identify potential sources of contaminants entering the aquifers, and monitor the conditions and integrity of subsurface groundwater. To begin this study the Bureau of Land Management in cooperation with the oil-and-gas industry, local land owners, the City of Carlsbad, and the center for Cave and Karst Studies at Western Kentucky University initiated a dye-tracing pilot study to help identify areas of potential concern. The purpose of the dye tracing study was to determine if contaminates could enter the groundwater through drilling and cementing operations, or during later phases of production or abandonment in the event of casing failure. Any positive results from the dye tracing study would then indicate that the BLM, in conjunction with the oil-and-gas industry, needs to ensure that all possible down-hole mitigation measures are being taken to protect these vital water resources.

As a pilot study a small area was selected to begin with. That area extends north from Whites City to Sheep Draw and east of Whites City to Black River (Figure 2). In August of 2005 activated-charcoal dye traps (bugs) were place in six locations, three in perennial springs, two in domestic water wells, and one in the outflow of a monitoring well for the City of Carlsbad. These bugs were retrieved after one month to insure that samples were taken before any dye was introduced into the system. New bugs were then installed prior to dye being added to drilling fluids during oil-and-gas drilling operations. New oil or gas wells drilled in the gypsum karst plains were then required to add 0.48 L (16 oz.) of fluorescein dye (Acid Yellow 73) to their surface interval drilling fluid. For wells drilled in the Capitan Massive or Carlsbad limestone, 0.48 L (16 oz.) of orange (eosin Y) dye were added. For wells that were drilled through the overlying gypsum karst and then through the Capitan Massif, both dyes were required to be added to the drilling fluid. Because of the large number of wells being drilled and the complexity of the project it was decided to use only two types of dye, one for the gypsum karst and one for the Capitan Limestone group. The amount of dye to add to the drilling fluid was calculated based on the amount of water needed to fill a standard reserve pit for drilling oil-and-gas wells in that area. This began during the fall of 2005. The bugs were changed out bi-monthly and sent to Western Kentucky University for analysis. In addition to the dyes in the drilling fluids, analysis was also run for rhodamine WT. This dye is sometimes used by the industry as a marker dye when conducting pre-flushing of the well bore before cementing operations. During the "pre-flush" the dyed water may also enter karst aquifers.

Initial Results

To date 21 wells have added dye to their initial drilling fluids. Thirteen of these wells are in the gypsum karst plains of the Delaware Basin. Five wells have been drilled in the transition area containing both gypsum karst and the Capitan Reef Aquifer, and three wells have been drilled on the crest of the Guadalupe Ridge anticline. Lost circulation has been reported in three of the wells drilled that were using dye. That is not to say that lost circulation zones were not encountered in the surface intervals of other wells, only that it was not reported to the Bureau of Land Management.

Twenty-seven dye traps have been sent in to Western Kentucky University for analysis. All the dye traps sent in before dyes were introduced to

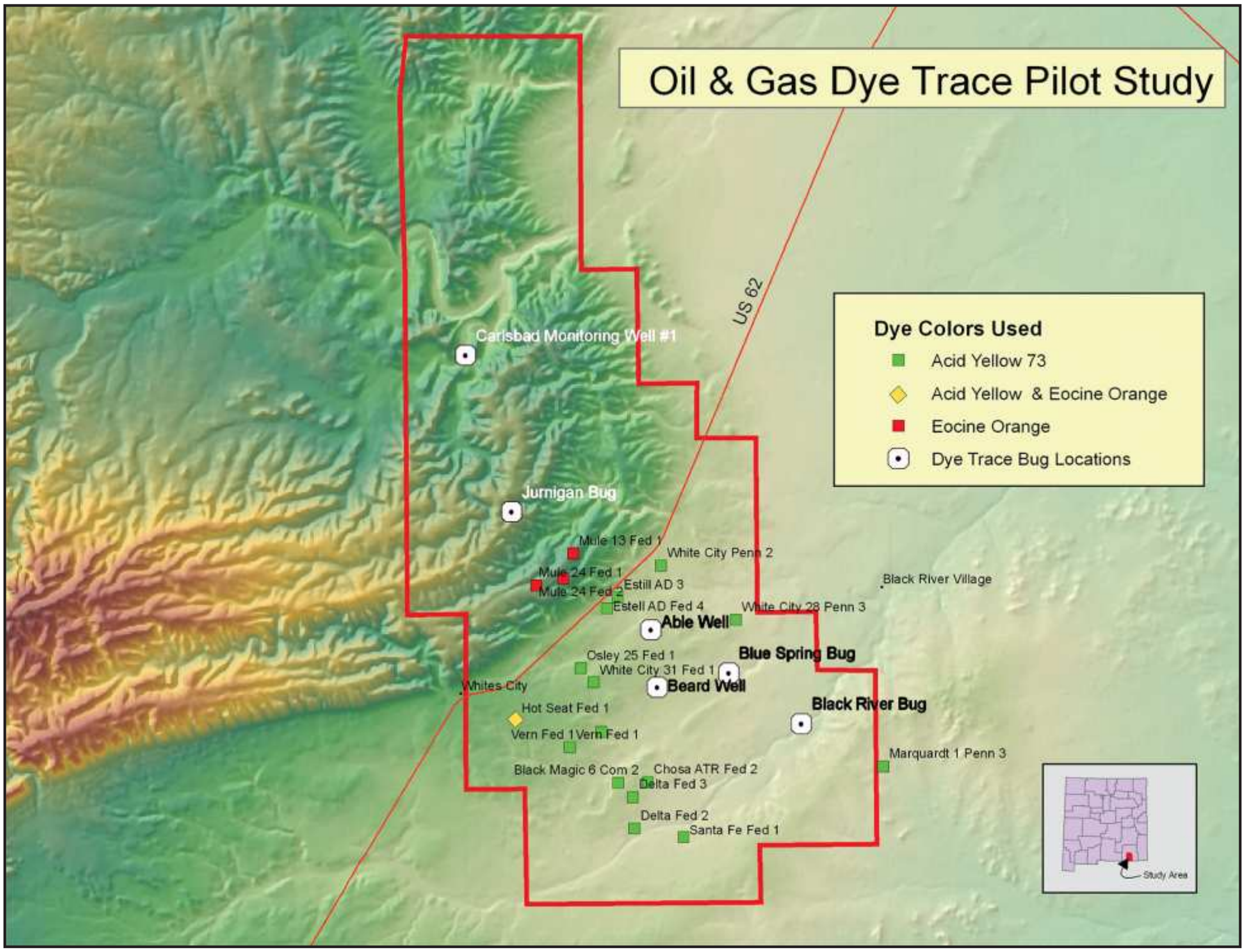

Figure 2 Oil and Gas Dye Trace Pilot Study Area.

the drilling fluids came back with no fluorescein detected and a weak background of eosine and rhodamine WT dyes detected. After 0.48 L (16 oz.) of dye were introduced to the drilling fluids the Able water well had a detectable concentration of eosine of 0.952 ppb, nearly two orders of magnitude greater than the previous background concentration of 0.042. The dye trap for this reading was put in on September 7, 2005, and taken out November 20, 2005. During that time the Estell AD #3 gas well was drilled with both eosine and fluorescein dyes being added to the drilling fluid.

The City of Carlsbad Water Monitoring Well in Juniper Canyon showed a similar increase in detectable eosine moving from a low background level up to 0.563 ppb. The dye trap showing the increase was put in on September 7, 2005, and taken out on August 20, 2006. During that time four wells were drilled using eosine dye. Subsequent dye-trap analysis produced concentrations of 0.508 ppb and 0.930 ppb of eosine dye and no detectable levels of fluorescein dye.

Another location that showed significant increases in detectable fluorescein dye was Blue Springs, from none detected to low background levels (0.068), then up to 0.601 ppb. Additionally, the detectable concentrations of rhodamine WT increased from a background level of 0.049 ppb to a concentration of 1.017 ppb. This occurred during the fifth sample period. The dye trap was put in October 20, 2006, and collected May 2, 2007. It is not known what wells in the area were drilled on private or state lands and which wells may have used rhodamine WT during their drilling operations.

The Jurnigan Spring location showed none to very low background concentrations of eosine and fluorescein dyes during the first three samplings. The fourth sample showed a possible positive detection of fluorescein dye of 0.528 ppb. The fluorescein dye could be from one of the wells drilled in the transition zone of the reef escarpment to basin margin.

At this time the Beard home and Black River are the only two dye trap locations that have not shown any detectable dye concentrations.

Below are the laboratory results (Tables 1-4) in the order in which they were received.

Tables 1-4 Laboratory results of dye tracing.

Page 1 of 4

CRAWFORD HYDROLOGY LAB * CENTER FOR CAVE AND KARST STUDIES

* *Hydrogeologists, Geologists, Environmental Scientists* * *Karst Geophysical Subsurface Investigations*
* *Karst Groundwater Investigations* * *Fluorescent Dye Analysis*

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LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Bureau of Land Management

Analysis requested by:

Jim Goodbar

TINOPAL CBS-X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
Fabric Brightening Agent 351	Color Index: Acid Yellow 73	Color Index: Acid Red 87	Color Index: Food Red 14	Color Index: Acid Red 388	Color Index: Acid Red 52
Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal
Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer

CHARCOAL SAMPLES

Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	TINOPAL CBS-X Results	TINOPAL CBS-X Conc in ppb	TINOPAL CBS-X Peak Center (nm)	FLUORESCEIN Results	FLUORESCEIN Conc in ppb	FLUORESCEIN Peak Center (nm)	Eosine Results	Eosine Conc in ppb	Eosine Peak Center (nm)	FD&C RED #3 Results	FD&C RED #3 Conc in ppb	FD&C RED #3 Peak Center (nm)	RHODAMINE WT Results	RHODAMINE WT Conc in ppb	RHODAMINE WT Peak Center (nm)	SULPHORHODAMINE B Results	SULPHORHODAMINE B Conc in ppb	SULPHORHODAMINE B Peak Center (nm)
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				
EL-001-0	02		Carlsbad Monitoring Well #1						ND			+?	0.563	535.4				ND					
EL-002-0	02		Jurnigan Spring #1						B	0.052	507.6	B	0.044	NPI				B	0.016	NPI			
EL-003-0	02		Able East Stock Tank #1						ND			+	1.160	536.2				ND					
EL-004-0	02		Blue Spring #4						B	0.068	NPI	ND						B	0.049	NPI			
EL-006-0	02		Black River (Beard) BRB-3						ND			ND						B	0.054	NPI			
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				

Analyzed by: Chad Martin on 11/8/2006

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

Page 2 of 4

CRAWFORD HYDROLOGY LAB * CENTER FOR CAVE AND KARST STUDIES

* *Hydrogeologists, Geologists, Environmental Scientists* * *Karst Geophysical Subsurface Investigations*
* *Karst Groundwater Investigations* * *Fluorescent Dye Analysis*

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LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Bureau of Land Management

Analysis requested by:

Jim Goodbar

TINOPAL CBS-X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
Fabric Brightening Agent 351	Color Index: Acid Yellow 73	Color Index: Acid Red 87	Color Index: Food Red 14	Color Index: Acid Red 388	Color Index: Acid Red 52
Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal
Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer

CHARCOAL AND WATER SAMPLES

Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	TINOPAL CBS-X Results	TINOPAL CBS-X Conc in ppb	FLUORESCEIN Results	FLUORESCEIN Conc in ppb	Eosine Results	Eosine Conc in ppb	FD&C RED #3 Results	FD&C RED #3 Conc in ppb	RHODAMINE WT Results	RHODAMINE WT Conc in ppb	SULPHORHODAMINE B Results	SULPHORHODAMINE B Conc in ppb
1			QA-ELUENT					ND									
2			QA-FLUORESCEIN						0.005								
EL-001-0	01	9/9/05	Blue Spring #1					ND		ND					0.008		
EL-002-0	01	11/20/05	Blue Spring #2					ND		ND				ND			
EL-003-0	01	5/1/06	Blue Spring #3					ND			0.050			ND			
EL-004-0	01	9/9/05	Able Home #1					ND			0.042				0.036		
EL-005-0	01	11/20/05	Able Home #2					ND			0.952			ND			
EL-006-0	01	5/1/06	Able Home #3					ND			0.289			ND			
EL-007-0	01	9/9/06	Beard Home #1					ND			0.163			ND			
EL-008-0	01	11/20/05	Beard Home #2					ND			0.311				0.012		
EL-009-0	01	5/1/06	Beard Home #3					ND		ND				ND			
EL-010-0	01	11/20/06	Black River #1					ND			0.018				0.031		
EL-011-0	01	5/1/06	Black River #2					ND			0.138				0.021		
EL-012-0	01		BLANK						0.020	ND					0.058		
3			QA-ELUENT					ND									
4			QA-FLUORESCEIN						0.005								

Analyzed by: Mike Firkins on

Comments: Eosine OJ,RWT,FL analysis GS = Grab Sample

Discussion

It appears that there are no "solid" positive (+), very positive (++), or extremely positive (+++) concentrations of dye detected in any of the dye-trap locations. This may be attributed to the increased dilution of the dyes as they move into the

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CRAWFORD HYDROLOGY LAB * CENTER FOR CAVE AND KARST STUDIES

* *Hydrogeologists, Geologists, Environmental Scientists * Karst Geophysical Subsurface Investigations*
* *Karst Groundwater Investigations * Fluorescent Dye Analysis*

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LABORATORY REPORT SHEET

FLUORIMETRIC ANALYSIS RESULTS

Bureau of Land Management

Analysis requested by:

Jim Goodbar

TINOPAL CBS X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
Fabric Brightening Agent 351	Color Index: Acid Yellow 73	Color Index: Acid Red 87	Color Index: Food Red 14	Color Index: Acid Red 388	Color Index: Acid Red 52
Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal
Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer

CHARCOAL SAMPLES

Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	TINOPAL CBS X Results	Conc in ppb	Peak Center (nm)	FLUORESCEIN Results	Conc in ppb	Peak Center (nm)	Eosine Results	Conc in ppb	Peak Center (nm)	FD&C RED #3 Results	Conc in ppb	Peak Center (nm)	RHODAMINE WT Results	Conc in ppb	Peak Center (nm)	SULPHORHODAMINE B Results	Conc in ppb	Peak Center (nm)
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				
EL-001-0	03	11/30/07	Carlsbad Monitoring Well #2						ND				0.508	535.8				ND					
EL-002-0	03	5/3/07	Carlsbad Monitoring Well #3						ND				0.930	533.8				ND					
EL-003-0	03	5/2/07	Jurnigan Spring #2						ND			ND						ND					
EL-004-0	03	5/2/07	Jurnigan Spring #3						ND			ND						ND					
EL-005-0	03	5/2/07	Blue Spring #5							0.601	513.0	ND							1.017	563.0			
EL-006-0	03	5/2/07	Beard Home #5						ND				0.047	532.6				ND					
EL-007-0	03	5/3/07	Black River #4						ND			ND						ND					
EL-008-0	03		BLANK						ND			ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				

Analyzed by: Chad Martin on 5/15/2007

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

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Bureau of Land Management

Analysis requested by:

Jim Goodbar

TINOPAL CBS X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
Fabric Brightening Agent 351	Color Index: Acid Yellow 73	Color Index: Acid Red 87	Color Index: Food Red 14	Color Index: Acid Red 388	Color Index: Acid Red 52
Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal	Dye Receptor: Activated Charcoal
Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer	Analysis by: Spectrofluorophotometer

CHARCOAL SAMPLES

Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	TINOPAL CBS X Results	Conc in ppb	Peak Center (nm)	FLUORESCEIN Results	Conc in ppb	Peak Center (nm)	Eosine Results	Conc in ppb	Peak Center (nm)	FD&C RED #3 Results	Conc in ppb	Peak Center (nm)	RHODAMINE WT Results	Conc in ppb	Peak Center (nm)	SULPHORHODAMINE B Results	Conc in ppb	Peak Center (nm)
W1			QA-WATER						ND			ND						ND					
W2			QA-FLUORESCEIN							0.008		ND						ND					
W3			QA-EOSINE OJ						ND				0.016					ND					
W4			QA-RHODAMINE WT						ND			ND							0.010				
WL-001-0	04	8/31/07	Jurnigan Spring #4							0.026	509.0	ND						ND					
WL-002-0	04	8/31/07	Jurnigan Spring Catchment #2						ND			ND						ND					
WL-004-0	04	7/9/07	Comanche Well #1						B	0.001	505.6	ND						B	0.010	577.4			
WL-005-0	04	7/19/07	Comanche Well #2						ND			ND						ND					
WL-006-0	04	8/31/07	Comanche Well #3						ND			ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.007		ND						ND					
3			QA-EOSINE OJ						ND				0.007					ND					
4			QA-RHODAMINE WT						ND			ND						ND					
EL-001-0	04	8/31/07	Jurnigan Spring #4						+?	0.528	515.4	ND						ND					
EL-002-0	04	8/31/07	Jurnigan Spring Catchment #2						+?	0.135	511.0	ND						ND					
EL-003-0	04	8/31/07	Carlsbad Monitoring Well						B	0.013	519.0	ND						ND					
EL-004-0	04	7/9/07	Comanche Well #1						+?	1.045	516.8	ND						ND					
EL-005-0	04	7/19/07	Comanche Well #2						+?	0.124	517.0	ND						ND					
EL-006-0	04	8/31/07	Comanche Well #3						B	0.008	513.8	ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.007		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND						ND					

Analyzed by: Laura Kreitzer on 9/12/2007

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

We analyzed the water too, but the vial for Carlsbad Monitoring Well leaked and there wasn't enough to analyze.

aquifers. A second possibility is that once the drilling operation looses circulation into the first open zone, all or most of the drilling fluid and dye are lost into that zone and any other lost circulation zones below that point that may connect to aquifers may not receive any dye.

To compensate for these two possible issues the dye amounts will be doubled to 0.95 L (32 oz.), and a second addition of dye will be added after the completion of the surface drilling interval. The dye will be added to the pre-flush fluids prior to casing and cementing the well bore. In this way dyes can be pushed into the lower portions of the drilling section and enter the bottom levels of the lost circulation zones.

An unanswered question is, "What is the residence time of the dye in the aquifers?" This question may be answered as the project progresses.

Conclusions

Dye-tracing of oil-and-gas drilling fluids in the Castile gypsum and Capitan Reef aquifers appears to be a viable way of determining if drilling fluids can enter the aquifers. I infer that if production casing and cementing failures occur, hydrocarbons may also be able to enter the aquifers. With this in mind, it then becomes incumbent on the land managing agencies and the oil-and-gas industry to ensure that the best possible drilling, casing, and cementing programs are put into practice. The initial results are moderately conclusive that the drilling fluids enter the aquifers. The changes in procedures of adding additional dye during the initial spudding of the well and before the casing and cementing of the surface string may aid in producing more detectable concentrations of dye in the collection locations.

The pilot study should be continued and built upon. A more definitive study should be designed and considered to monitor and document the potential impacts in the shadow of impending oil-and-gas development in the karst areas to the south of the pilot study area.

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STUDY OF A KARST-GEOCHEMICAL DATA SET FROM A MARBLE CAVE: OREGON CAVES NATIONAL MONUMENT

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Abstract

Oregon Caves National Monument (ORCA) is situated in the Applegate group, a formation in the Western Triassic-Paleozoic tectonostratigraphic terrane of the Siskiyou Mountains in southwest Oregon. This cave is unusual because it occurs in marble, most dissolution caves are formed in limestone or dolomite. The U.S. National Park Service (NPS) has over 3,900 caves, but only Oregon Caves National Monument, Kings Canyon, and Great Basin National Parks have caves formed in marble. Though much has been written about karst water chemistry in limestone, little has been written about marble.

A water-chemistry data set for Oregon Caves National Monument was compiled by the National Park Service between late 1991 and fall 1995 from both drip water and cave streams. Seventeen months of data were selected for this study, covering the period May 1992 through October 1993 from six sampling sites within the cave and one surface stream. Along with pH and temperature, major ions and total organic carbon concentrations were recorded. This study showed that water from most of the sites was supersaturated with respect to calcite, and levels of P_{CO_2} were up to two orders of magnitude higher than atmospheric. Distinct similarities in ionic composition were observed for sites with similar source-water travel histories. The data indicate that karst water chemistry varies more as a function of passage geometry, soil type, rock chemical composition, and source water than of differences in texture (marble vs. limestone).

Key words: Oregon Caves National Monument, geochemistry, marble caves, Pettyjohns Cave, Georgia, Lilburn Cave, Sequoia and Kings Canyon National Park, California

Introduction

Oregon Caves National Monument (ORCA), in southwest Oregon (Figure 1), was dedicated in 1909. The ORCA region has a high diversity of plants (~3,800) and animals (~50,000) because of diverse habitats over a range of climatic and geologic conditions (NPS 2007). NPS has over 3,900 caves (NPS 2007), but Oregon Caves National Monument, Kings Canyon National Park, and Great Basin National Park are the only ones that have caves formed in marble. This makes Oregon Caves distinct among other caves.

The water that flows through Oregon Cave is fed by stream piracy (discrete water input) and by water dripping from speleothems (diffuse water input) (White 1988). A water-chemistry data set exists for ORCA, compiled from a ten-year sampling activity which began in 1991 and continued through 2001. The samples were collected from various drips in the cave and a few locations from the subsurface stream. A special feature of this data set is the inclusion of total organic carbon (TOC) concentrations. This data set provides an opportunity to compare the chemistries of marble and limestone karst waters, compare drip water chem-

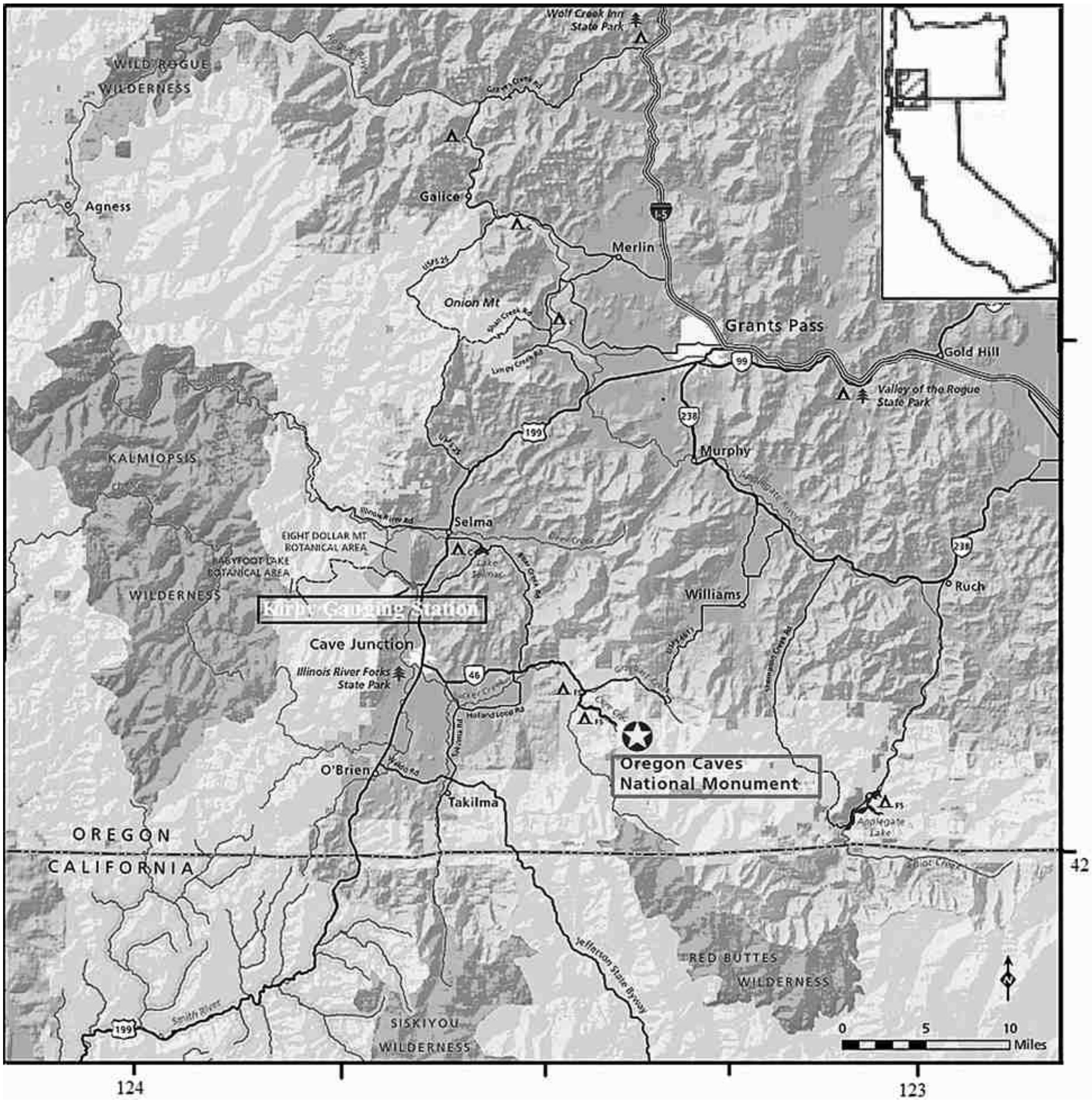

Figure 1 *Location of Oregon Caves National Monument and USGS Gauging station near Kirby in SW Oregon. After an ORCA informational brochure.*

istry to that of stream water, and to assess temporal variation in TOC in both drip and stream water.

Previous geochemical studies of cave-drip and stream water have mostly been done in limestone. A recent limestone drip-water study of a tour cave in Slovakia (Motyka et al. 2005) found that the composition of the host rock strongly influenced the water composition. For example, calcitic rock produces water concentrations high in calcium (Ca) and bicarbonate (HCO_3), while dolomitic rock with pyrite produces water concentrations high in Ca, HCO_3, magnesium (Mg), and sulfate (SO_4). Surface conditions in Slovakia, such as climate, plant cover and soil type, influenced total dissolved solid (TDS) content (332 to 520 mg/L) and calcite saturation indices (SI) (0.78 to 1.39). Drip-water testing in Lititz Spring, Pennsylvania (Toran and Roman 2006), found a reverse correlation between calcite SI and the partial pressure of carbon dioxide (P_{CO_2}). Calcite SI ranged from 0.2 to 0.6 for log P_{CO_2} values from -1.9 to -2.4 atm respectively.

Seasonal variations in ionic concentrations were noted in drip water studies at several limestone caves (Doctor and Alexander 2004, Drever 1982, McDonald et al. 2002). Seasonal variations of soil carbon dioxide (CO_2) were determined to account for correlative concentrations of total dissolved ions (TDI) in drip-water chemistry at Pettyjohns Cave, Georgia (Mayer 1999) as higher levels of CO_2 increases carbonate dissolution (drip-water TDI ranged from 175 to 298 mg/L, log P_{CO_2} levels ranged from -3.19 to -2.1 atm. Work by Vesper and White (2006) indicate that as trace metal concentrations rise, carbonate concentrations decrease.

Study at Pettyjohns Cave (Mayer 1999) observed that stream-water ionic concentrations become dilute during periods of high flow (TDI from 34 to 40 mg/L at high flow, 124-153 mg/L during low flow) and tended to be lower than those in the drip water (stated above). Surface input streams at Pettyjohns had significantly lower calcium and bicarbonate concentrations (0.62 and 0.25 mg/L respectively) than the subsurface streams (10.51 and 29.5 mg/L) for the same date.

Few studies have been performed in marble caves. A study in Lilburn Cave, a marble cave in Sequoia and Kings Canyon National Park (Abu-Jaber et al. 2001) found Ca concentrations in the discharge spring ranged from 14 to 44 mg/L while input water concentrations ranged from 3.5 to 5.6 mg/L. The implication being that carbonate dissolution is occurring in the cave. Dissolution rate decrease during periods of high discharge was attributed to passage geometry. Water gushing through steep and wide passages has little residence time and limited rock-water interaction. Oregon Caves and Lilburn Cave are formed in a low-grade marble lenses. Metamorphism of limestone produces a hard and dense marble (Ford and Williams, 1989) with low porosity and (usually) low permeability, making the rock less penetrable than limestone. This may account for the development of cave passsages in marble, which are dominated by bedding planes and faults (Roth 2007).

Total organic carbon (TOC) is the sum of dissolved organic carbon (DOC) in solution with particulate organic carbon (POC). Some geochemical water studies discuss dissolved organic carbon (DOC) concentrations in water, but rarely report TOC. Because organic carbon is vital to support microbial life, an understanding of TOC in a system may help evaluate the health of the system. Howcroft and Hess (1997) performed a hydrology study of Redwood Canyon karst aquifer (Sequoia and Kings Canyon National Park) that measured TOC concentrations at several sites. However, the TOC levels that they measured were so low (< 0.1 to 1.0 mg/L), further analysis of TOC concentrations was abandoned.

Scientific research typically begins with a question and proceeds to data collection. However, I received the data first and then asked the questions. Here is this data set, the labor and costs have already been expended. This data set provides an opportunity to study marble karst water chemistry with the added distinction of having TOC information and allows the following questions to be addressed: 1) What differences, if any, are there between limestone and marble karst water chemistry? Although the composition of limestone and marble is the same, the expectation would be that the more stable configuration of the marble grains would inhibit rock-water interaction and limit the mineral contribution from the host rock. 2) What differences, if any, exist between drip water and stream water? The expectation would be for drip water to have higher concentrations of most chemical species given the longer contact time between the water and host rock. 3) What can be learned from the change in total organic carbon (TOC) over time and the relationship (if any) between the various sites? One would expect to see higher concentrations of TOC in the drip water given the organic content of soil.

Field Site Description

Oregon Caves National Monument (ORCA) is located on a north-facing slope of Mt. Elijah in the Siskiyou Mountains (Figure 2). These steep, densely-forested mountains consist of rocks from the Western Triassic-Paleozoic tectonostratigraphic terrane of the Klamath Mountains (Irwin, 1966) and are a "collage of oceanic and continental fragments juxtaposed against each other and the North American continent" (Charvet et al. 1990). The cave at ORCA lies within the Applegate group (Barnes et al. 1996) which consists of extrusive volcanics with lenses of slate, quartzite, chert, limestone and marble. The age of the marble has been estimated at 210 Ma (Irwin and Blome 2004). Adjacent rock includes meta-argillite, serpentinitized peridotite and quartz diorite.

Oregon Caves is only one cave at ORCA, but

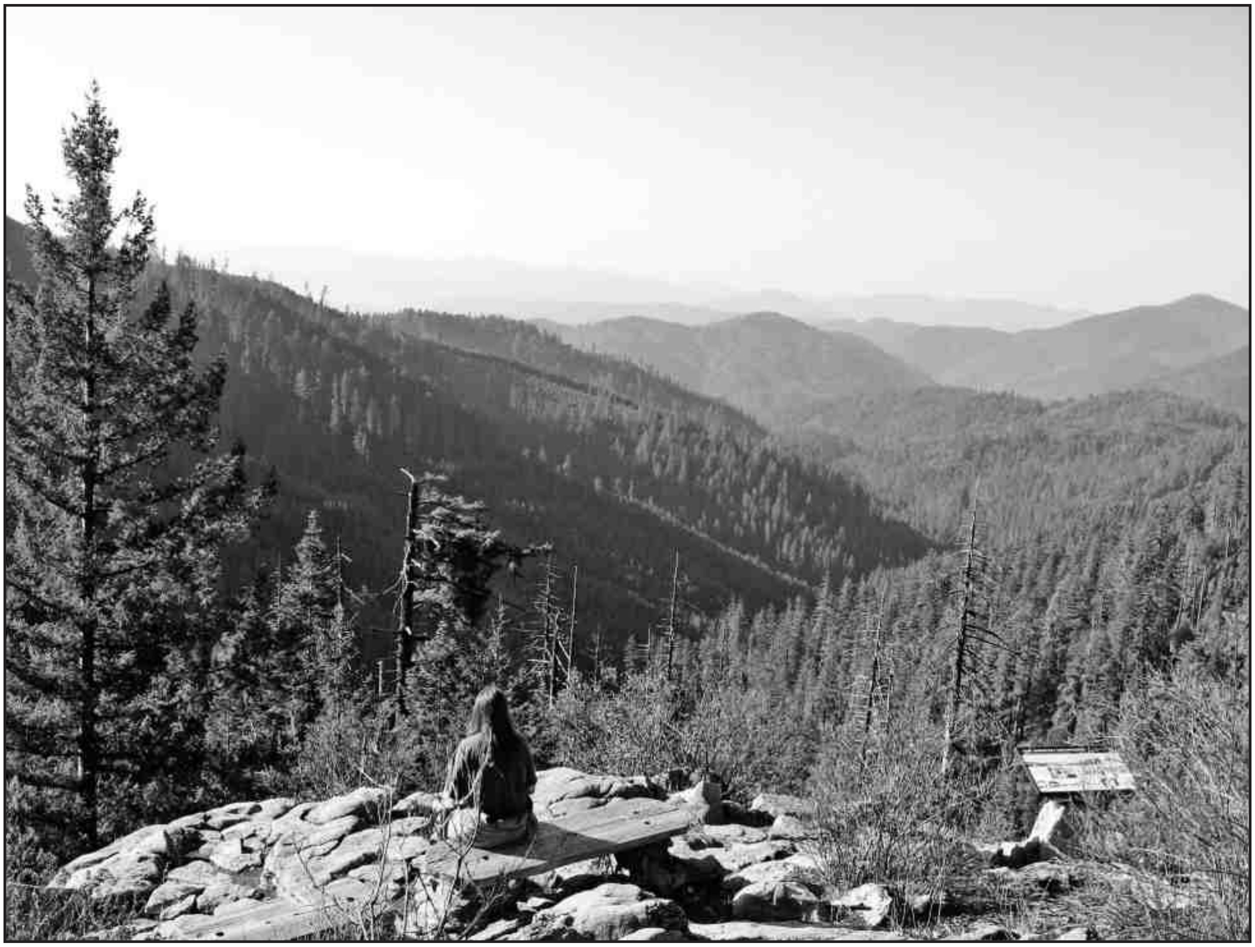

Figure 2 View of the Siskiyou Mountains from a trail above the cave.

because of multiple openings it was once thought that there were multiple caves, and so the name Oregon Caves. It is a solution cave formed in a faulted and folded marble lens, carved by meteoric waters that have percolated through the soils. The cave has four natural openings and one additional man-made exit tunnel. There are 4.86 km of mapped passage. The marble is metamorphic limestone laced with bands of graphite and veins of chert. Soils of ORCA eroded from various parent materials. These are predominantly loamy and are ideal for the flora (Table 1) that shade the grounds and maintain the soil moisture content. The elevation at the exit spring is about 1220 m, 730 m below the summit of Mt. Elijah, where snowmelt waters supply the drainage basin.

A previous hydrological study (Roth 2005) indicates that most water enters the cave through vertical cracks and dome-pits and to a lesser degree by stream piracy. Precipitation entering the cave

Table 1. Some of the plant species found at Oregon Caves National Monument and the soil type parent rock material in which they grow. (Oregon State University, 2007)

Plant Species	Granitic	Serpentinite	Altered sediment and igneous
Oregon Grape	X		X
Douglas Fir	X	X	X
Pacific Ocean Spray	X		X
Deerfoot Vanillaleaf	X		X
Pacific Madrone	X	X	X
Poison Oak	X	X	X

takes hours to days to reach the upper part of the cave. Dye tracing at a stream above the cave took about 50 hours to reach the cave exit. Upper parts of the cave dry out by the end of summer but deeper parts remain wet year round. It is believed that some water takes months or years to work its way down cracks parallel to the orientation of the rock layers (Roth 2005).

The water samples used for this study were collected from two drip pools, three drip sites, two locations from the subsurface stream and one from a surface input stream (Figure 3). The sites are as follows: Bridge-Styx (Bridge River Styx), a lower cave stream, is 9 m above the spring and 18 m below the surface. Bridge-Styx is a mix of diffuse (drip) and discrete (surface stream infiltration) water. Imag (Imagination room) is 15 m above the spring and 17 m below the surface. It is a drip from a crack (diffuse). MI (Lake Michigan) is a drip pool 21 m above the spring and 47 m below the surface (diffuse). The Shower is a dome drip pool 30 m above the spring and 58 m beneath the surface (discrete). Ghost-Styx (Ghost River Styx) is an upper cave stream (discrete) 15 m above the spring and is 67 m beneath the surface. Wedding (Wedding Cake) is a drip from a bedding plane (diffuse) 40 m above the spring and is 52 m beneath the surface.

Materials and Methods

Geochemical data for this study were selected from a thirty-four-month collection period from November, 1991 through September, 1995. Samples were collected on a near-monthly basis at several surface and subsurface sites within ORCA. However, sampling was not always performed in the same locations, and not all tests were performed on all dates. Seven of the sites had fairly consistent sampling from May 1992 through October, 1993, these data were selected for this study. Hydrologically, the Shower drip pool is upstream of Ghost-Styx. MI drip pool, Wedding and Imag drips are at higher elevations than the subsurface streams. Bridge-Styx is downstream of all the sites

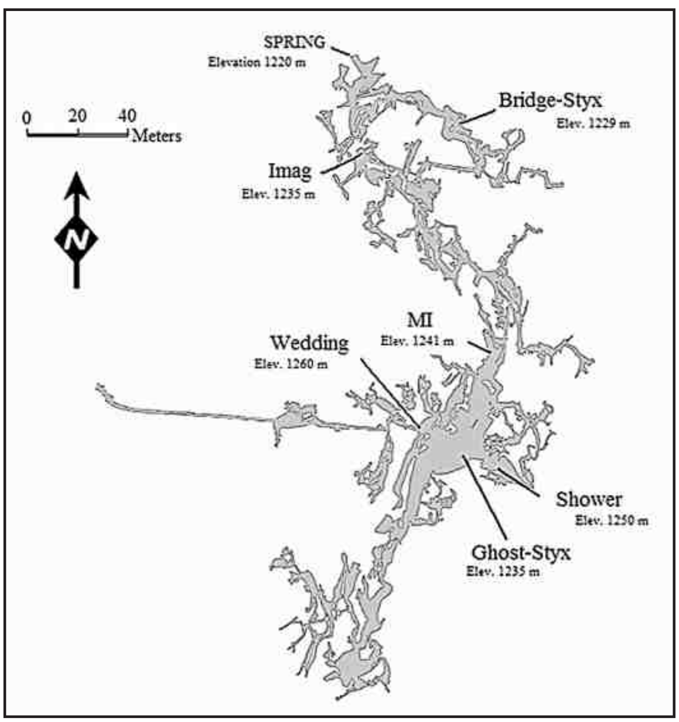

Figure 3 *Plan view of cave depicting locations of sampling sites used in this study. (After Roger Brandt, Oregon Caves National Monument Trail Brochure)*

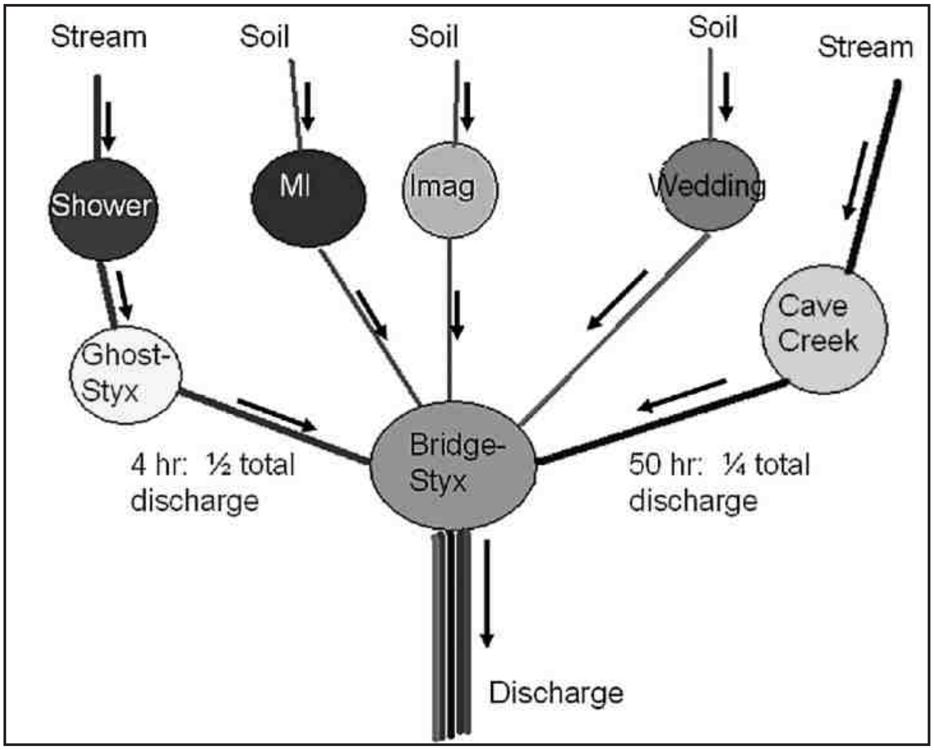

Figure 4 *A diagram of the flowpaths, including discharge results from previous dye tracing.*

sampled within the cave. Cave Creek is one of the cave's input streams. Dye injected at Cave Creek arrived downstream at Bridge-Styx but not at Ghost-Styx. Dye injected at Ghost-Styx also arrived downstream at Bridge-Styx. A diagram of the flowpath is in Figure 4. Included are the time delay and discharge contribution results from previous dye tracing.

At each site, the pH and temperature were recorded *in situ*. Water samples were collected and were sent to an analytical laboratory (Waterlab Corporation, certified lab #008) to be analyzed (using standard titration methods) for the following: total dissolved solids (TDS), carbon dioxide (CO_2), total organic carbon (TOC), total alkalinity ($CaCO_3$), calcium (Ca), magnesium (Mg), sulfate (SO_4), chloride (Cl), sodium (Na), iron (Fe), and zinc (Zn). Preliminary numerical analysis (median, maximum, minimum and standard deviation) was then performed. Graphs of water-chemistry variations over time were generated and analyzed. A Piper plot was constructed to show the ionic composition at the different sample sites. Both Piper and Stiff diagrams were constructed using RockWare® science applications software. The saturation index (SI) = -log (IAP/Kt) (ionic activity of reaction/ equilibrium constant) of the water with respect to calcite and the partial pressure of CO_2 (Pco_2) were calculated using PHREEQC1, speciation water resource application software (Parkhurst, 2007). The charge balance error was offset by adding potassium (K^+), which was not measured, although expected considering the granitic diorite in the area. For three sites on only three dates, the charge balance error could not be rectified even with the addition of 1000 mg/L K^+, an excessive amount. In close examination of those samples, the pHs were found to be particularly low (5.11, 5.38, and 5.60) and likely incorrect, however these were the reported values. Instead of adjusting the pH to correct for charge balance, an option in PHREEQC1, the samples were removed from further consideration.

Results

Two distinct source waters are present in the cave—diffuse water and discrete water. Diffuse water is meteoric water that percolates through the soil, drips into the cave through cracks (Imag) and

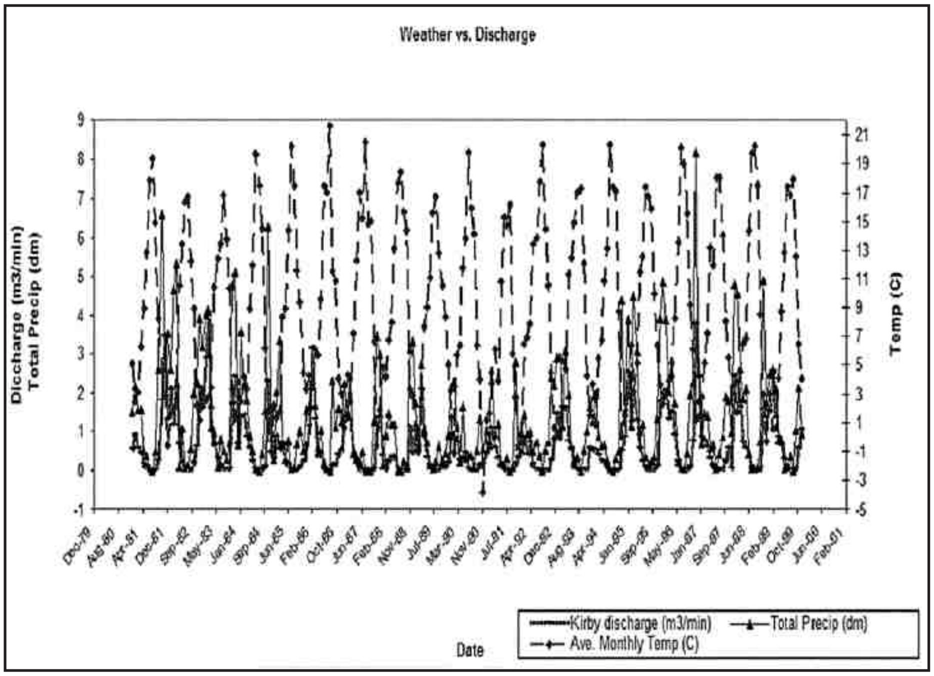

Figure 5 *Graph showing average monthly temperatures, total monthly precipitation levels and downstream discharge rates for August, 1980, through December, 1999, at Oregon Caves National Monument.*

bedding planes (Wedding) and forms drip pools (MI). Discrete water is surface input stream (Cave Creek), dome water (Shower) and upper cave stream (Ghost-Styx). Eventually, the two source waters converge downstream at Bridge-Styx (Figure 4).

The stream spring is 1220 m above sea level. Average air temperature in the cave is 7°C (Roth 2005). Low temperatures tend to increase the solubility of calcite. Average precipitation at ORCA is approximately 132 cm/year (Hale 2007). The average monthly temperatures rarely fall below 0°C (Figure 5), therefore little time delay between snowfall and snowmelt was assumed. Discharge data obtained from Kirby station (USGS Hydrologic Unit, Figure 1), which is downstream from the spring and along the Illinois River, seemed to support this assumption.

Numerical analysis, diffuse water. Mean values for water chemistry of diffuse sites are shown in Table 2. Drip and pool water pH ranged between 5.38 and 11.82. Temperature ranged between 5.8 and 11.8°C. Total dissolved solids ranged from 0.02 to 1.3 mg/L. Carbon dioxide levels were between 200 and 2050 ppm. Total alkalinity for diffuse sites ranged between 96.0 and 182.0 mg/L. Total organic carbon concentration ranged from 0.1 to 24.1 mg/L. Calcium concentrations spanned from 21.5 to 60.8 mg/L. Magnesium concentrations ranged between 0.32 and 9.12 mg/L. Sulfate concentrations ranged from 0.1 to 10.8 mg/L. Chloride concentrations spanned from 0.1 to 55.5 mg/L. Sodium concentrations for diffuse flow ranged from 0.1 mg/L to 47.7 mg/L. Iron concentrations were consistently less than 0.01 mg/L at both Wedding and MI, but reached concentrations as high as 8.64 mg/L at Imag. Zinc concentrations were consistently less than 0.001 mg/L at both Wedding and MI, but reached concentrations as high as 0.29 mg/ at Imag.

Numerical analysis, discrete water. Mean values for water chemistry of discrete sites are shown in Table 2. Discrete water pH ranged between 4.27 and 11.78. Temperatures ranged from 5.80 to 11.5°C. Total dissolved solids ranged from 0.07 to 2.0 mg/L. Carbon dioxide concentrations were between 200 and 2,325 ppm. Total alkalinity for discrete sites ranged between 100 and 300 mg/L. Total organic carbon ranged from 0.1 to 47.1 mg/L. Calcium concentrations were between 6.10 and 57.6 mg/L. Magnesium concentrations ranged between 0.44 and 47.2 mg/L. Sulfate concentrations ranged from 0.1 to 4.5 mg/L. Chloride concentrations ranged from 0.1 to 16.5 mg/L. Sodium concentrations were from 0.1 mg/L to 19.8 mg/L. Iron concentrations were less than 0.2 mg/L, but Bridge-Styx (downstream) had a one-time, high iron concentration of 11.1 mg/L. Zinc concentrations were less than 0.001 mg/L for all discrete sites.

Table 2. Mean values for diffuse, discrete, and surface stream water

Water sampling sites	Ca (mg/L)	pH	Temp. (C)	TDS (mg/L)	Alkal. (mg/L $CaCO_3$)	TOC (mg/L)	SI (Calcite)	P_{CO_2} (atm.)
Diffuse								
Imag	45	8.14	8.82	0.17	134	7.25	0.63	$10^{-2.3}$
Wedding	46	8.42	8.62	0.20	138	6.91	0.81	$10^{-2.2}$
MI	43	8.42	8.13	0.16	126	8.99	0.83	$10^{-2.2}$
Discrete								
Shower	42	8.51	7.88	0.22	119	6.36	0.93	$10^{-2.2}$
Ghost-Styx	43	8.22	8.09	0.18	123	11.04	0.84	$10^{-2.2}$
Bridge-Styx	39	8.01	7.51	0.15	140	15.84	0.31	$10^{-2.0}$
Surface								
Cave Creek	25	8.22	9.09	0.12	84	6.85	0.13	$10^{-2.6}$

Mean values for water chemistry of the surface stream are in Table 2. Cave Creek water pH ranged between 7.35 and 9.48. Temperatures ranged from 5.70 to 13.3°C. Total dissolved solids ranged from 0.05 to 0.80 mg/L. Carbon dioxide concentrations were between 150 and 600 ppm. Total alkalinity for Cave Creek ranged between 18 and 142 mg/L. Total organic carbon ranged from 0.4 to 27.9 mg/L. Calcium concentrations were between 6.13 and 49.6 mg/L. Magnesium concentrations ranged between 1.44 and 12.00 mg/L. Sulfate concentrations ranged from 1.07 to 3.8 mg/L. Chloride concentrations ranged from 0.11 to 4.7 mg/L. Sodium concentrations were from 1.64 mg/L to 12.7 mg/L. Iron concentrations were less than 0.01 mg/L. Zinc concentrations were less than 0.001 mg/L.

Temporal analysis, diffuse water. Graphs of diffuse, water-chemistry variability over time indicate the sites were very similar in overall composition and fluctuation patterns. Diffuse water temperatures fluctuated greatly during the study period. Except for winter 1993-1994, the diffuse data had similar variation patterns in temperature, but with different amplitudes. Seasonal pH variations at the diffuse sites were seen. During dry summer months, pH tended to increase. During wet winter months pH level and during spring pH declined. Except for two samples, one collected in spring 1993 and one in summer 1994, TDS concentrations remained low and unchanging. Calcium concentrations increased slightly during the summer of 1992 and except for a slight decline spring 1993 remained relatively constant for the rest of the study period. Diffuse sites had relatively little variation in total alkalinity during the study period. Saturation indices for calcite (Figure 6) indicate that, except for late winter 1993, diffuse sites were oversaturated with respect to calcite. Partial pressure of carbon dioxide (P_{CO_2}) (Figure 7) ranged from $10^{-3.5}$ to $10^{-1.29}$ atm. For the study period, these sites had P_{CO_2} levels 1 to 200 times the atmospheric standard of about $10^{-3.5}$ atm. A plot of SI for calcite verses log P_{CO_2} values (Figure 8) indicates a strong reverse correlation between P_{CO_2} and calcite SI. Total organic carbon concentrations at all three sites increased slightly during summer 1992. Concentrations of TOC then diminished at Wedding and Imag as concentrations at MI continued to increase through early fall. Fluctuations in TOC concentrations at all three sites were moderate for most of 1993. Seasonal variations in CO_2 concentrations were evident, with higher concentrations during dry summers and lower concentrations during wet winters. Magnesium (Mg) and SO_4 concentrations were low with relatively little variation during the study period. Chloride and Na concentrations were likewise, except at Wedding, which had high concentrations in May and August, 1992.

Temporal analysis, discrete and surface water. Discrete water chemistry variability over time indicates the sites were very similar in overall composition as well as fluctuation patterns. The surface stream, Cave Creek, had generally lower ionic concentration than discrete water. Discrete water temperatures fluctuated widely between sites as well as seasonally during the study period. Cave Creek and Bridge-Styx showed greater response to surface temperature changes than did Shower or Ghost-Styx. Seasonal pH variations at the discrete sites were seen. During late, dry summer months, pH tended to peak but during wet winter months pH would decrease. A drop in pH occurred at Ghost-Styx in July, 1993. Except for two events, spring 1993 and summer 1994, TDS concentrations remained low and unchanging. Calcium concentrations increased slightly during the summer of 1992 and (except for a slight decline in spring 1992 and a drop at Bridgen in fall 1993) remained relatively constant for the rest of the study period. Cave Creek had notably lower Ca concentrations. Discrete sites had relatively little variation in total alkalinity during the study period except for a peak at Bridge-Styx fall 1993. Cave Creek had notably lower alkalinity concentrations. Calcite SI (Figure 6) indicate that for most of the study period, discrete sites in the cave were oversaturated with respect to calcite. Cave Creek was oversaturated with respect to calcite 60% of the times sampled. Partial pressure of carbon dioxide (Figure 7) ranged from $10^{-3.3}$ to $10^{-1.1}$ atm. For the study period, these sites had $P co_2$ levels 1.5 to 250 times the atmospheric standard of about $10^{-3.5}$ atm. A plot of SI for calcite verses log $P co_2$ values (Figure 8) indicates a strong, reverse correlation between $P co_2$ and calcite SI. Total organic carbon concentrations fluctuated greatly during the second half of 1992. Concentrations decreased slightly in spring 1993, increased early June, and held fairly constant for the remainder of the study period. Seasonal variations in CO_2 concentrations (except in Cave Creek) were evident, with higher concentrations during dry summers and lower concentrations during wet winters. Magnesium (Mg) and SO_4 concentrations were low with relatively little variation during the study period, except at Bridge-Styx, which had a peak in Mg concentrations during spring and fall of 1993. Chloride concentrations were low and showed little variation during the study period except for two dates at Ghost-Styx and one at Shower. Sodium concentrations displayed an increasing trend until May1993 then decreased. Ghost-Styx displayed greater Na concentration fluctuations than the other discrete sites.

Piper/Stiff analysis, diffuse water. The Piper diagram in Figure 9 shows the ionic composition of the water samples. The open circles represent samples from diffuse sites and plot in the carbonate-bicarbonate. The samples plot in the high

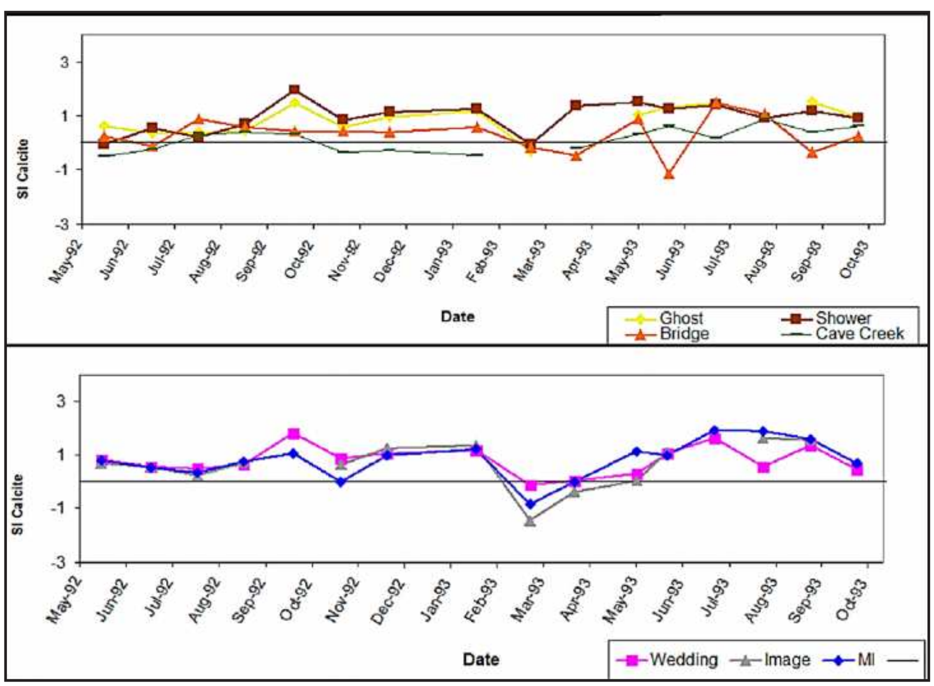

Figure 6 Graphs showing saturation index (SI) for calcite. The top graph shows discrete water sites. The lower graph shows diffuse water sites.

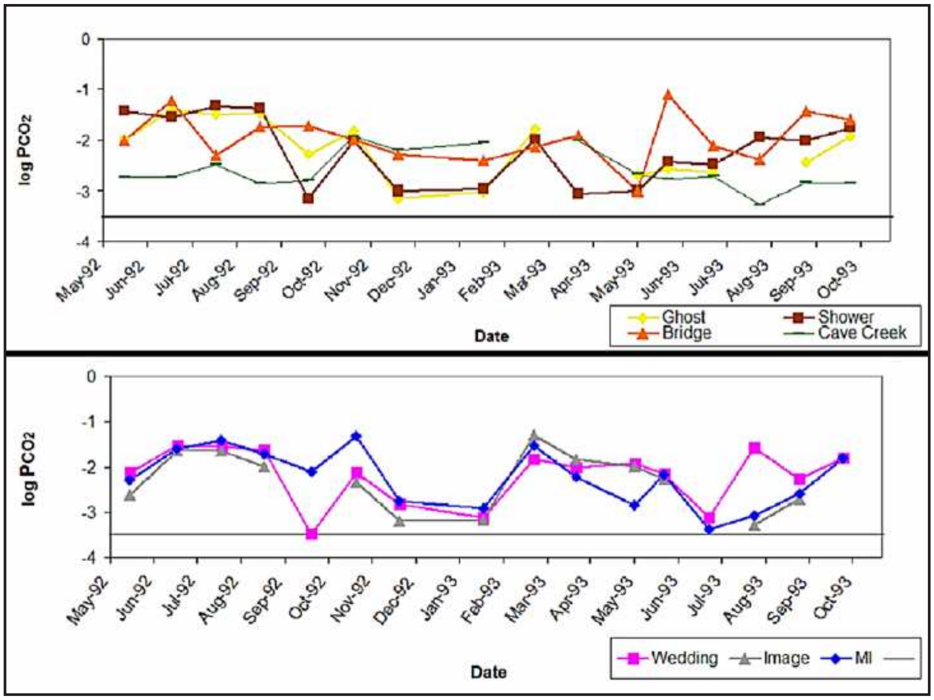

Figure 7 *Graphs showing partial pressure for CO_2. The top graph shows discrete water sites. The lower graph shows diffuse water sites. Pco_2 levels were 1 to 250 times atmospheric pressure.*

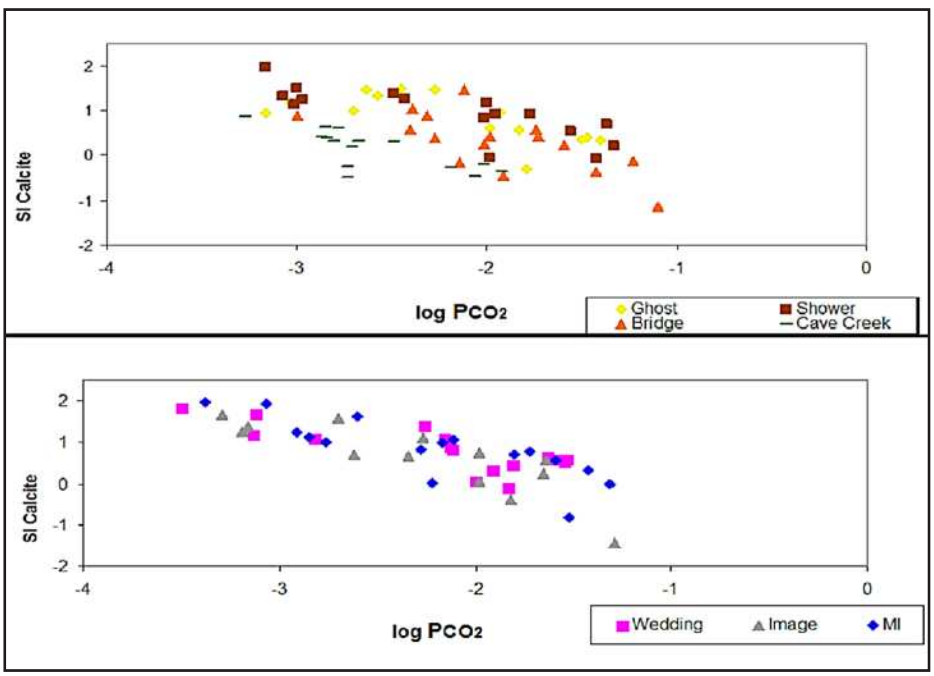

Figure 8 *Plots showing a reverse correlation between calcite SI and Pco_2.*

carbonate range with low magnesium content. The outlying open circle in the cation triangle represents the high concentrations of Na detected in the samples at Wedding, and the outlying open circle in the anion triangle represents the high concentrations of Cl detected in the samples at Wedding. The samples plot in the high carbonate range, as would be expected from a highly calcitic marble. The Stiff (shape) diagram in Figure 10 shows the relative abundance of major ion concentrations of

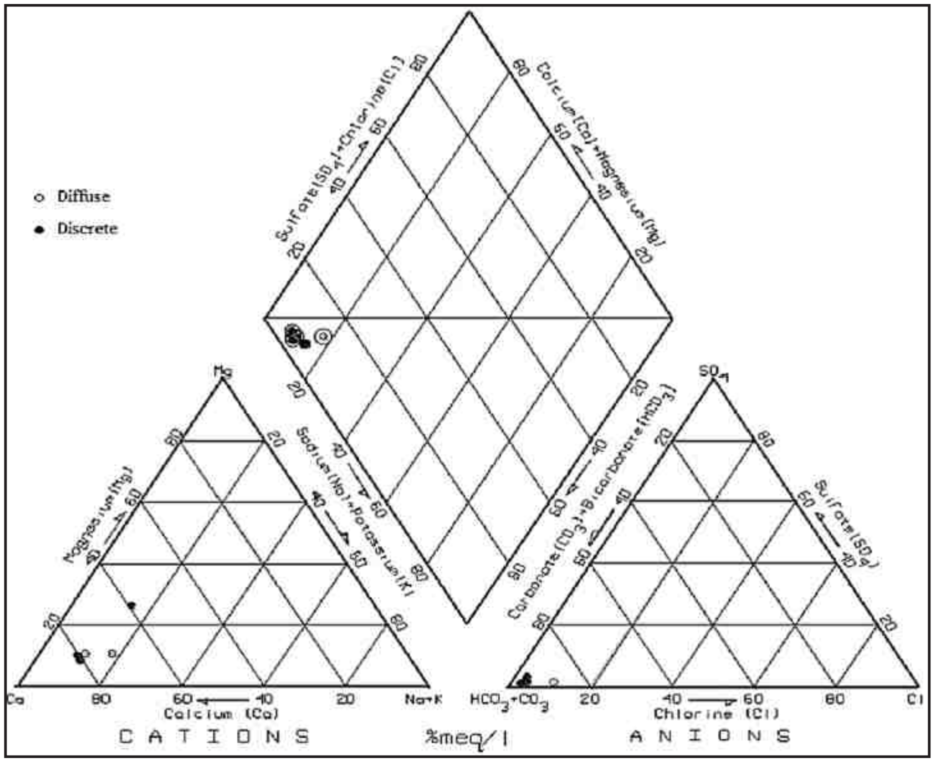

Figure 9 *Piper diagram showing ionic composition of the samples. Open circles are from diffuse water sites, closed circles are from discrete water sites.*

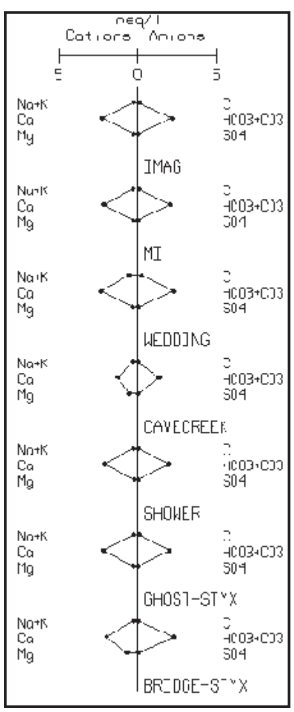

Figure 10 *STIFF (shape) diagram of mean cation/anion of the sites showing relative abundance of ion concentrations of the different sample sites.*

the different sample sites. Mean ionic concentrations for diffuse sites are plotted at the top of the diagram. A glance at the diagram shows that the ionic composition for the three diffuse sites were very similar, though Wedding has higher concentrations of Cl and Na.

Piper/Stiff analysis, discrete and surface water. The closed circles on the Piper diagram in Figure 9 represent samples from discrete and surface sites. The outlying closed circle in the cation triangle represents higher concentrations of Mg found in the samples from Cave Creek and Bridge-Styx. The discrete samples plot in the high carbonate range as would be expected from a highly calcitic marble. The Stiff diagram in Figure 10 shows the relative abundance of major ion concentrations of the different sample sites. Mean ionic concentrations for discrete sites are plotted on the lower part of the diagram. A glance at the diagram shows the ionic composition for Shower and Ghost-Styx were very similar. Bridge-Styx reflects the higher concentrations of Mg found in Cave Creek but not seen at Shower or Ghost-Styx.

Discussion and Conclusions

The goal of this study was to compare the chemistries of marble and limestone karst waters, compare drip-water chemistry to that of stream water, and to assess temporal variation in TOC in both drip and stream water. As to the question of would there be differences between limestone and marble water chemistry, the expectation was that the more stable configuration of the marble would inhibit rock-water interaction and limit the mineral contribution from the host rock. The ionic composition in this cave was highly carbonate with little Mg, which is a reflection of the composition of the marble, and indicates extensive rock-water interaction. As in the Slovakian cave (Motyka et al. 2005), composition of the host rock strongly influenced the water composition. Because the water in Oregon Caves was usually supersaturated with respect to calcite, further dissolution of Ca could not take place. This explains the relative flat line of the Ca graph. The high Ca concentrations may account for this cave's relatively low concentrations of TDS, Fe, Zn, and Mg (Vesper and White 2006). A reverse correlation between calcite SI and $P\text{co}_2$, similar to that observed by Toran and Roman (2006), is seen in Figure 8. When samples became undersaturated in calcite during February, 1993 (Figure 6), there was an increase in TDS concentrations as well as $P\text{co}_2$. This coincided with a heavy snowmelt event. Similar correlation between high flow, TDS, $P\text{co}_2$, and calcite SI were noted in several limestone caves (Mayer 1999, McDonald et al. 2002, Doctor and Alexander 2004, Motyka et al. 2005). These observations suggest that differences in the rock's crystal structure had little influence on differences in resultant water chemistry.

As to the question of what differences exist between drip (diffuse) water and stream (discrete) water, the expectation was that drip water would have higher concentrations of most species. As expected, drips were higher in Ca. The cold temperatures of the cave and the acidic pH of the soil would promote dissolution of Ca. The composition of the samples from MI and Image were very similar, which indicates similar source water with similar travel histories. The notable difference in the samples at Wedding was the occasional presence of Na and Cl. Part of the cave is overlain by paved trails. It may be that ice melt (salt) used for the trails is finding its way into the source water for Wedding. Cave Creek, the surface stream had concentrations of Mg that were seen downstream at Bridge but not seen in the samples from the drips, or other discrete sites. This indicates that Cave Creek is not the source water for Shower, Ghost-Styx, or the drips but joins the subsurface stream before the Bridge. This is supported by previous dye tracing. What was unexpected was that water of Cave Creek was often saturated with respect to calcite. This would indicate that surface water flows over marble outcrops prior to entering the cave.

Total organic carbon (TOC) was surprisingly similar in drips (diffuse), streams (discrete) and in Cave Creek. The expected result was that TOC would be higher in the drips, attributed to high organic material in the soil. The inference, therefore, is that the surface stream passes over high amounts of organic material prior to entry into the cave. There were insufficient data to understand the reason for the TOC fluctuations seen across the site over the study period.

Now that we have this information, we could learn more with subsequent work. Therefore, a future study should have a consistent set of collection sites with consistent collection criteria. Optimally, those criteria should include site discharge information, when possible, and collection order. It would be beneficial to collect specific soil information, such as depth. One area for further investigation would be to identify the source water for Shower and Ghost-Styx. It is known that there are other surface creeks that could be possible source water. Future study could be expanded to include these streams in the sampling.

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MAPPING VISITOR IMPACTS WITH GIS AT OREGON CAVES

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Abstract

Managing visitor impacts is a major issue in all show caves, where thousands of visitors annually can have a profound effect on a cave's scientific, ecological, and aesthetic integrity. Visitor-impact mapping, a monitoring technique first presented by Bodenhamer (1996) was joined with Geographic Information Systems (GIS) to assess the condition of Oregon Caves and its resources. Hazard and fragility were assessed throughout the cave to map areas of potential impact. Data on the presence and severity of more than 20 readily visible impacts were collected along heavily traveled corridors. Features of interest or concern were photo-inventoried, including paleontological sites, and photos were hyperlinked to GIS layers to establish monitoring. These inventories and assessments helped identify significant impacts, define off-trail access zones, and plan for off-trail caving tours. GIS-based visitor-impact mapping helps balance cave use and protection.

Key words: show cave management, GIS, hazard mapping, fragility mapping, photo-inventory, Oregon Caves, Oregon

Introduction

Visitor-impact mapping is the technique of mapping impacts and resources to monitor the condition of a cave (Bodenhamer 1996). In 2005-07, resource management staff and interns at Oregon Caves engaged in a project to assess and monitor impacts using Geographic Information Systems (GIS). The goal was to determine the severity and extent of impacts and whether impacts are becoming more severe over time. The objective of this project was to systematically and comprehensively collect and integrate photos; visitor-caused, negative impacts; and cave resources in a geodatabase to:

- Quantify impacts,
- Monitor the condition of resources, and
- Better inform management decisions.

The approaches to mapping visitor impacts were:

- Assessment of hazard and fragility,
- Inventory of impacts,
- Photo-monitoring and inventory,
- Survey of paleontological sites, i.e. bones and other animal evidences, and
- Mapping of lampenflora, i.e. nonnative plant growth, including algae and cyanobacteria, around tour path lights.

Oregon Caves

Oregon Caves National Monument is located in the Siskiyou Mountains in southwestern Oregon between Interstate-5 and the Pacific coast. The main cave entrance is situated at an elevation of 1,219 m. Oregon Caves is a marble cave that showcases regional geology and is a habitat to at least seven endemic macroinvertebrate species. Additionally, the cave contains many significant paleontological resources, including salamander bones, bear scratches, bear bones >50,000 years old, and the remains of a jaguar >38,600 years old.

The total surveyed length of the cave is 4.8 km. An average of 48,000 visitors tour the cave annually using a 1-km developed route. The off-trail caving tour, which was offered once a week to the public for the second time in summer 2007, follows a route through about 200 m of off-trail cave passages, including passages that were part of the old tour route.

Visitor impacts in the cave include damage to resources that are deemed significant in the study of earth processes and natural history, such as animal remains, geological features, and sediment deposits, ecologically significant impacts resulting from tour path lighting, lint deposition, sediment compaction and translocation, and historic entrance and passage enlargement, and the aesthetic devaluation of cave formations from souvenir collecting, illegal graffiti, or excessive touching.

Background

At the time this project was being formulated, the need to increase understanding and monitoring of impacts in Oregon Caves was underscored by planning for off-trail caving tours. Nineteen fixed-point, photo-monitoring stations had been installed in 2003 along the developed tour path, a portion of the proposed caving tour route and at cave entrances. Bodenhamer (1996) showed that photo-monitoring supplemented by visitor-impact mapping can provide a more complete picture of the condition of a cave and its resources. However, efforts to intensively quantify and monitor impacts through mapping have been largely focused on relatively pristine or undeveloped caves, not show caves (Bodenhamer 1996, Bunting and Balks 2001).

A GIS had already been established for Oregon Caves before the project. It included layers of survey stations, survey shots, and photo-monitoring stations, and a table of resource inventory data. Though GIS is widely used to map caves and manage inventory data, assessing and monitoring impacts in caves are only beginning. Notably, Sainsbury (2005) used GIS to hyperlink photos to a GIS layer of monitoring stations in order to evaluate impacts and their spatial pattern.

Ethics

In preparation for fieldwork, resource management staff and interns outlined minimum-impact protocols. These included confining all travel and equipment to the most impacted path, handing off an item only when the receiver has verbally affirmed it is in her/his grip, and planning ahead to complete work in as few trips as possible. In the cave, staff and interns practiced low-impact caving techniques and packed a small bag to collect trash.

Materials and Methods

Assessment of Hazards and Fragility. An assessment of hazards and fragility was conducted to map areas of potential impact. Passages were classified according to the hazard they pose to the caver and their fragility, i.e. vulnerability to damage. The assessment was conducted for areas defined by survey shots, i.e. the portion of passage between two survey stations. Data collected in the cave were input into a GIS layer of survey shots using ESRI ArcPad® on a Pocket PC. Hazard was assessed based on vertical exposure, instability of the passage, and caving equipment and expertise required to negotiate the passage (Table 1). Fragility was assessed as the average of four equally weighted ratings: resource condition, proximity to fragile resource, resource value, and density of breakable formations (Tables 2-5).

Impact Inventory. An inventory of more than 20 readily visible impacts was conducted along heavily traveled corridors to provide a baseline of information to better understand the nature of impacts as well as a starting point for restoration and mitigation. Cave resource inventories are conducted for similar purposes (Kovarik and Kambesis 2006). Modeling the methodology of Oregon Caves' resource inventory from the 1990s, impacts were inventoried for areas defined by their proximity to survey station markers and extending outward to a boundary halfway in each direction to adjacent markers. Data collected in the cave were input into a GIS layer of survey stations using ESRI ArcPad® on a Pocket PC. Severity was based on percentage categories or how widespread the impact (Table 6). The inventoried impacts included various manifestations of disturbance to cave sediments and speleothems, evidence of improper caving, and impacts resulting from tour paths and heavy visitation.

Table 1 Hazard Rating Criteria

	Criteria
0	Paved, clearly marked pathway. Lighted trail. Some stooping, but no crawling is necessary.
1	No known loose ceiling rocks. Well-defined main passageways with only dead-end lateral passages. No drop over 3 m. Basic caving equipment is required.
2	Maze-type passageways. Vertical drops up to 9 m. Loose rocks on ceilings >2 m in height. No known loose rocks on passages <2 m. Balanced rocks on uneven floor.
3	Vertical drops over nine m. Loose ceiling rocks in crawlways <1.5 m.

Table 2 Fragility Rating Criteria: Resource Condition

Rating	Resource Condition	Criteria
4	Pristine	100% of the cave features in the area are undamaged.
3	Very Good	75 – 99% of the cave features in the area are undamaged.
2	Good	50 – 74% of the features in an area are undamaged.
1	Poor	Less than 50% of the features in an area are undamaged.

Table 3 Fragility Rating Criteria: Proximity to Fragile Resource

Rating	Proximity to Fragile Resource	Criteria
4	Must Contact	Resource must be touched to pass.
3	Likely Contact	Resource will probably be touched.
2	Possible Contact	It is possible to touch resource along path, but unlikely.
1	Not Possible	There is no way to touch or damage the resource.

Table 4 Fragility Rating Criteria: Resource Value

Rating	Resource Value	Criteria
4	Very High	The resource is regionally rare, very aesthetic, or may be of great scientific interest.
3	High	The resource is uncommon, aesthetically pleasing, and may have some scientific value.
2	Medium	Resource is pretty, but has little scientific value.
1	Low	Resource is very common.

Table 5 Fragility Rating Criteria: Density of Breakable Formations

Rating	Density of Breakable Formations	Criteria
4	High Concentration	High number of breakable formations.
3	Medium Concentration	Moderate number of breakable formations.

Table 6 *Severity Rating Criteria*

Rating	Severity of Impact	Criteria
4	Extreme	60% - 100% extent of impact OR further impacts would not register
3	Heavy	30% - 60% extent of impact OR multiple impact detections, though further impact still possible
2	Moderate	10% - 30% extent of impact < 30% OR impact detected by several instances, but not widespread
1	Light	<10% extent of impact OR impact only detected by one minor instance

Photo-monitoring and Inventory. High-resolution digital photos were retaken at all (19) fixed-point photo-monitoring stations. Other resources and sites of interest or concern were captured in a photo inventory, e.g. landmark formations, rare or exceptionally pristine resources, passages or features already showing impact, or areas in which increased visitation was anticipated. Photos were taken with an object for scale (pencil, keys, etc.). The nearest survey station marker to the photo subject was recorded. Photo-monitoring and inventory were conducted with a Canon Digital Rebel XT camera.

Paleo Survey. All known paleontological sites and others discovered during fieldwork were surveyed from the nearest convenient survey marker with a Suunto compass and inclinometer with a Disto laser distance meter. Each site was photographed in detail and context with an object for scale (pencil, keys, etc). Photos were taken with a Canon Digital Rebel XT. Following recommendations of Toomey (2006), site descriptions included the quantity, color, and size of the paleontological items, their context, location and, if feasible, their supposed origin. Additionally, the condition, likelihood of disturbance, and value of the paleo site were assessed. Descriptions, assessments and survey data were input into a spreadsheet on a Pocket PC. A labeled flag or surveyors tape was placed at paleo sites most likely to be disturbed by foot traffic (Figure 1).

Lampenflora Mapping. The presence and amount of lampenflora were attributed in a GIS layer of cave lights using ESRI ArcPad® on a Pocket PC.

Figure 1 *Paleontological resources were surveyed, described, and photographed with an object for scale. Sites were flagged when in danger of disturbance.*

Results

Assessment of Hazards and Fragility. Maps were created to highlight hazardous or fragile areas (Figures 2–3). Caving zones were mapped based on combined hazard and fragility (Figure 4). The Oregon Caves Subsurface Management Plan (Department of the Interior, National Park Service 2005) clarifies access restrictions for each zone (Table 7). Similar criteria-based classifications are used to determine access for caves in Canadian national parks (Horne 2006).

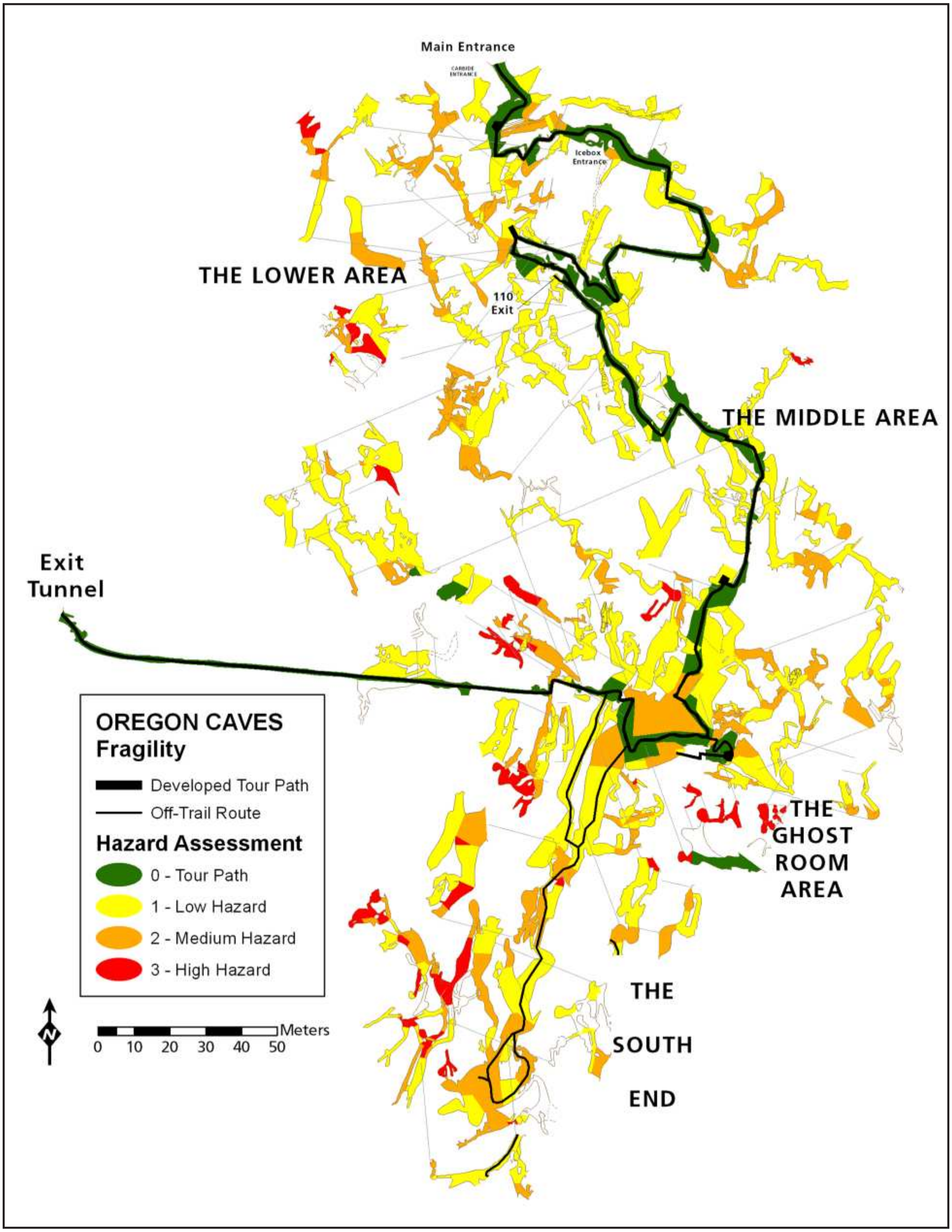

Figure 2 Hazard Map. A rating of zero does not mean that there are no hazards at all.

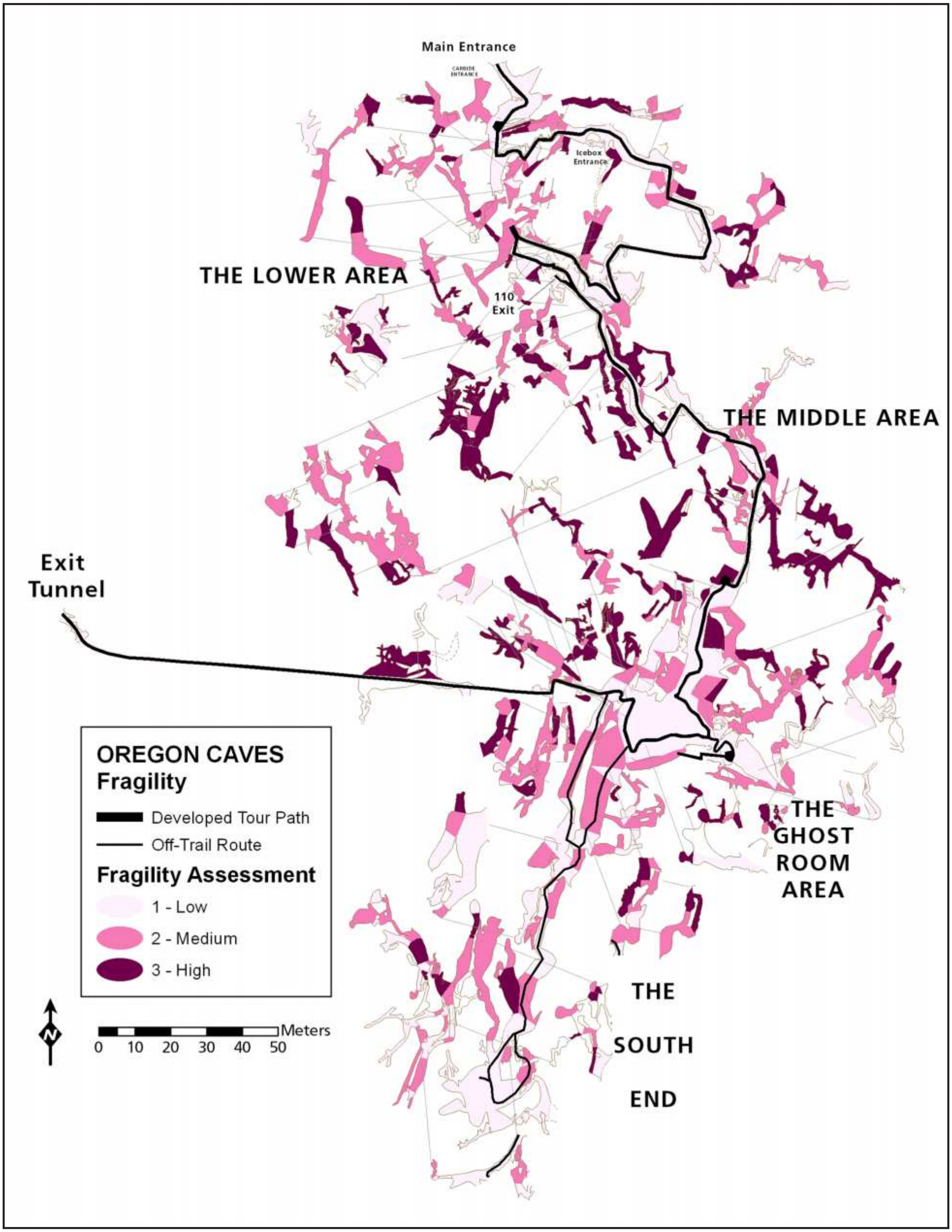

Figure 3 *Fragility Map.*

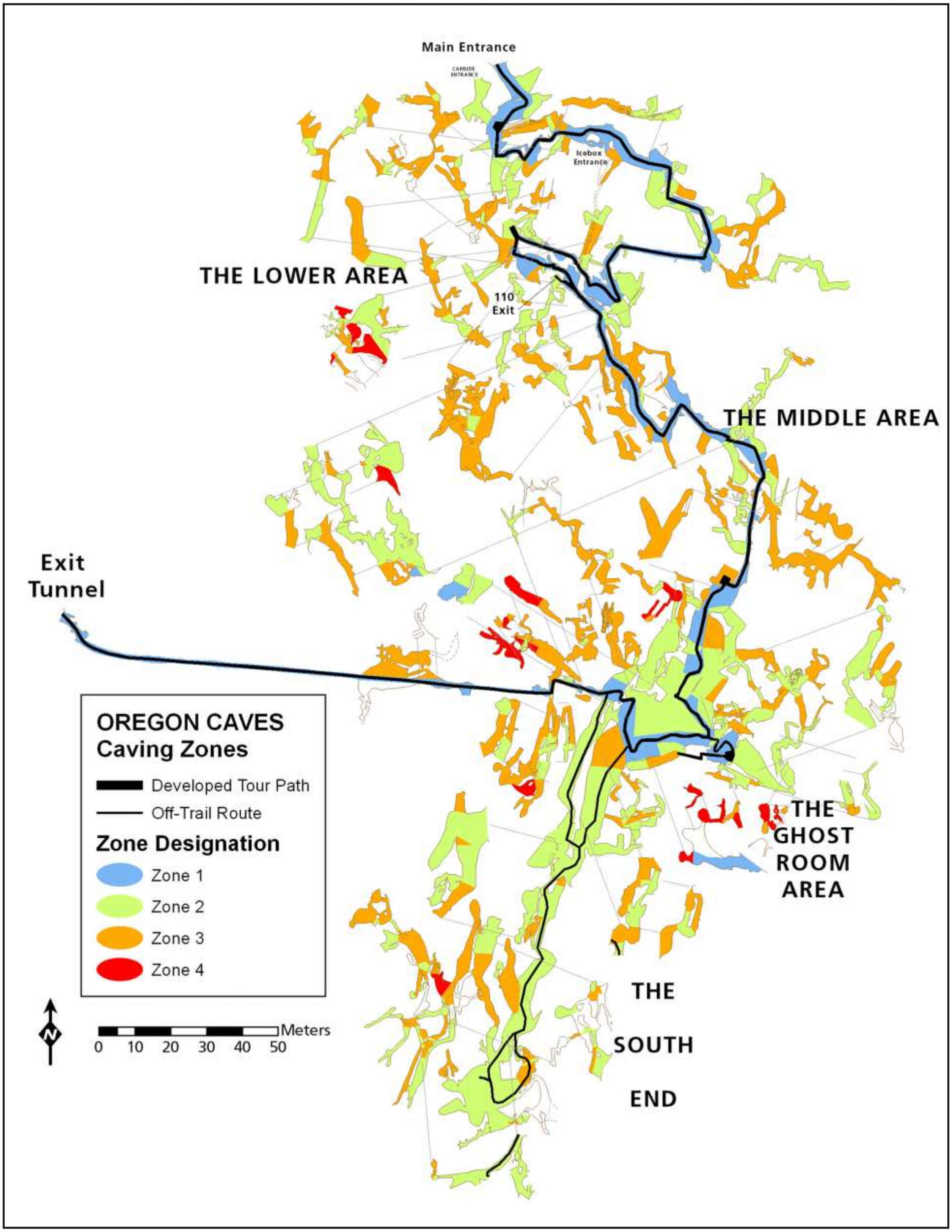

Figure 4 *Caving Zones Map. Cavers must obtain the permit required for the most restricted zone they visit on their trip*

Table 7 Caving Zone Descriptions (Source: 2005 Oregon Caves National Monument Subsurface Management Plan)

	Description
1	These developed areas include most public use areas that provide visitors with comfort and convenience (e.g. hard surfaced trails, handrails, and electric lights). No special clothing, equipment, knowledge or skills is needed. National Park Service (NPS) staff must accompany all visitors.
2	These areas may be visited by permit without an NPS escort. Permitees are responsible for providing their own equipment. Evidence of incompetence, previous cave abuse or disregard for park regulations are grounds for denying a permit. All members of the group will stay within the trail zone bounded by tape.
3	These areas may be visited only when scheduled in advance and when a designated NPS trip leader accompanies the visitor.
4	To obtain access, the superintendent must approve a collection permit. The researcher must show in writing how potential damage to resources from research in a specific part of a cave will be more than balanced by knowledge gained that would protect park resources. Zone 4 designation does not exclude administrative entry to monitor research activity and impacts upon these caves. All newly discovered caves or cave passages will be initially assigned a Zone 4 designation.

Table 8 Hazard-Fragility Results (% of survey shots)

Classification	Hazard	Fragility	Zone
0	9	--	--
1	54	33	9
2	25	37	44
3	9	28	40
4	--	--	4
undetermined	4	3	4

Table 9 Impact Inventory Results: Detection Rate (% of survey markers where impact was possible to occur)

Ranking	Developed Tour Path (1 km)	Off-Trail Caving Tour Route (202 m)
1	Polishing/Darkening (97%)	Sediment Compaction (97%)
2	Path Cutting (95%)	Polishing/Darkening (94%)
3	Lint (85%)	Flowstone Surface Scratches (93%)
4	Hair (84%)	Sediment Translocation (71%)
5	Soda Straw Breakage (79%)	Sediment Erosion (63%)
6	Sediment Compaction (76%)	Vermiculation Smearing (50%)

7	Flowstone Surface Scratches (71%)	Crystal Wall Damage (50%)
8	Stalactite Breakage (68%)	Soda Straw Breakage (45%)
9	Trash (56%)	Stalactite Breakage (45%)
10	Crystal Wall Damage (50%)	Hair (43%)
11	Drapery Breakage (49%)	Lint (37%)
12	Stalagmite Breakage (39%)	Drapery Breakage (33%)
13	Gunnite (39%)	Path Cutting (26%)
14	Sediment Translocation (36%)	Imprint in Wall Mud (20%)
15	Vermiculation Smearing (29%)	Sediment Transfer to Speleothem (20%)
16	Sediment Erosion (26%)	Trash (14%)
17	Imprint in Wall Mud (9%)	Gunnite (14%)
18	Sediment Transfer to Speleothem (9%)	Stalagmite Breakage (13%)
19	Pool Damage (7%)	Pool Damage (6%)
20	Crystal Pool Damage (0%)	Crystal Pool Damage (0%)
AVERAGE	50%	42%

Table 10 Impact Inventory Results: Average Severity (% of survey markers where impact was detected)

Ranking	Developed Tour Path (1 km)	Off-Trail Caving Tour Route (202 m)
1	Path Cutting (3.5)	Path Cutting (3.4)
2	Soda Straw Breakage (3.1)	Stalactite Breakage (3.4)
3	Stalactite Breakage (3.1)	Sediment Compaction (3.1)
4	Drapery Breakage (3.0)	Stalagmite Breakage (3.0)
5	Stalagmite Breakage (2.9)	Soda Straw Breakage (3.0)
6	Sediment Compaction (2.9)	Polishing/Darkening (2.8)
7	Crystal Wall Damage (2.8)	Sediment Erosion (2.8)
8	Polishing/Darkening (2.7)	Pool Damage (2.5)
9	Flowstone Surface Scratches (2.5)	Flowstone Surface Scratches (2.4)
10	Pool Damage (2.4)	Drapery Breakage (2.3)
11	Gunnite (2.3)	Gunnite (2.2)
12	Imprint to Wall Mud (2.3)	Sediment Translocation (2.0)
13	Vermiculation Smearing (2.1)	Vermiculation Smearing (1.9)
14	Lint (2.0)	Crystal Wall Damage (1.5)
15	Sediment Erosion (1.8)	Lint (1.5)
16	Hair (1.8)	Imprint to Wall Mud (1.4)
17	Sediment Translocation (1.6)	Hair (1.4)
18	Trash (1.4)	Sediment Transfer to Speleothem (1.3)
19	Sediment Transfer to Speleothem (1.3)	Trash (1.2)
20	Crystal Pool Damage (0.0)	Crystal Pool Damage (0.0)

The majority of off-trail passages were classified "low hazard" and "low or medium fragility," and therefore categorized zone 2 or 3 (Table 8). In most cases off-trail visits will need to be scheduled in advance, according to zone 3 regulations, because most routes taken will pass through at least one zone 3 area. Passages that were classified as both "high hazard" and "high fragility" were usually domes, several of which require roped ascent. A few zone 4 passages are bottlenecks to farther reaches of the cave. Network analysis tools provided in ESRI ArcGIS Desktop® can help plan routes of least hazard and fragility through the cave (Ohms 2003).

Impact Inventory. Data on the presence and severity of impacts along the developed tour path and the off-trail caving tour route were summarized (Tables 9-10). Polishing/darkening was the most frequently detected impact on the tour path, and second most frequent on the off-trail route following sediment compaction. Other abundant impacts along the developed tour path were related to speleothem breakage and human-caused debris.

The impact inventory was completed for the off-trail route before the first off-trail tour season. Sediment compaction was usually rated "heavy" or "severe" when detected. Scraping on sediment floors and sediment translocation, sometimes referred to as sediment tracking or transfer, were frequently detected. Flowstone surface scratches were observed at 90 percent of the areas where it was possible, as were polishing/darkening and sediment compaction. Surface scratches are an enduring impact from rubble, most of which was hauled out in the 1980s and 90s.

Photo-monitoring and Inventory. Photos retaken at fixed-point photo-monitoring stations in 2006 revealed no new impacts when compared to the baseline from 2003. Over 80 other resources or sites were captured in the photo inventory, and additional photos from park files were incorporated into the photoset. A photo-mosaic of a flowstone formation was created in order to read its entire collection of historic signatures and monitor vandalism. To manage cave photos, a polygon GIS layer of the cave was divided into sections to represent areas defined by proximity to survey markers. Photos were hyperlinked to this GIS layer, allowing photosets to be retrieved for specific locations and directly compared (Figure 5).

Paleo Survey. The paleo survey resulted in a baseline of over 140 paleo sites. The majority appeared to contain rat or bat bones. Several contained large mammal bones. A GIS layer of paleo sites was created from survey measurements that were processed with Compass software. Paleo survey photos were hyperlinked to paleo sites in this layer.

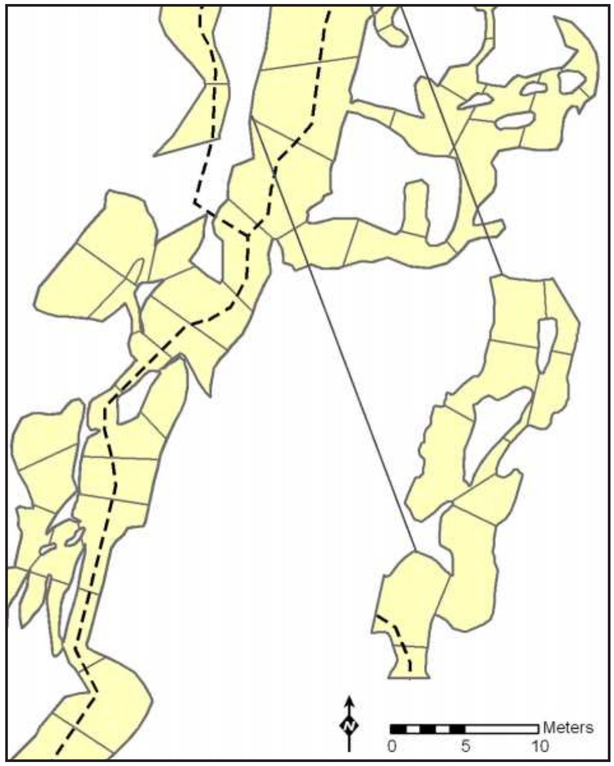

Figure 5 *A GIS layer of the cave was divided into sections based on proximity to survey marker. Photos that are hyperlinked to this GIS layer can be retrieved by location.*

Lampenflora Mapping. In 2007 mapping revealed that slightly more than 60 percent of cave lights harbored lampenflora (Table 11). Recessed lights, which account for 40 percent of cave lights, supported significantly less lampenflora than other light types.

Planning for Off-trail Tours

Visitor-impact mapping was completed along the off-trail caving tour route in 2006 to help determine how to conduct off-trail tours and protect cave resources along the route. No part of the off-trail route was classified high hazard or high fragility, but a significant portion was classified medium hazard and medium fragility (Figures 2–3). Haz-

Table 11 2007 Algae Survey Results (% of lights)

	TOTAL SURVEYED (293 lights)	Spotlight (151 lights)	Recessed (117 lights)	Mini (14 lights)	Globe (11 lights)
No Algae	39	17	71	29	0
Algae Present	61	83	29	71	100
Amount of Growth					
Light	49	44	85	40	0
Moderate	27	31	9	40	27

ards include slippery muddy steps and footholds, uneven floor surfaces, and potentially claustrophobic squeezes. Except for passages historically used for tours, the off-trail route is absent of speleothems, but other fragile resources include bones, wall crystals, and sediment pools. Results from the impact inventory suggested that polishing/darkening, sediment compaction and translocation, and hair were the impacts most likely to increase due to off-trail tours.

Many hazards were addressed by ensuring that cave guides were trained to emphasize safe caving techniques, such as three points of contact, and follow protocols for safely leading visitors through route, such as climbing or descending vertical areas one caver at a time. A hazard of particular concern—a scramble down some muddy rocks with a potential fall of about 3 m—was alleviated by placing rocks to create additional footholds.

Guides were trained to proactively ensure that visitors practice low-impact caving techniques in fragile areas, and trailing guides were trained to check on key resources along the way. Twelve bone sites were documented in the paleo survey, and 11 were flagged for protection. Footholds and tight areas, which may show signs of increased polishing, were photo-inventoried along with landmarks and fragile resources. Flagging was placed to call attention to crystals and pools. Other measures of protection included flagging path boundaries and purchasing souvenir bandanas for visitors to secure loose hair.

Discussion

The visitor-impact mapping methods employed at Oregon Caves can be adapted for other caves. The two-pronged strategy for mapping visitor impacts in any cave is to first, target and assess impacts of interest, as was done with the impact inventory and lampen-flora mapping, and second, identify and document resources of concern, as with the photo inventory and paleo survey. A third, supplemental approach is to identify areas of potential impact, as with the hazard-fragility assessment.

GIS has many advantages for long-term, visitor-impact monitoring, which cannot be accomplished without repeatable methodology and accessible data. Geographic data can be systematically collected in the field with ESRI ArcPad®. GIS data and linked tables can be synthesized and analyzed using ESRI ArcGIS Desktop®, at the same time, hyperlinked photos can be retrieved and reviewed by location. GIS is a valuable tool for solving problems and making decisions, and its applications for understanding and managing the problems associated with humans in caves should continue to be explored.

Visitor-impact mapping, whether or not it is GIS-based, is only a starting point for protecting cave resources. Visitor-impact data introduce cave managers to significant or potential impacts, once they are identified, protection, mitigation and/or monitoring are the next actions. Some impacts can at least be partially reversed, but many permanently impair unique or nonrenewable resources. Further studies and/or scientific analyses are warranted in instances when prevention may be the only option for mitigation. Only when visitor-impact mapping leads to cave management decisions can it help find the balance between providing for recreation, research and education vs. protecting cave resources.

Acknowledgments

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CAVE MANAGEMENT IN THE OZARK NATIONAL SCENIC RIVERWAYS: A PUBLIC AND PRIVATE PARTNERSHIP

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Abstract

The Ozark National Scenic Riverways, a unit of the National Park Service, contains more than 340 caves. Managing these resources is difficult given the limitations of budgets and personnel. Through a series of agreements with Cave Research Foundation (CRF) and the efforts of caver volunteers, cave management at the Ozark Riverways is accomplished for relatively minimal funding. CRF works through the Resource Management office to coordinate the work of paid and unpaid help in performing a wide range of management activities on lands within the park. Special emphasis will be given to the mechanisms and personnel management through which this is accomplished.

Key words: cave management, Ozark National Scenic Riverways, National Park Service, Cave Research Foundation, Missouri

Introduction

The Ozark National Scenic Riverways (OZAR) of the National Park Service (NPS) was created by PL. 88-492 in 1964 in order to protect and preserve 215 km (134 mi.) of the free-flowing Jacks Fork and Current Rivers. The enabling legislation of the park specifically mentioned the karst resources, "For the purpose of conserving and interpreting unique scenic and other natural values and objects of historic interest, including preservation of portions of the Current River and the Jacks Fork River in Missouri as free-flowing streams, preservation of springs and caves, management of wildlife, and provisions for use and enjoyment of the outdoor recreation resources thereof by the people of the United States."

Figure 1 Dawn on the Current River.

The karst component was well-known to the proponents of the Riverways. Beyond that, it is obvious that the values greatly admired in the region owe much to karst processes. The Current River is largely spring-fed by a number of springs, great and small. This results in a river that is of nearly constant flow and temperature with a smooth and gentle gradient. It is an easy river on which to use a boat, and in the summer the cool waters create a microclimate suitable for enjoyment. In the winter, the warm waters do the same. The Jacks Fork River is also spring-fed, although to a lesser degree for the greatest portion of its length. Below Alley Spring, however, the Jacks Fork is very similar to the Current.

Figure 2 *Big Spring is the nation's second largest. Photo by William R. Elliott.*

The Karst Resource

Caves. In 2007 there were over 360 inventoried caves within the authorized boundaries of Ozark Riverways. Of these, more than 300 were on NPS land *per se*; the rest are on state and private lands. Some of the privately-owned caves within the boundaries are on scenic-easement lands, in which the NPS owns an interest. The Code of Federal Regulations extends some powers or consideration of the NPS to all lands within the authorized boundaries for certain purposes. Thus, all of the caves within the boundaries are of interest to OZAR.

Figure 3 *The Park's show cave, Round Spring Cavern.*

Springs. The springs of the Ozark Riverways comprise the finest collection of karst springs within the National Park system. Four springs are of first magnitude size (average flow >2.8 m^3/sec (100 ft^3/sec). Six more springs within the Park boundaries are second magnitude (0.28-2.8 m^3/sec or 10-100 ft^3/sec), while hundreds of additional springs of lesser magnitude dot the landscape. In addition there are large springs along the Current and Jacks Fork Rivers that lie outside of the park boundaries. The springs contribute the majority of the flow of the rivers.

Karst Features. Other karst features within the park include sinkholes, small natural bridges or tunnels (larger ones are classified as caves), sinking or losing streams, seeps and surface travertine deposits.

Cultural Resources. Many of the caves and springs have prehistoric archaeological sites associated with them. Additionally, many of the springs have historic mills or remnants associated with them. There is a variety of historic structures both within and without the caves. There is also a plethora of oral traditions and local history associated with the caves, including historic signatures in several of the caves dating back to Civil War times.

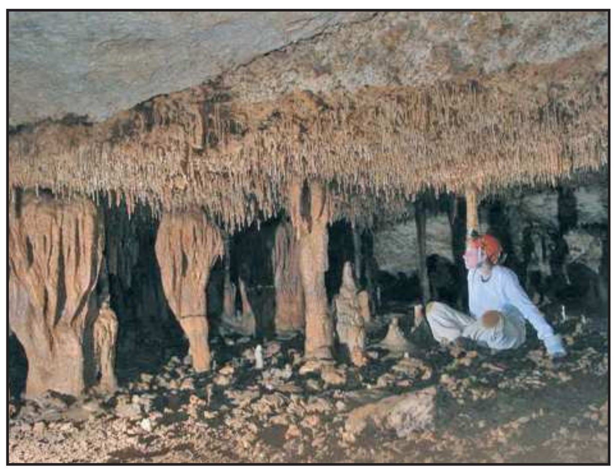

Figure 4 *Bluff Cave is now a permit cave.*

Geologic Resources. Most of the caves and springs are developed in dolomites of Cambrian and Ordovician age. A small number of caves are in or on the boundary with Precambrian rhyolites. The solutional caves display a wide variety of speleothem types: beyond the considerable displays of normal speleothems such as stalactites, stalagmites, columns, and flowstones are more unusual forms such as spathites and aragonite clusters.

Biological Resources. OZAR caves are home to many cave species. The park is important to the endangered Gray and Indiana bats (*Myotis grisescens, M. sodalis*), as well as the blind Grotto salamander (*Eurycea spelaea*), southern cavefish (*Typhlycthys subterraneus*), Salem cave crayfish (*Cambarus hubrichti*), and a new, rare species of trechine beetle (*Pseudanophthalmus n.sp.).*

Figure 5 An adult Grotto salamander underwater. Photo by William R.

Paleontological Resources. Vertebrate paleontological resources are numerous in the caves. Within the park boundaries are remains of at least two species of bear, dire wolf, peccary, elk-moose and a variety of other Pleistocene mammals. The full extent of these resources is not known.

Cave Exploration

For years relatively few of the caves had been explored, documented or mapped. A few notable exceptions included the Devils Well, Round Spring Cavern, Cave Spring, and very few others. By the late 1970s only 78 caves had been located within the boundaries. In 1980, a volunteer effort of the Missouri Speleological Survey (MSS) was initiated. Within a few years the Cave Research Foundation (CRF) joined the effort. Within a decade, the number of known caves had tripled. This effort is ongoing at this time with the result that over 270 caves within the park have been mapped.

Cave Management Problems

As the Riverways became more popular, the resulting visitation resulted in increased cave management concerns. Bat hibernacula and maternal colonies were disrupted, caves suffered vandalism of various sorts, illegal pot-hunting and treasure seeking destroyed cave floors and safety concerns manifested themselves. Around 1980 OZAR contracted with Ozark Underground Laboratory (OUL) to conduct two overview surveys of certain high-use and high-profile caves. This led to OZAR's involvement with a cooperative cave survey in the early 1980s, focusing on biology and public use, contracted through the Missouri Department of Conservation and partially effected through the use of MSS volunteers. Last, studies of river and cave recreation were performed by the University of Missouri, Columbia (UMC). Some management steps were taken, including the construction of several cave gates, not all of which were appropriate, and the placement of unusually large signs at certain cave entrances, warning of dangers within.

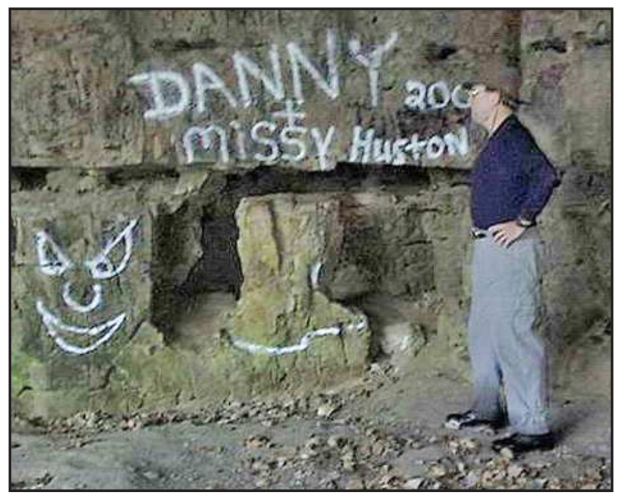

Figure 6 Cave vandalism is a recurring problem.

Cave Management Plan

As all studies pointed toward continued cave management problems, the NPS initiated work on a cave management plan. As part of this process, outside experts from CRF/MSS, UMC and OUL were involved. What came from this process was the Cave Management Plan (CMP) of 1988. Rather than focus on specifics, the plan was a blueprint for a process that would evolve over time. This is the strength of the plan. Three components of the plan were critical:

- A cave management team was to be established. The team would meet with a goal to developing consistent cave management. People outside of the NPS would be part of the team.
- Cave management was to be done by individ-

ual prescription rather than by pigeon-holing caves into pre-set categories.
- More specific objectives (general) and goals (specific) were set.

Objectives of the Cave Management Plan

- Protect natural and cultural cave resources.
- Provide for acceptable types and levels of visitor use
- Promote appreciation of cave resources through interpretation and furthering of education and scientific knowledge about caves.

These objectives are the normal content found in management plans everywhere. They are clearly not measurable. However the goals of the Cave Management Plan were much more specific.

Goals of the Cave Management Plan

- Complete an inventory, evaluation and classification of Riverways caves and develop a resource database integrated with information from cooperating agencies and organizations.
- Establish guidelines for restrictions, access and use of popular caves for recreational, interpretive and scientific purposes that will assure resource preservation.
- Assure the preservation of identified rare and endangered cave species and their habitat.
- Provide opportunities for recreational cave use and integrate park interpretive programs and materials with resources protection, visitor safety and resource management concerns.
- Evaluate existing problems of vandalism, overuse, impact on cave biota, safety hazards and information needs identified in current surveys and implement corrective actions.
- Establish a long-term monitoring system for cave resources and visitor use which will document impact and indicate need for management response.
- Cooperate with other agencies, educational institutions and organizations to increase public awareness and appreciation of cave resources.
- Encourage investigations and scientific research which will improve existing knowledge of Ozark Riverways' cave resource and further the park's management objectives for preservation, use and interpretation.

Implementing the Cave Management Plan took several years but finally during the 1990s the Cave Management Team began to meet and some changes were effected. It was not, however, until several CRF/NPS projects got under way that real progress was made. These included:

- A data synthesis project in which all available information was collected, filed in hard copy form, and entered into a database. The database of park cave information is a subset of the MSS cave database.
- A biological study of aquatics of certain caves along the lower stretches of the Current River.
- Photographic documentation of Round Spring Cavern and other caves.
- A biological survey of Round Spring Cavern.
- Development of a monitoring program, the field work of which would be done by law enforcement rangers.

Additionally, a series of extensive archaeological surveys performed by NPS and the University of Missouri identified additional caves as archaeological sites. In essence, this identification further delineated the extent of the management problems.

A New Approach

Despite these additional initiatives, cave problems continued and the specific goals of the CMP were not being met. Because of the elongated nature of the park and its heavy recreational use, a large portion of park resources is dedicated to facilities, infrastructure, and maintenance. Funding does not permit additional resource management staff in the form of a cave management specialist or karst hydrologist. Finally in 2001, NPS decided to put dedicated manpower to work. Initially this manpower was in the form of a CRF member working seasonally, but owing to the year-round nature of the work and other considerations, this was shifted to a contract with CRF.

This contracted work includes a large number of field and office responsibilities, performed by one lead worker (the author) and such other help as CRF can supply. Included within the scope of work are:

- Database management of caves and cave species

Figure 7 CRF worker installing a cave sign.

- Coordinating the monitoring program, relying on contracted and volunteer labor in addition to the ranger work.
- Development and implementation of a cave signage program.
- Maintenance of cave gates and locks.
- Development of cave permit program.
- Cooperation with other groups and agencies.
- Providing environmental review for cave issues.

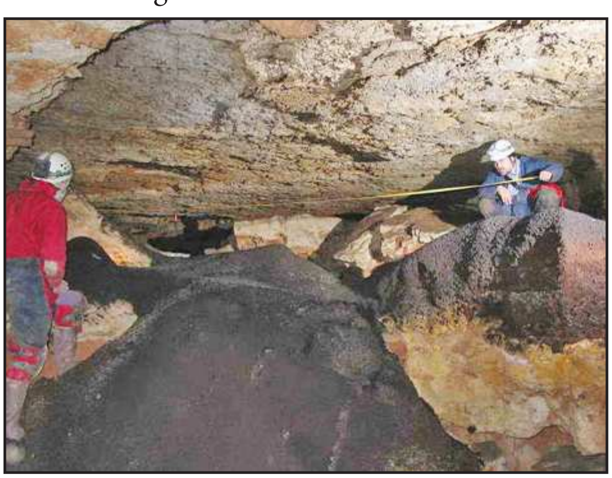

Figure 8 CRF crew measuring guano.

- Numerous other tasks, providing immediate resolution of necessary management actions.

Concurrently with the cave management contract, NPS and CRF embarked on a series of cooperative projects funded by a variety of NPS initiatives plus volunteered labor and time. These include:

- A winter census of all park bat caves, counting individuals or measuring guano.
- A cave gating project which resulted in ten new cave gates on known bat caves or restorative sites. Additional funding was provided by the state of Missouri.
- A detailed biologic survey and analysis of seven caves used by the public.
- A cave restoration project focusing on a number of heavily-used caves.

Figure 9 A cave gate under construction on a hibernation cave.

Most of the above funded projects use considerable volunteer labor. In addition to CRF the volunteers come from a number of partners. These include grottos, state groups, and university groups. The university groups are typically biology or natural resource classes that receive hands-on cave management and biology experience by working with CRF personnel on projects. The partners include:

- Meramec Valley Grotto
- Springfield Plateau Grotto
- Mid-Mississippi Valley Grotto
- Kansas City Area Grotto
- Southeast Missouri State University

- Missouri Speleological Survey
- Missouri Caves and Karst Conservancy
- Washington University of St. Louis
- Missouri State University
- Missouri Western State University

Strictly volunteer projects include:

- Continued identification and survey of park caves. Several active cave surveys are ongoing at this time.
- Monitoring caves. This is a high priority for the park. Each year, volunteers monitor more than 50 caves within the park.

Figure 10 *Volunteers monitor a cave on the Jacks Fork River.*

Volunteer time on projects in the park amounts to more than 1,200 hours a year for the past three years. These volunteers are provided camping at no cost. Most, however, stay at the Powder Mill Research Center, which was designated in 2004. The Center provides living quarters with bunks for eight people plus kitchen and other amenities such as equipment storage and office space. The Center is used heavily by volunteers, CRF workers, researchers, and cooperating agencies. The actual preparation of the Center was done primarily by CRF volunteers who also do minor maintenance at the facility.

The result of the management contract, additional cooperative projects, and volunteer projects is that the goals of the Cave Management Plan are now being met. All are not resolved completely, but every issue is being actively addressed. A cave-management, action-hit-list is maintained by CRF and action on problems usually takes only weeks, rather than years.

Summary

- Resources are actively protected and managed by those who know the resource and care about it.
- New information is being gained, including maps, biotic censuses, locations, and photographs.
- GPRA (Government Performance Results Act) goals for caves and volunteers are met.
- Volunteers feel enabled – they can actually assist in rectifying a cave problem.
- Money is saved. The CRF contract is currently for $17,000 a year which includes over 2,000 hours of skilled labor both paid and volunteered.

Figure 11 *Law enforcement ranger and volunteers monitor a cave.*

CRF and OZAR feel that this is an exemplary cave management program, one that protects and manages the cave resources with a fairly minimal amount of funding. People interested in further details of this work and/or the agreements are encouraged to contact the author.

Acknowledgments

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RECENT RESEARCH AND MONITORING EFFORTS AT ONONDAGA CAVE STATE PARK

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Abstract

Over the past four years research and monitoring of cave resources has increased at Onondaga Cave State Park (OCSP). Projects were initiated through partnerships with local state universities and federal agencies, and by Park staff. Biological research was done recently in two significant cave systems. Studies on potential interbreeding of salamander species have begun in a previously commercialized portion of Onondaga Cave. This project, led by Maria Potter, OCSP, will attempt to identify potential hybrid salamanders through DNA fingerprinting using Amplified Fragment Length Polymorphism. By partnering with Dr David C. Ashley, Missouri Western State University, *Fontigens aldrichi* snail counts resumed in the stream in Cathedral Cave. In 2003 a project was started to determine the recharge areas of Onondaga Cave and Cathedral Cave. The delineation of the recharge areas of the cave stream was accomplished through dye-tracing techniques, with 18 total dye injections to date. This cooperative project, led by Ben Miller, OCSP and Bob Lerch, USDA/ARS, has thus far outlined a recharge area of 19.8 km^2 for Onondaga Cave and 2.4 km^2 for Cathedral Cave. Flow monitoring recently began to better study the hydrologic behavior of both cave streams. Microclimate data have been collected in various portions of Onondaga Cave using Hobo® dataloggers. By continuing to partner with educational institutions and other public agencies, additional research and monitoring opportunities will lead to better understanding of these cave systems.

Key words: show cave management, cave ecology, genetics, salamanders, cavesnails, hydrology, dye tracing, water quality, contaminants, sediments, handrails, cultural resources, speleothems, microclimate, Onondaga Cave, Cathedral Cave, Missouri

Introduction

Onondaga Cave State Park is located in Crawford County, Missouri along the Meramec River. This area is within the Upper Ozarks Region of the Salem Plateau. The Park consists of approximately 526 ha (1,300 ac.) split between the Main Park Unit and the Vilander Bluff Natural Area. Located on the Park are two significant cave systems, Onondaga Cave and Cathedral Cave, and more than 25 other small caves. Onondaga Cave, with 2.7 km of passage, is known for its large quantity and high quality of speleothems as well as being extremely biodiverse. Cathedral Cave, with 4.7 km of passage, is a large stream cave with areas of intense speleothem development. Both Onondaga Cave and Cathedral Cave are shown on commercial cave tours led by Park staff, however only Onondaga Cave has electric lighting in use today.

Over the past four or five years research and monitoring were done to better understand the processes ongoing in the cave systems. These efforts were initiated by Park staff and outside researchers, in most cases requiring a partnership between agencies and educational institutions. The projects focused on three major areas: biological investigations and inventories, geological and hydrological studies and the impact of a handrail-replacement project in Onondaga Cave. Many of these projects are continually ongoing and this paper is to highlight the major areas of each project undertaken thus far.

Recent Research Initiated

A variety of different research projects were initiated in Onondaga Cave and Cathedral Cave since 2002. The major projects included a study of salamander genetics in Onondaga Cave, population counts of the aquatic cavesnail *Fontigens aldricihi* in Cathedral Cave, recharge delineation for both Onondaga Cave and Cathedral Cave, and size analysis of cave sediment particles in Cathedral Cave.

Salamander genetics study in Onondaga Cave. In September 2005 Park superintendent Maria Potter began examining the potential interbreeding of salamander species within a previously commercialized section of Onondaga Cave. Six species of salamanders are known to currently reside in the Missouri Caverns portion of Onondaga Cave. Of these six species, four species are *Eurycea* and two are *Plethodon*. It is believed that three of the *Eurycea* salamanders may be interbreeding. These three are *Eurycea longicauda* (Longtail Salamander), the subspecies *E. longicauda melanopleura* (Dark-sided Salamander) and *E. lucifuga* (Cave Salamander). The reason for this speculation is the observation of unusual salamanders, which seem to share morphological attributes between one another but not characteristic for their own species. The fourth *Eurycea* species, *E. spelaea* (Grotto Salamander), is a cave-adapted species which is much rarer and typically found deeper into the cave system near water sources. It is also strongly believed that the absence of human interaction from this portion of the cave system may have played a role as well as the fact the majority of salamanders are located near an old artificial entrance.

Developing methods for sampling and testing has been a multi-phased process. The number of individuals per species may be different based on time, season, and outside temperature. Therefore multiple trips into this portion of the cave are conducted in order to see what species are present. Any Cave, Longtailed, or Dark-sided Salamanders are collected, photographed, and measured for head width, head length, body length, femur length, weight and number of costal grooves. A 3–5mm segment of the tip of the individual salamander's tail is then clipped and placed in a small sealed tube to await DNA analysis. The salamander is then released back into the cave environment. Duplication of salamander documentation is avoided through the photographing of the individual and the morphological measurements. Once the samples have been collected they are taken to the lab and analyzed using DNA fingerprinting or Amplified Fragment Length Polymorphism (AFLP) analysis, which measures genotypic differences. The results from this process are then scored to determine the individual species and at this point any hybrid salamanders can be identified. As of the writing of this paper, AFLP analysis has been completed and the samples are being scored.

Population counts of aquatic cavesnail, *Fontigens aldrichi*. Cathedral Cave has a large, active stream, which flows through the majority of the cave system. This stream is an essential corridor for the movement of the biota. One of the important species found in the cave stream is the aquatic cavesnail *Fontigens aldrichi*. For the past 14 years Dr David C. Ashley from Missouri Western State University (MWSU) brought students from MWSU and St. Louis University to the Park to conduct snail population surveys. The surveys take place along a 20-meter section of the main cave stream near the commercial tour path. By examining chert and dolomite cobbles in the cave stream individual cavesnails are counted and observations recorded about the location where the snail was found. These surveys observe and record different factors including color and dimensions of the stream cobble, number of snails per rock, distance from start of survey, and location within the width of the cave stream. Three transportable PVC pipe grids are used in order to better facilitate the survey and provide easy recording of the sample location. A data recorder writes down all observations into a form that is later transferred to digital format. As the snails measure only 1-2 mm in diameter there may be questionable specimens, so Dr Ashley brings a portable field station with a microscope, which is used to verify individual snails.

The *F. aldrichi* counts in Cathedral Cave indicate that there is a fairly healthy population within the main cave stream. The snails need a chert or dolomite stream substrate in order to inhabit an area, though the snails seem to prefer manganese-coated chert cobbles. Along the 20 m of cave stream, regularly-surveyed population counts have varied from 130 to four cavesnails. If recent numbers and densities of the snails were extrapolated to the other portions of the cave system with similar stream substrate the total population for the cave could easily be in the thousands of individuals.

Recharge delineation of Onondaga Cave and Cathedral Cave. A major area of research since the winter of 2003 was dye tracing to delineate the recharge areas of Onondaga Cave and Cathedral Cave. This project has been a cooperative effort between Ben Miller, Onondaga Cave State Park, and Bob Lerch, USDA, Agricultural Research Service. In 2003 none of the recharge area for either cave was known, and as a management consideration the project was initiated, and it continues today. Dye tracing was conducted using three distinct fluorescent dyes: fluorescein, eosin, and Rhodamine WT. Local springs, streams, and each of the cave streams were monitored using activated-charcoal packets. The charcoal packets were changed at regular intervals in order to determine travel time from the injection site. Analysis of the charcoal was completed by the Environmental Geology Section of the Missouri Division of Geology and Land Survey in Rolla, Missouri.

Since the start of this project 17 dye injections were done. From these 17 injections, five were successfully traced to Onondaga Cave and one was successfully traced to Cathedral Cave. This work has allowed for a recharge delineation of Onondaga Cave, which has a total area of 19.8 km^2. The one successful trace to Cathedral Cave was in a very small, second-order stream, which does not seem significant enough to fully account for the stream flow observed in the cave. Further work will be needed to delineate the recharge area of Cathedral Cave. The work from this project can now be used in the management of the caves as well as help to work with neighboring landowners located within the recharge areas of the cave systems.

Size analysis of sediment particles from Cathedral Cave. In August of 2007 work began in Cathedral Cave looking at various aspects of the geology and morphology of the cave to determine what processes may have contributed to the formation of the cave system. As part of this work clay samples were collected from five sites located along the main cave stream. This clay is a distinct feature of the cave system, nearly filling some cave passages, and is a common characteristic of caves located in the Salem Plateau of Missouri. Sample sites in Cathedral Cave were selected based on the vertical faces of the clay bank, location within the cave system, any visibly distinct layers and the approachability of the sample site. The exterior face of the clay bank was excavated to remove any superficial clay deposits. Once this thin outer layer was removed stratification of the sediments became apparent. Using a metric fiberglass tape, each layer was described in a field book and a representative sample was bagged for removal from the cave. The clay samples, once removed from the cave, were sorted using soil sieves, dried in a forced-air oven and analyzed for particle size. This lab work took place in the USDA, Agricultural Research Service soil lab located in Columbia, Missouri.

The particle-size analysis indicated much more about the speleogenesis of the cave system than might have been previously speculated. One of the major findings was that the cave system appeared to have been in an air-filled environment during the time period when the sediments were being deposited. This conclusion is based on the observation of thin layers of calcite intermixed in the sediment beds at multiple locations in the cave system. Previous theories about the processes depositing this clay had placed the deposition event during the phreatic stage in cave development. Also discovered was that the sediments appear to be from episodic events. Multiple flood events washing sediments into the cave might account for the distinct stratification of the clay banks. The clay banks were not homogenous, but in fact the individual layers within a site would have differing amounts of silt, sand, and gravel-sized particles. This difference would indicate a change in flow velocities during the period of deposition. Work on the sediments of Cathedral Cave will continue as mineralogical analysis and sediment dating are examined.

Monitoring of Cave Systems

Each of the major cave systems at Onondaga Cave State Park has had various forms of monitoring in the past. Most of this work related to photo monitoring, water quality, airflow, and commercial tour impacts. Additional monitoring at the Park has contributed to previous knowledge of the caves, and added new information for that proper cave management. This monitoring includes discharge measurements of the cave streams, water-quality testing, and examining the impact of a handrail-replacement project that incorporated metals/geochemical analysis of drip pools and microclimate data collection.

Discharge measurements of cave streams. Onondaga Cave has a large stream, which flows through the majority of the cave system and issues as a spring from the cave's natural entrance. While some sporadic measurements had been taken in the past, no concentrated effort had regularly measured the stream discharge. Cathedral Cave, which also contains a perennial cave stream, had little to no previous work relating to discharge measurements. As part of the dye-tracing research, discharge measurements were taken at Onondaga Spring, the King's Canopy in Onondaga Cave and in the Cathedral Cave stream. These measurements were taken using a wade stick and pygmy meter. At each location the stream channel was divided into several sub-channels across the width of the stream. The depth was recorded at the middle of each sub-channel. The pygmy meter was placed in the middle of the sub-channel and at a depth of 40% below the surface of the stream. Rotations of the pygmy meter were then recorded for 20-40 seconds based on relative velocity of the stream. Discharge was then computed using the measured velocity and the cross-sectional area of the stream channel.

Discharge monitoring trends have begun to appear which, we hope, will contribute to establishing a rating curve for the cave streams and spring. Onondaga Spring has an average base flow of approximately 5,000,000 L/day, though following rain events this can jump to as much as 18,000,000 L/day. Interestingly, a difference in volume was noted between the in-cave location in Onondaga Cave and the spring outlet. The cave stream at the King's Canopy in Onondaga Cave routinely averages approximately 2,000,000 L/day less than the flow recorded at the Onondaga Spring outlet. Cathedral Cave has a significantly smaller cave stream, which averages 280,000 L/day with a high flow of 2,300,000 L/day. Measurements continue to be collected, and it is hoped that in the future a pressure transducer can be installed at the spring in order to provide a higher resolution of discharge data.

Water-quality testing. Water-quality tests were done at Onondaga Cave State Park since 1994. Much of this earlier work focused on testing the Meramec River and occasionally an in-cave site, or the spring would be monitored as well. Originally Park staff tested for 13 elements and chemicals. The analysis of water samples is conducted on-site using several small Hach field test kits; laboratory work used a Hach spectro-photometer. These tests indicated that Onondaga Cave and Cathedral Cave are exceptionally high-quality water sources. The Meramec River, which flows through the Park, is designated as a Missouri Outstanding State Resource Water by the Clean Water Commission.

Recent, primary changes include streamlining of the testing process, adding additional information collected, increased frequency of testing dates, and incorporation of cave sites as permanent testing sites. Today the water-quality monitoring process has been somewhat streamlined with nine elements and chemicals being tested in the samples. This testing continues to use the same equipment as before. Turbidity, conductivity, surface weather conditions, temperature and other stream conditions have been added to the process for all testing sites. Park staff increased the testing frequency to monthly and seasonal spans. The frequency depends on the availability of staff and the conditions at the testing site. Water quality monitoring has typically not taken place directly following major rain events. Cave sites incorporated as permanent testing sites are Onondaga Cave stream at the King's Canopy, the Lily Pad Room (Figre 1) in Onondaga Cave, and the main cave stream in Cathedral Cave. Onondaga Spring has also been added as a permanent site, though cave-related this site is technically a surface site. The addition of these sites and the increase in the frequency of testing have given Park staff a much deeper understanding of the hydrologic processes in each cave.

Metals and geochemical analysis of drip pools. In November 2005 a project was started at Onondaga Cave State Park to replace the existing iron and aluminum handrails with a new stainless-steel handrail system. This decision was made based on the height and structural integrity of the older handrails. To better study the impacts of this project a number of different monitoring methods were undertaken. Drip pools, located near the tour route, were monitored before and after the handrail project for metals as well as a thorough geochemical analysis. Park staff was concerned that the cutting of the old handrails would create a large amount of metal shavings that could contam-

Figure 1 *The Lily Pad Room in Onondaga Cave. Photo by Eugene Vale.*

inate the drip pools and harm biota. The project was initiated by Park superintendent Maria Potter and was assisted by Park staff Ben Miller as well as Missouri University of Science and Technology (University of Missouri, Rolla) student, Jeffery Crews. Grab samples of water from the drip pools were collected along with some sediment samples taken nearby. Samples were sent to Environmental Analysis South Incorporated, a private chemical and metals analysis company located in Jackson, Missouri.

The results were helpful in evaluating the impact of the handrail project on the drip pools. The tests were for ten of the more common metals: chromium, copper, iron, mercury, nickel, lead etc. The drip pools luckily did not show any major impact or increase in metals from the replacement of handrails. However, some low amounts of metals were detected in the Lily Pad Room in the form of copper, and it may be attributed to a pre-Park time when pennies were allowed to be thrown into the pools. One of the more interesting geochemical results was the high level of nitrates in a few of the drip pools. These higher levels may be from bat guano that can be seen throughout the pools in question. Septic tanks above the cave could have contributed to these elevated levels. Additional work on the drip pools is planned, including dye traces from structures above the cave to look at the interconnectivity of the surface structures to the cave environment.

Microclimate data collection. During the handrail-replacement project the airlock to Onondaga Cave was opened much more frequently than during the cave-tour season. Also during this period of time some of the lighting in the cave was on for several hours to improve work site visibility and to aid teams of workers removing old handrail material. These activities, however necessary, do have an adverse impact on the temperature and relative humidity in the cave environment. In order to better monitor the extent of this impact Hobo Pro® temperature and relative humidity dataloggers were placed at two locations within Onondaga Cave, and several Hobo temperature dataloggers were placed at four to five additional locations. The Hobo Pro monitors were provided and downloaded by Dr Ashley, MWSU, who visited the cave at least twice a year. The monitors were programmed to record a temperature and relative humidity reading once every half-hour. This resolution of data was fine enough that in many cases the start of a workday could be determined from the data output. Data loggers were placed at in-cave locations in late June 2006 during normal tour operation and were removed in mid-May, 2007 after the completion of the handrail replacement.

Once the data from the dataloggers was plotted using Boxcar Pro and Microsoft Excel, the impact on relative humidity from the handrail project became apparent. The Hobo Pro datalogger that was located in the Lily Pad Room showed a dramatic drop in relative humidity of almost 40% from the normal 99-100% level. This drop, recorded March 20, 2007, was not immediate, but it was the low point of a series of drops in relative humidity from the start of the work in early November, 2006. Upon the completion of the project the relative humidity stabilized at near 100%. Other dataloggers did not record this behavior in the cave system during the same time period. Therefore it is believed that this drop in relative humidity may have been because of the sensitive nature of the Lily Pad Room and the location of the room, which is higher in elevation than the majority of the cave system. Microclimate data is continuing to be collected today thanks to a partnering with Dr Ashley and his students from Missouri State Western University.

Future Work

An array of future projects is planned to look further at aspects of both Onondaga Cave and Cathedral Cave. Many of these upcoming projects build on research and monitoring that has already been initiated. Dye-tracing work will refine the boundaries of Onondaga Cave's recharge area, and better delineate the Cathedral Cave recharge area. Biological inventories of Cathedral Cave will be conducted to expand the list of known species in the cave system. Sediment work for Cathedral Cave may continue as mineralogical analysis could define the composition and help on potential origin of the sediments. Dating of these sediments will also be pursued which could help to understand the chain of events leading to the massive deposition of sediments seen in the cave. Cultural research is pursued as volunteers help on restoration projects in each of the cave systems. Many times this restoration work uncovers historical artifacts that can be added to the Park Cultural Resource Collections. Lighting in Onondaga Cave is also being adjusted to decrease the amount of algal growth, and to lower the amount of heat generated by the large number of bulbs. LED (light emitting diode) lighting is being added to many portions of the tour route with monitoring of temperature and algae beginning to look at the impacts of these changes. Hydrologic monitoring of stream discharge will continue to be collected using a wade stick and pygmy meter system. Eventually park staff hope to install a pressure transducer at the spillway of Onondaga Spring to gain better resolution of the discharge data. A network of temperature and relative humidity monitors is planned for Onondaga Cave and eventually Cathedral Cave. This will add to the microclimate dataloggers that Dr Ashley has helped establish in Onondaga Cave.

Summary

For the previous four or five years research and monitoring have been a major management focus at Onondaga Cave State Park. We have focused on the ongoing processes in the two major cave systems at the Park, Onondaga Cave and Cathedral Cave. This work has looked at the hydrological, geological, biological, and meteorological aspects of the caves, as well as the impacts of a handrail-replacement project. Much of the work has been a cooperative effort among Park staff, educational institutions, state agencies and federal agencies. This cooperation has allowed for a wide range of work to take place. Future projects are planned to continue the monitoring that has been established, and to pursue additional research opportunities. As this research and monitoring continue the information gathered is added to the Park records and is used in the management of the resources for each of these significant cave systems.

Acknowledgments

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HUMAN MODIFICATION OF KARST IN THE ST. LOUIS AREA, MISSOURI

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Abstract

The significance of karst to St. Louis is exceptional as this landscape dominates one of the oldest and most populous regions of Missouri. Many notable karst features have been variously used, misused, and eventually destroyed by humans over time, but the most severe impacts involve the gross modification of the region by urbanization and suburban sprawl. Rectangular remnants of the original topography are preserved in areas such as Carondelet Park, pockmarked by sinks, yet surrounded by expansive, topographically featureless development. Remarkably, the Old Jamestown Association has vigorously defended progressive zoning ordinances that have preserved their cherished natural landscape. Contrary examples are more common and include the destruction of numerous significant caves, obliteration of cave entrances, widespread topographic leveling, and the conveyance of polluted street runoff, and formerly untreated sewage, into karst drainage systems. Insufficient recognition of the consequences has caused groundwater pollution, and may have contributed to devastating historical cholera epidemics. Many small scale engineering problems have also arisen, such as cracked roads and foundations, as well as conspicuous leaky impoundments, including the repeated disappearance of 10 ha Lake Chesterfield. More balance is needed between development inevitabilities, construction standards, and environmental preservation.

Key words: urban karst, karst land management, contaminants, Missouri

Introduction

Carbonates and other soluble rocks underlie more than 20% of Earth's land surface, including 40% of the eastern and central parts of the United States (White et al. 1995). It follows that karst is a major landform, and that the special engineering and environmental problems associated with it have special significance to humans. An incomplete list of some widely-recognized problems is provided in Table 1. While not all of these problems are unique to karst, the special character of this landscape tends to make them all particularly common or severe.

Considered together, nearly two-thirds of the city and county of St. Louis are underlain by limestone or subordinate dolostone. The special features and problems associated with karst are thus common here, and the problems are magnified in different ways because parts of the region have been settled for centuries, while others are undergoing rapid urban and suburban development. This paper briefly describes some of the issues and the disparate approaches to land development taken by different local communities.

Geologic Setting

The St. Louis region is part of the Ozark border with special proximity to major rivers and to the southern limit of Pleistocene glaciation (Vineyard

Table 1 *Some Problems of Uninformed Development of Karst*

Habitat & Landform Destruction

Structural Problems: roads, foundations, water and gas lines...

Water Quality Degradation
- Contamination: road salt, pesticides, oil, sewage, animal waste...
- Salinity & temperature fluctuation
- High Turbidity
- Excess Nutrients: organics, phosphates, fertilizers

Flooding & Drainage Problems
- Flash Floods: Surface & Subterranean
- Drainage
- Leaky Lakes

1967). Elevations vary from about 115 m (380 ft.) along the Mississippi River in the southernmost St. Louis County to 278m (890 ft.) near its western border. The greatest relief occurs along the river bluffs, which are nearly 100 m (300 ft) high along Meramec River about 2 km north of Eureka.

The geologic section of the region includes Quaternary and Recent deposits that overlie a section of Paleozoic strata that is > 1 km thick (Harrison 1997). The youngest deposits predominantly consist of unconsolidated alluvial deposits along the rivers, streams and floodplains. These are flanked by surficial loess deposits that thin away from the rivers, and then by thin, residual soils with abundant chert clasts on hillsides; see Lutzen and Rockaway (1971) for more details. The youngest bedrock includes the Pennsylvanian shale and subordinate siltstone, limestone, and thin coal beds that predominantly crop out in the east-central part of St. Louis. As these uppermost units are dominantly clastic, however, they host few karst features, although they commonly mantle underlying karst or constitute the fill of sinkholes that formed during Paleozoic to recent times.

Beneath these predominantly clastic units, however, is the thick, carbonate-dominated, commonly karstified stratigraphic section that makes Missouri the “Cave State”. Included are thick Mississippian strata, of which the St Louis and Burlington-Keokuk limestones have the greatest outcrop distribution. Devonian and Silurian strata are very thin or absent in this region, however. Beneath the major unconformity represented by these missing units are Ordovician strata dominated by the Kimmswick and Plattin limestones, the Joachim dolostone, and finally by the St. Peter sandstone which is the oldest unit that crops out in the area. Drill holes have penetrated about 600 m of subjacent Paleozoic strata, mostly Ordovician and Cambrian dolostones, that host many of the remarkable karst features of the Ozarks, but do not crop out near St. Louis.

Problems of Uninformed Development of Karst

Landform Destruction. The St. Louis area includes zones that have been settled for centuries, areas that are undergoing rapid development, and protected and unprotected areas that remain undeveloped. Karst has different relevance to these disparate areas.

Many long-settled parts of St. Louis were developed on karst, though their areal extent is difficult to quantify. This is because these areas are now devoid of outcrops, and because the landforms were profoundly modified long before accurate topographic maps were made. Some of the oldest maps (e.g., Paul 1844) show features such as Chouteau’s Pond that have been described as impounded sinkholes whose waters became incredibly polluted (Schroeder 1997). Its place is now occupied by railroad yards and high-rise buildings in the heart of the city, within 2 km of the Arch. In such areas, nothing remains of the original landscape on which the geologist can base conclusive deductions.

Farther from downtown, in areas that have not been settled quite as long, several parks and other protected areas preserve remnants of the original topography (Table 2). A good example is Carondelet Park (Figure 1), pockmarked by sinks, yet surrounded by developed expanses that are topographically featureless. Clearly, much land has been grossly modified and leveled. The Webster Grove area has many similar examples (Table 2), but also includes some subdivisions where sinkholes remain.

Even farther out, near the western, southern, northern, and southeastern boundaries of St. Louis County, are many large parks that preserve mostly unmodified topography. Of these, Cliff Cave County Park and Rockwoods Reservation are the best areas to observe karst features (Table 2, Missouri Speleological Survey 1966). An interesting difference, however, is that Cliff Cave park preserves part of the sinkhole plain that is similar to the terrane upon which the City of St. Louis was built, whereas Rockwoods Reservation preserves mostly hilly, wooded terrane with few sinkholes. The latter type of area is common in the Ozarks, and in part can be described as "mantled" karst.

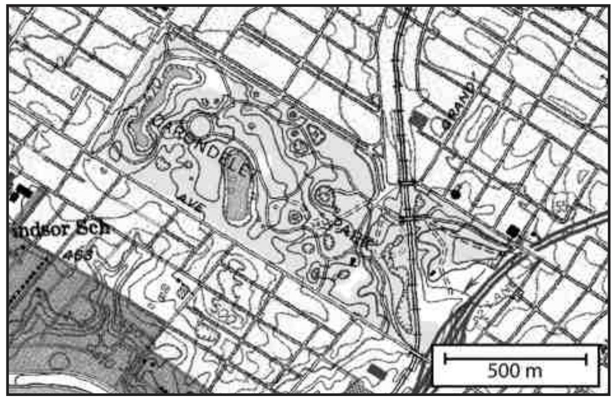

Figure 1 *Map of Carondelet Park (light grey), showing the preservation of several sinkholes and other karst features within its rectangular boundary, and the comparatively featureless topography outside. Just west of the railroad tracks is a sinuous depression that may represent collapsed cave passage, that formerly included features called Carondelet Park Cave (now blocked) and Big Spring (Light 2007). Modified after part of the USGS Webster Groves 7.5" topographic quadrangle.*

Cave and Habitat Destruction. Caves and cave habitat are commonly destroyed during the gross modification of the topographic surface described above, but are here considered separately as caves and their special life forms are remarkable parts of the subsurface (Elliott 2007). The pattern of intensive use, modification, and ultimate destruction of caves has been ongoing in St. Louis for two

Table 2 *Area Parks Preserving Significant Karst Features*

Park	Size, ha	Karst Features
Carondelet Park	73	Sinkholes, former cave and spring
Tower Grove Park	117	Sinkholes
Blackburn Park	13	Sinkholes, karst window
Bohrer Co. Park	7	Sinkholes
Sylvan Springs Co. Park	28	Sinkholes, spring
Cliff Cave Co. Park	104	Sinkholes, caves, springs
Jefferson Barracks	172	Sinkholes, springs
Ft. Bellefontine Co. Park	124	Spring, sinkholes, small cave
Forest 44 Cons. Area	388	Springs, swallow hole
Lone Elk Co. Park	221	Spring, leaky lake, small sink
Babler State Park	988	Small cave, springs
Greensfelder Co. Park	711	Caves, pits, springs, few sinkholes
Rockwoods Reservation	768	Springs, swallow holes, small caves, pits, estavelle, few sinkholes

centuries. None of the dozens of caves once present in what is now the City of St. Louis resemble their original character (Rother and Rother 1996). Few of these caves are even enterable, and their waters have become heavily polluted by sewage and other urban wastes. For example, Cherokee Cave once served as beer cellars, its rooms expanded by quarrying and blasting. Next it was used for waste disposal, and then it was cleaned out and further excavated to facilitate its use as a tour cave. Finally, in the 1960s the commercial cave was closed and partially filled and grouted to permit construction of I-55 (Weber 1964). Cherokee Cave is probably the most intact city cave, and parts of it are yet reported as enterable, but only via the basements of private businesses.

Moving outward into the next successive "shell" of historical development, external to the original city, are densely populated karst lands where many caves survive, albeit with significant modifications or impacts. Many of these caves are now enterable only through culverts, as they are commonly integrated into systems for storm-water drainage (e.g., Cave of the Falls). Others are reported to be very foul or to contain bad air, as they were formerly used to convey raw sewage. The entrances to many others have been filled, so they are no longer enterable. More than 10% of the county's caves mapped or described by Missouri Speleological Survey contributors have been destroyed or blocked in the last few decades (Criss et al. 2006). Many other significant caves were destroyed before they were documented. For example, former caves along Meramec River near Kirkwood were allegedly used for powder storage during the Civil War (Yegge 2007).

Finally, several enterable caves are preserved along the fringes of St. Louis County, particularly in protected areas such as the large county parks listed in Table 2. Unfortunately, many adjacent areas are undergoing rapid deforestation and suburban development, and several small caves have been recently destroyed by this process (Criss et al. 2006). The rapidity of this "urban sprawl" process is remarkable given that both the city and county of St. Louis have had negative population growth since 2000 (U.S. Census Bureau 2006).

Structural Problems. Problems associated with construction on karst are common in the St. Louis area, though most are of small scale. Examples are collapses that damage streets or foundations, repeated cracking of streets and sidewalks, and pipe breaks. These problems are typically corrected soon after they occur, and they seem not to have been systematically described. Such problems may be particularly common in the Concord (Appendix) and Spanish Lakes areas. A systematic study would be useful.

One significant sinkhole, about 30 m in diameter, formed since WWII at Washington University's Tyson Research Center, possibly because of groundwater pumping. No economic loss occurred at this forested collapse site, but the potential for damage is evident. Two small ponds on this property have experienced water-retention problems, one via a small sink that rapidly formed on its bottom ca. 1991, but far more larger examples of this sort are described below.

Water Quality Degradation. Ground and surface waters are intimately connected in karst terranes, so they are similarly impacted by human development. The everyday concept of degraded water quality actually embodies many different chemical and physical effects. Even the notion of "contamination" is not simple. One type of contamination is the deleterious increase in the concentrations of naturally-occurring substances, including road salt or certain toxic metals, or human and animal wastes. A particularly important class of such contaminants are nutrients, such as organics, phosphates, and fertilizers, that are commonly applied in great excess to cultivated fields, lawns, and golf courses. Moreover, in populated areas raw or insufficiently-treated sewage is an important contaminant that can pollute both surface streams and groundwater by several paths, including pipe leaks, septic systems, and combined sewer overflows (CSOs). Another type of contamination embodies the presence of unnatural substances such as pesticides, herbicides, or petroleum products, which now occur in local ground and surface waters (e.g., Hauck and Harris 2005). Stueber and Criss (2005) demonstrated the close interrelationships between ground and surface waters in nearby Monroe County, Illinois, and proved that both concentrations and loads of many substances of concern are greatest during storm flow. Additional study of St. Louis waters is needed, but it is evident most of our streams have biodiversity far below natural levels, and most are not even fit for human contact.

A commonly overlooked type of water quality degradation involves changes to its physical character. Most obvious are large increases in turbidity, which is also the most serious problem because bacteria, viruses, and many toxic metals are hosted by suspended particles. Like many chemical contaminants, turbidity of surface waters and many cave streams is greatly increased during storm flow (for example, Stueber and Criss 2005).

A final class of problems that is largely unstudied is related to rapid and large fluctuations of physical and chemical properties. Large fluctuations in the temperature and salinity of groundwaters and springs may be harmful to animals in these habitats, particularly to troglobitic organisms that are highly adapted to a nearly invariant subsurface environment. Clearly, increased contributions of surface waters to cave streams will amplify such variations. Examples include gross changes in salinity because of road salt applications, rapid fluctuations in discharge, turbidity and temperature related to the use of caves for storm-water conveyance, and large seasonal variations because of leaking impoundments (Figure 2).

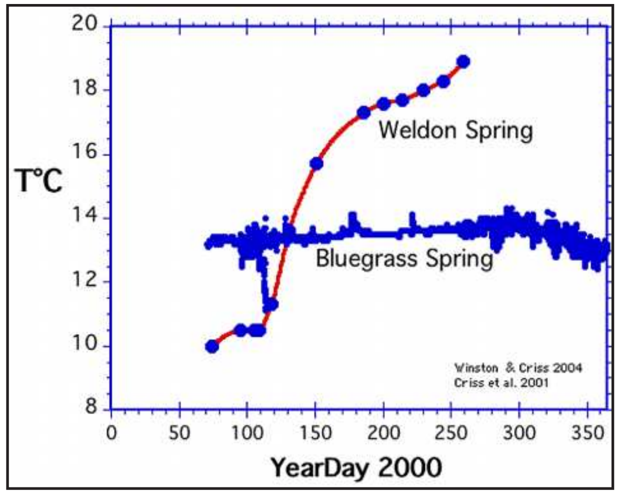

Figure 2 The subsurface environment normally has very uniform temperatures, as seen in the small temperature variations in Bluegrass Spring at Tyson Research Center. In contrast, Weldon Spring in southern St. Charles County now has flow dominated by lake leakage, and its temperature variations have become comparatively large. Data from Winston and Criss (2004) and Criss et al. (2001).

Flooding and Drainage Problems. Both surface streams and cave streams commonly experience flash flooding in the St. Louis area, and the frequency and magnitude of these events have increased in response to development of the land surface. Many local waterways that once had perennial flow are now mostly dry, but experience severe intermittent flash floods. These high, intermittent flows are well documented by gauging stations, and are evidenced by many physical characteristics including erosion, entrenchment of the stream channels below the natural floodplain, and the removal of fine sediments so that the channels are now lined with coarse gravels and cobbles. These changes are aggravated by the construction of impervious surfaces, and more widely by deforestation and the disturbance of soils that mantle the karst, which are quite thin on many local hillsides.

Now, what do the aforementioned conspicuous processes have to do with karst groundwater? Probably a great deal, because the excess runoff that is now delivered rapidly to stream channels represents water that no longer slowly infiltrates the soil. This change has reduced recharge to the shallow groundwater systems that sustain the flow of streams during dry spells. It would be expected under these circumstances that many springs are drying up. However, many cave streams are experiencing increased flow because of the intentional routing of urban and suburban runoff directly into large cave conduits, described above, which clearly would amplify subterranean flash floods. Here again, monitoring of area springs is insufficient to clearly establish these trends, even though they may be very significant.

In contrast, problems with drainage and with the catastrophic failure of impoundments occurs so rapidly that they cannot be overlooked. Drainage problems occur when conduits cannot remove storm waters as rapidly as they are delivered, which is very fast where impervious surfaces are common or where natural soil infiltration has been reduced. Storm-water detention basins are commonly constructed in St. Louis County to offset these problems.

Finally, the catastrophic failure of lakes is common in the St. Louis area. Interestingly, the most important examples have occurred in areas under-

Table 3 *Disparate Zoning Ordinances of two St. Louis Co. Communities*

Oakville	**Old Jamestown**
High Density Residential & Commercial	Low Density Residential (mostly 3 to 5 acre lots)
Homes, roads commonly built on filled sinkholes	Topography preserved by mandated construction setbacks
Stormwater diverted into sinks, caves	Alterations to natural flows are prohibited

lain by the Burlington-Keokuk Limestone, which hosts many deep, clay-filled grikes and fractures. If excavations remove too much epikarst so that such fractures are intersected, their clay fill can be removed by percolating waters, and the conduits rapidly enlarged. The most notorious example is Lake Chesterfield, which catastrophically failed in 2004, was grouted, then failed again in 2005. Lone Elk Lake has not failed in such a manner, but it is unable to retain water depths as great as originally planned, and is clearly leaking to a spring near Meramec River (Criss 2001). Similarly, Prairie Lake in southern St. Charles County is constructed on the Burlington-Keokuk limestone, and its leakage has significantly affected Weldon Spring (Figure 2, Criss et al. 2001).

Different Zoning Approaches. Different municipalities in the St. Louis area have remarkably different approaches to development. It is useful to contrast and compare the approaches of the Old Jamestown (Smith et al. 1988) and the Oakville areas, respectively located in the northernmost and the southernmost parts of St. Louis County (Table 3). In particular, the Old Jamestown Association has attempted to minimize the impacts to its karst areas by mandating low density housing, requiring construction setbacks from sinkholes, and prohibiting changes to natural drainage patterns. In contrast, topographic leveling and construction of roads and high-density housing is common in the Oakville area, and caves are commonly filled or incorporated into storm-water drainage systems. Figure 3 exemplifies these differences.

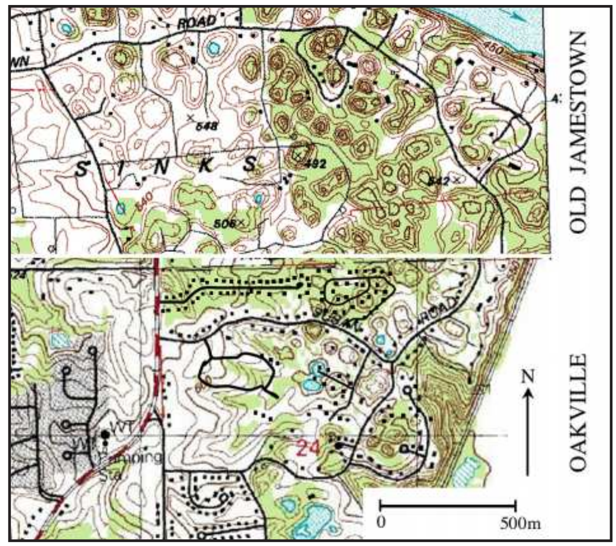

Figure 3 *Comparison of parts of the Old Jamestown and the Oakville areas in St. Louis County, showing the difference in the locations and density of construction relative to karst features. Modified after the USGS Florissant and Oakville 7.5' topographic quadrangles, but included on the latter map are the approximate positions of some of the new roads and buildings shown on satellite photographs (Appendix).*

Conclusions

The St. Louis area has abundant karst lands with great aesthetic, environmental, and economic value. However, problems have arisen historically and recently with the use of these special lands, especially with inappropriate construction. Karst lands are now being severely impacted by the regional urbanization and suburban sprawl, which has severely degraded shallow groundwaters and greatly impacted surface streams. Local zoning regulations and construction standards are commonly inappropriate for karst, causing problems that are costly to homeowners, costly to taxpayers, or harmful to natural habitat. Many of these problems could be easily avoided if more balance were found between these standards and environmental preservation.

Acknowledgments

I have greatly benefited from many discussions, field work or productive collaborations with Bob Osburn, Bill Winston, Philip Moss, Jenny Lippmann, Joe Light and Owen Sexton.

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Appendix

Urban Karst Field Trip, St. Louis County, Missouri

Bob Criss and Bob Osburn, Washington University

Abstract

This three-hour tour will provide an introduction to some historical karst features of St. Louis County and their modification by human and natural processes. Surviving karst features include the antebellum Rott Springhouse (stop 1), which now issues contaminated water, and the sinkhole plain and associated features in Cliff Cave County Park (stop 6). Problems associated with residential and commercial development of karst lands include ground collapse, cracking, and settling (Stop 2), associated drainage problems (stop 3), and the destruction or gross modification of caves and sinkholes by infilling, topographic leveling, and/or their incorporation into stormwater drainage systems (stops 4 & 5). The remarkable historical efforts to preserve public lands in the St. Louis area are being offset by rapid urban sprawl and by construction standards that commonly prove inappropriate for karst.

Road Log.

0.0 Leave Holiday Inn/Viking Conference Center at Lindbergh Ave & Watson Rd., go West (right) on Watson Rd. for 0.4 mi. to light

0.4 Turn S (left) on Geyer Rd, continue S on Rott Rd for 0.9 mi., right at stop sign (go under I 270)

1.5 Left into drive at 9268 Rott Rd.

1.6 Stop 1 Springhouse at Rott Spring

1.7 Return to Rott Rd. go S (left)

2.4 Continue 1.4 mi. then left on Weber Hill Rd

3.8 Jog left to ramp, I 270 South, go SE for 2.8 mi. and get off at next exit

5.1 Exit Tesson Ferry Rd., go NE (left) on Tesson Ferry for 0.5 mi.

6.2 SE (right) on E. Concord Rd, go 0.35 mi. to T intersection at Theis Rd.

6.6 Short jog to right, take immediate left on Conger Dr, go 0.1 mi.

6.7 Stop 2 Conger Drive

7.0 Return to E. Concord Dr, go NW and proceed 0.1 mi.

7.1 Right turn on Tescord Dr, proceed NE for 0.45 mi., & park in cul de sac

7.6 Stop 3 Tescord Drive

7.6 Turn around & return to E Concord Rd.

8.0 Go NW (right) and go 0.4 mi. to Tesson Ferry Rd.

8.3 SW (left) at light on Tesson Ferry, go 0.5 mi. to I 270 ramp

8.9 SE on I 270/ I 255, get to center lane & go 3.7 mi. to Telegraph Rd exit.

12.6 Exit Telegraph Rd, go S (right) on Telegraph Rd. for 2.2 mi.

14.9 Reliance Bank parking lot on right, SW corner of Telegraph and England Town Rd.

14.9 Stop 4 Detention Basin Overlook

14.9 Continue S on Telegraph for 0.8 mi.

15.7 Go East (left) on Susan Rd & proceed for 0.4 mi., left on Clifton Oaks Pl.

16.1 Stop 5: Clifton Oaks Place

16.8 Return to Susan Rd, go W (right) & go 0.4 mi. to return to Telegraph Rd.

17.2 N (right) on Telegraph Rd, go 1.1 mi. to Cliff Cave Rd.

18.3 Go E (right) on Cliff Cave Rd, for 1.5 mi., down steep hill, and park

19.8 Stop 6: Cliff Cave County Park

20.0 Stop 7: Riverside Park & Mississippi River Trail

21.7 Return to Telegraph via Cliff Cave Rd, go N (right) for 1.9 mi. to I 255/I 270 ramp on right

23.6 Take I 255/I 270 to west (left) & go 7.7 mi. to Watson Rd. exit.

31.3 Go E (right) on Watson Rd. for 1.2 mi. to Viking Conference Center

32.5 Viking Conference Center on left

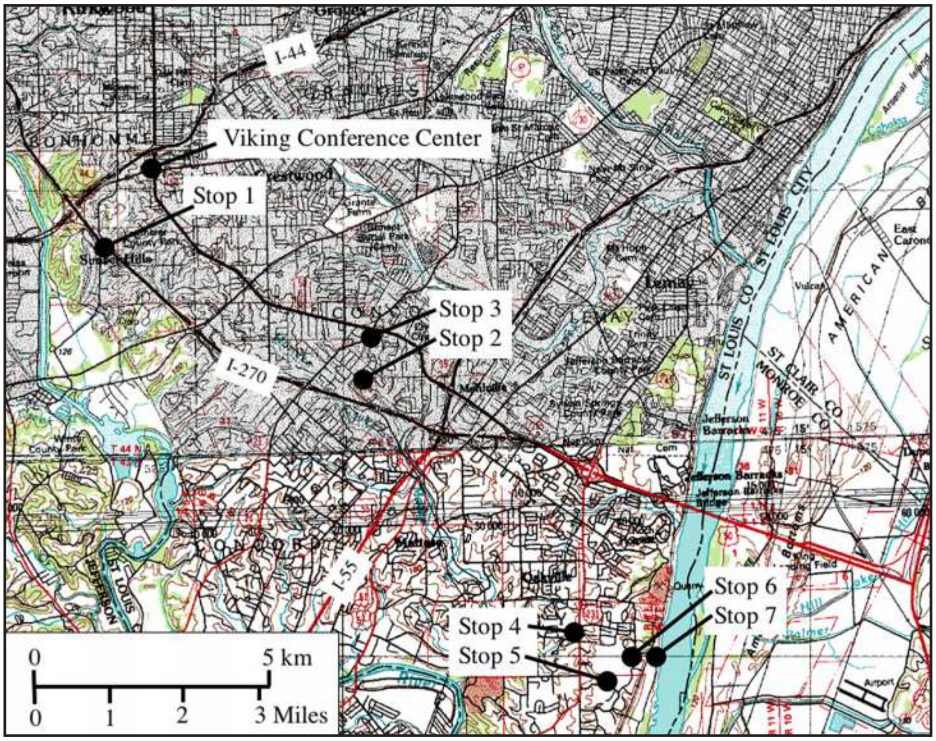

Figure 1 Map showing the urban karst field trip stops, modified after the USGS 100k topographic sheets for the St. Louis and Festus quadrangles.

Site Descriptions

Stop 1 Springhouse at Rott Spring

Private Property T.44N R.5E NWSENE Sec. 23 Kirkwood 7.5″ Quadrangle

Rott Spring emerges from what is arguably the best surviving example of an antebellum springhouse in St. Louis Co., on the property of Clarence Morrison, 9268 Rott Rd. (Fig. 2). The watershed for this remarkable spring clearly includes forested hillsides and low-density suburban areas to the northeast, but development has had several impacts. First, the watershed was greatly modified by the construction of I-270, located only 100 m to the northeast of the springhouse, and this has visibly decreased the flow of the spring according to field trip participant Earl Biffle. Second, the spring has conductivity in excess of normal values, perhaps due to road salt, and was contaminated in 1994 by oil from a leaking tank located a few thousand feet to the NE. This leak caused a fish kill in the pond and imparted a petroliferous odor that is still noticeable today, though the fish have returned. The host rock at the springhouse is mapped as Warsaw Fm. (Harrison 1997).

Figure 2 The antebellum Rott Springhouse has survived much development in St. Louis County, though its watershed has been impacted (Stop 1).

Stop 2 Conger Dr.

Private Property T.44N R.6E NENWNW Sec. 33 (proj) Webster Groves 7.5″ Quadrangle

The Concord area of St. Louis Co. is built on a sinkhole plain developed in the St. Louis Limestone, and has associated engineering, structural, and drainage problems. A pronounced, 1-km-long line of sinkholes, parallel to E. Concord Rd., extends into a SE-trending valley that includes a spring (now dry), and at least one small cave with a flowing stream (Fiedler Cave; SLO 114). Diversion of storm water into sinkholes and caves is common in the Concord area. Concord residents described several water line breaks this month, and mentioned historical instances of sinkhole collapses and gas line leaks.

Several homes along Conger Dr. were constructed along the side of a large sink, that according to one lifelong resident formerly hosted a cave entrance. The area was partly filled and graded, and is now traversed by an MSD storm sewer. Several homes in the immediate vicinity still have septic systems, while others are connected to municipal sewer lines. Evidence for continued settling and/or collapse are abundant on this block. These include 1) a 10m-long, 10 cm-high scarp displacing the turf in a front yard, that is associated with a septic system trickle field; 2) numerous small, recent collapse pits proximal to the MSD line, and 3) numerous cracks and patches in Conger Drive.

Stop 3 Tescord Drive

Private Property T.44N R.6E NW NESE Sec. 28 Webster Groves 7.5″ Quadrangle

The residence of Alice Bradenberg at 11606 Tescord Drive has experienced repeated flooding since 1966 due to backflow from a sinkhole into which too much storm water has been diverted (Fig. 3). Ms. Bradenberg reports that the water from the "drain" can "geyser" several feet into the air following storms. MSD has attempted to excavate, rebuild and relocate the drain into the limestone several times, but has not been able to correct the problem, and commercial development on proximal Lindbergh Ave. has probably exacerbated the situation. Note the 6 m-diameter, 25 cm-high, circular subsidence "scarp" around one of these drains. The neighborhood was converted from septic systems and connected with the municipal sewer system ca. 1997.

Stop 4 Telegraph Road detention basin

Commercial Property T.43N R.6E SESENE Sec. 14 Oakville 7.5″ Quadrangle

This 1.5-ha detention basin (Fig. 4) is developed above a large composite sinkhole that formerly contained two cave entrances, Cave of the Falls (SLO 98; see Vandike et al., 1989), and Jagged

Figure 3. Collapse near a storm drain situated in a sinkhole in the Concord area. The capacity of the natural bedrock conduits is too small to drain storm water as fast as it is delivered, so this yard frequently floods to depths of several feet (Stop 3).

Pit (SLO 86), that are not now enterable through these concrete drain structures. Though little information is currently available, the Cave of the Falls is alleged to be the largest cave in St. Louis County, with more than 2 km of passage.

Cave of the Falls terminates about 1 km to the northwest at a natural entrance hosting a flowing cave stream. Thus, this detention basin exemplifies the routing of urban storm water into caves. These cave conduits of course provided drainage for waters entering the large sinkholes that originally occurred in this location, so the argument is commonly advanced that this pattern of drainage is basically "natural." Questions that arise include the following: (1) Is water being diverted from adjacent areas, so that mean flows in the cave are now significantly greater than before? (2) Are storm waters from impervious surface now delivered to cave systems at faster rates than under natural conditions, so that peak flows are now greater? (3) Is the quality of water delivered from impervious, urban and suburban surfaces degraded in its chemical and physical nature compared to the quality under natural conditions? (4) What effects do these changes have on the cave environment and habitat?

Figure 4. This detention basin near Telegraph Road in Oakville diverts storm runoff into culverts that intersect two caves, including the longest cave in St. Louis County (Stop 4).

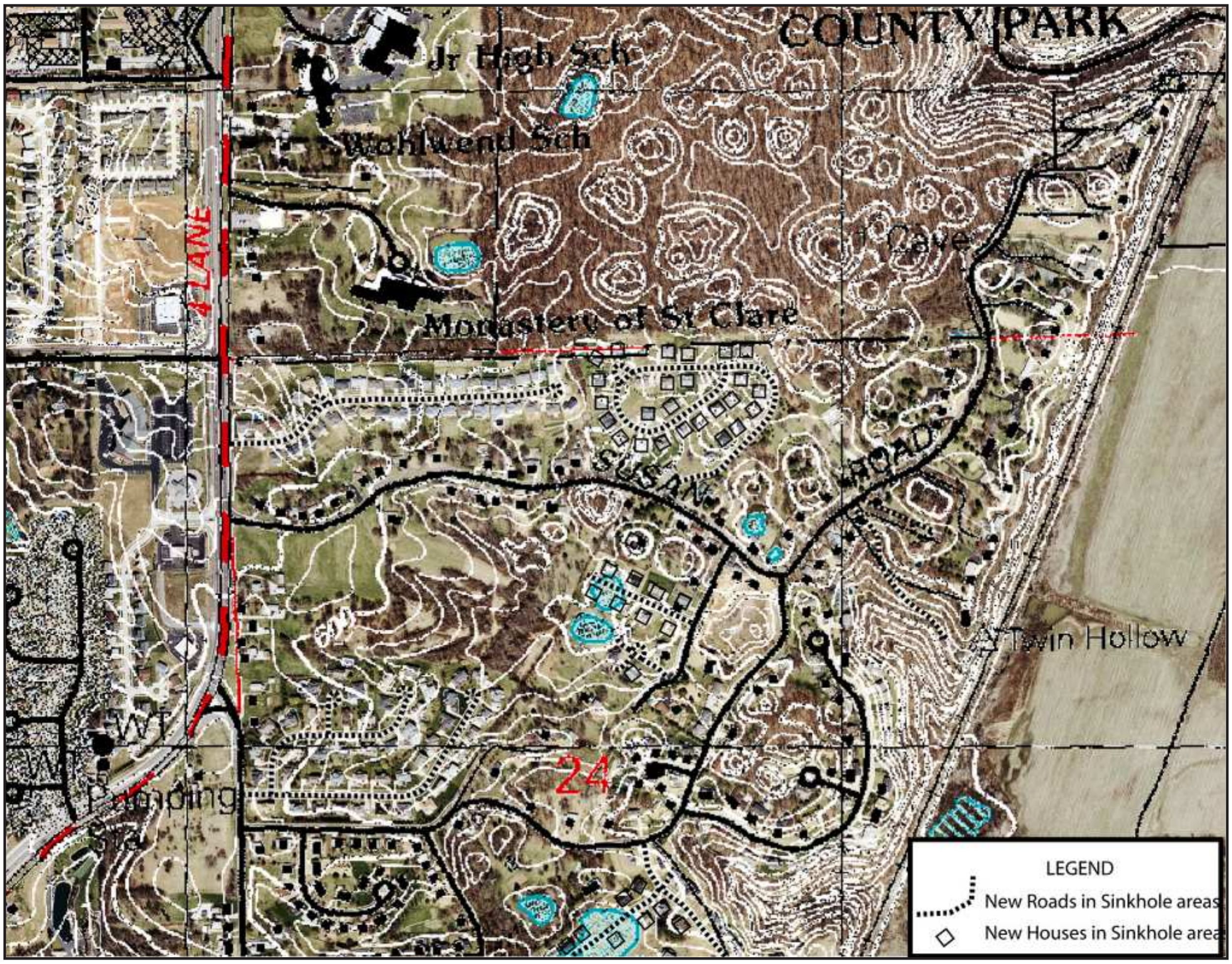

Figure 5 *Topographic contours (white, from Oakville 7.5" map 1991) superimposed on a recent satellite image (USGS Urban Area Imagery, March 2004) of an area within and immediately south of Cliff Cave County Park. Many houses and roads have been constructed on filled sinkholes and sinkhole ponds, and others are directly above caves.*

Stop 5 Clifton Oaks Place

Private Subdivision T.43N R.6E NENENW Sec. 24 Oakville 7.5″ Quadrangle

The roads and houses in this relatively new residential area have been developed over several prominent sinkholes (Fig. 5). Some of these sinkholes contained the entrances to small caves, no longer enterable, but now used to convey storm water. Only 250 m to the SW, several homes along Briartree Ln. are constructed above former sinkhole ponds.

Stop 6 Cliff Cave County Park

County Property T.43N R.6E SESWNE Sec. 13 Oakville 7.5″ Quadrangle

Much of section 13 is protected by Cliff Cave County Park, preserving a topographic remnant of the forested sinkhole plain. At least 10 caves occur in this section. Best known is Cliff Cave (SLO 13; Fig. 6), the second longest cave in the county with more than 4700 feet of passage (MSS 1966, Marty et al. 1982). The picturesque entrance to this cave, some 16 m wide and 7 m tall, contains a stone archway that is a remnant of its former use as a storage area. Before that, Cliff Cave was used by native Americans. Eastern pipistrelles (*Perimyotis subflavus*) and Big Brown bats (*Eptesicus fuscus*) hibernate in the cave (William R. Elliott, pers. comm.), and the perennial cave stream that exits from the main entrance hosts abundant flatworms, isopods, and amphipods.

Cliff Cave has three additional entrances, one now collapsed, located in sinkholes to the south-

Figure 6 NCKMS field trip participants at the main entrance to Cliff Cave (Stop 6). Photo by Bill Elliott.

west. These are part of the overlying sinkhole plain which clearly lacks an integrated, dendritic system of surface streams. The cave clearly serves as the subsurface drain of this sinkhole plain, and was probably developed at the water table in this setting. The cave mostly consists of air filled passages above a flowing stream with either a gravel or bedrock floor. The cave walls have well-developed scallops, and the ceiling has remarkable cupolas, but speleothems are uncommon, particularly in the main passage, probably because they are broken by subterranean flash floods. Cliff Cave was gated following a fatal incident in 1993 that involved several spelunkers caught in such a flood.

Spit Cave (SLO-079), a cavelet located only 200 m east of the main entrance to Cliff Cave, has had its entrance modified by natural collapse since it was mapped in 1977 (Koenen and Eddleman 1977, Criss et al., 2006).

Stop 7 Mississippi River Bluff and Floodplain at MRT Park

County Property T.43N R.6E Sec. 18
Oakville 7.5″ Quadrangle

This site abuts the "Middle" Mississippi" River at Mile 167, approximately 28 river mi. (45 km) below the Missouri confluence. Above confluence point, navigation on the "Upper" Mississippi River is facilitated by a network of huge locks and dams that extends all the way to Minneapolis-St. Paul. Downstream of the confluence the river flows freely to the Gulf of Mexico, and navigation is facilitated only by dredging and wing dikes, prominent examples of which are visible here at low water (Criss and Wilson, 2003). Barge activity will be conspicuous as this is a "fleeting area", so called because the huge tows are appropriately resized or reconfigured for the next stage of their passage. The Mississippi River at this point drains a watershed of just over 1,810,000 km^2 (700,000 mi^2), 3/4 of which is represented by the huge Missouri River basin. The elevation of the river here is only about 150 m MSL (380 ft.), even though it must flow 1,800 km (1120 mi.) to the Gulf. Although the topographic gradient over this huge distance is very small, the flow sustained by the tiny slope is colossal. Mean flow of the Mississippi River at St. Louis (Mile 180) is 5,350 cms (189,000 cfs), but peak flows during the 1993 flood exceeded 29,700 cms (1 Mcfs; Hauck and Harris, 2005).

At this site the Mississippi River is about 60 m (200 ft.) below the elevation of the sinkhole plain to the immediate west, separated by a prominent bluff visible along the railroad tracks. Middendorf and Brill (1991) include the entire bluff and proximal sinkhole plain within the St. Louis Limestone, though their map and cross section require about 100m (300') of thickness for this unit in this area, which may be excessive. Several caves are developed along and near the river bluff, and they clearly provide conduits for the internal drainage system of the proximal sinkhole plain.

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WATSON CAVE AND DEE KOESTERING PARK: AN URBAN KARST SUCCESS STORY

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Abstract

Beginning in 2000, St. Louis caver Tom Clifton and concerned citizens of suburban Kirkwood began work to preserve from redevelopment a 3.2-ha (8-ac.) tract containing Watson Cave. The cave is located in the old Meramec Highlands Quarry, abandoned around 1900, not far from our symposium site. The tract was proposed to be rezoned for multifamily housing, eliminating an urban, reforested, private tract used for informal recreation by local residents. A citizens' group was formed, and the Open Space Council and Audubon Society were enlisted. Clifton, Tom Cravens and members of the Kirkwood-based Meramec Valley Grotto were enlisted to aid in bioinventory of the cave, which had originally been examined by Lang Brod in 1964. By 2003 sufficient funding was obtained to purchase the land as a city park. Since then, the Kirkwood Parks Board has included geological interpretation (the quarry is the type locality for the Salem geological formation) and cave management in its plan for the park. The cave was gated, but access is still permitted to qualified groups.

Key words: urban karst, karst land management, Watson Cave, Dee Koestering Park, Missouri

The Setting

Kirkwood, Missouri, is a suburb of 30,000 to St. Louis, Missouri, with middle to upper-middle-class residents. The town was established in 1853 on the Pacific Railroad and named for the railroad's chief engineer. The residents are actively involved in local government, very conscious of their history and environment, and support 121 ha (300 ac.) of parks within the city's 2,331 ha (9 mi.^{2}) area.

The disputed land lies in a portion of Kirkwood known as the "Meramec Highlands," after a turn of the twentieth century resort which existed on the site (Figure 1). The 177-ha (438-ac.) resort opened in May of 1895, and featured an imposing bluff-top hotel, with a spectacular view of the Meramec River and its valley, direct rail access, a mineral spring and bathhouse spa, boating, a Meramec River swimming beach, a store, and rental cottages. The establishment was close enough to St. Louis to draw clients for the weekend, but far enough to maintain an illusion of isolation (Baker 1995).

The specific area of concern was the site of the old Meramec Highlands Quarry (Figure 2). To develop the resort a local source of stone was required, and the quarry on the nearby hill served that purpose. The first confirmed quarrying occurred in 1891, and stone was extracted until 1903. By this time headward expansion of the quarry was limited by the presence of the rail line, and sideways development limited by topography. In the course of excavation to the west, the quarry encountered a small cave.

The quarry consists of two major Mississippian-age limestones: the medium-bedded Salem (Spergen Hill, also called Meramec bluestone locally) which is separated from the overlying, thinner-bedded St. Louis Limestone by a distinctive layer of cannonball-sized chert nodules. The Salem may be quarried in large blocks, the St. Louis is better used as crushed stone. Rumors abound that the quarry furnished stone for the St. Louis Worlds

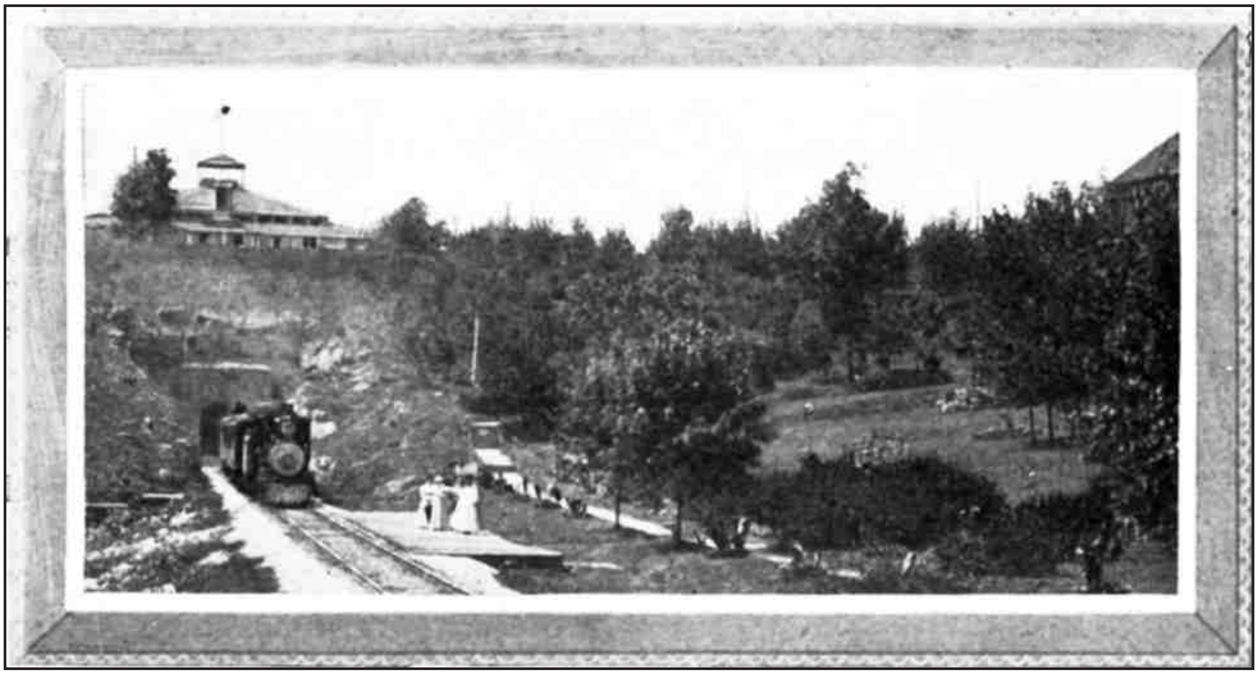

Figure 1 The Meramec Highlands Resort was the ideal St. Louis getaway. Photo from World's Fair book, The state of Missouri, 1904.

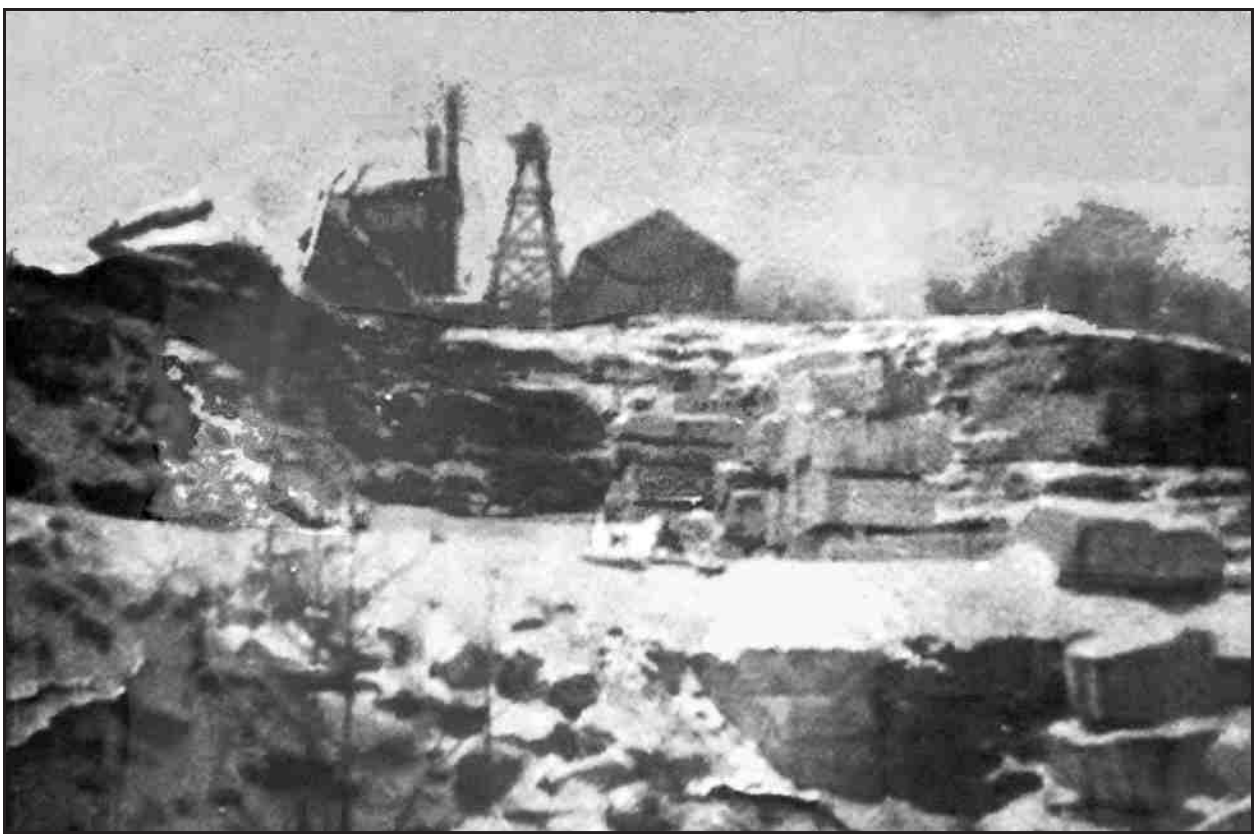

Figure 2 Meramec Highlands Quarry operated from 1891 to 1903. The plant burned in 1916, and the property was essentially abandoned. Photo courtesy Kirkwood Parks and Recreation.

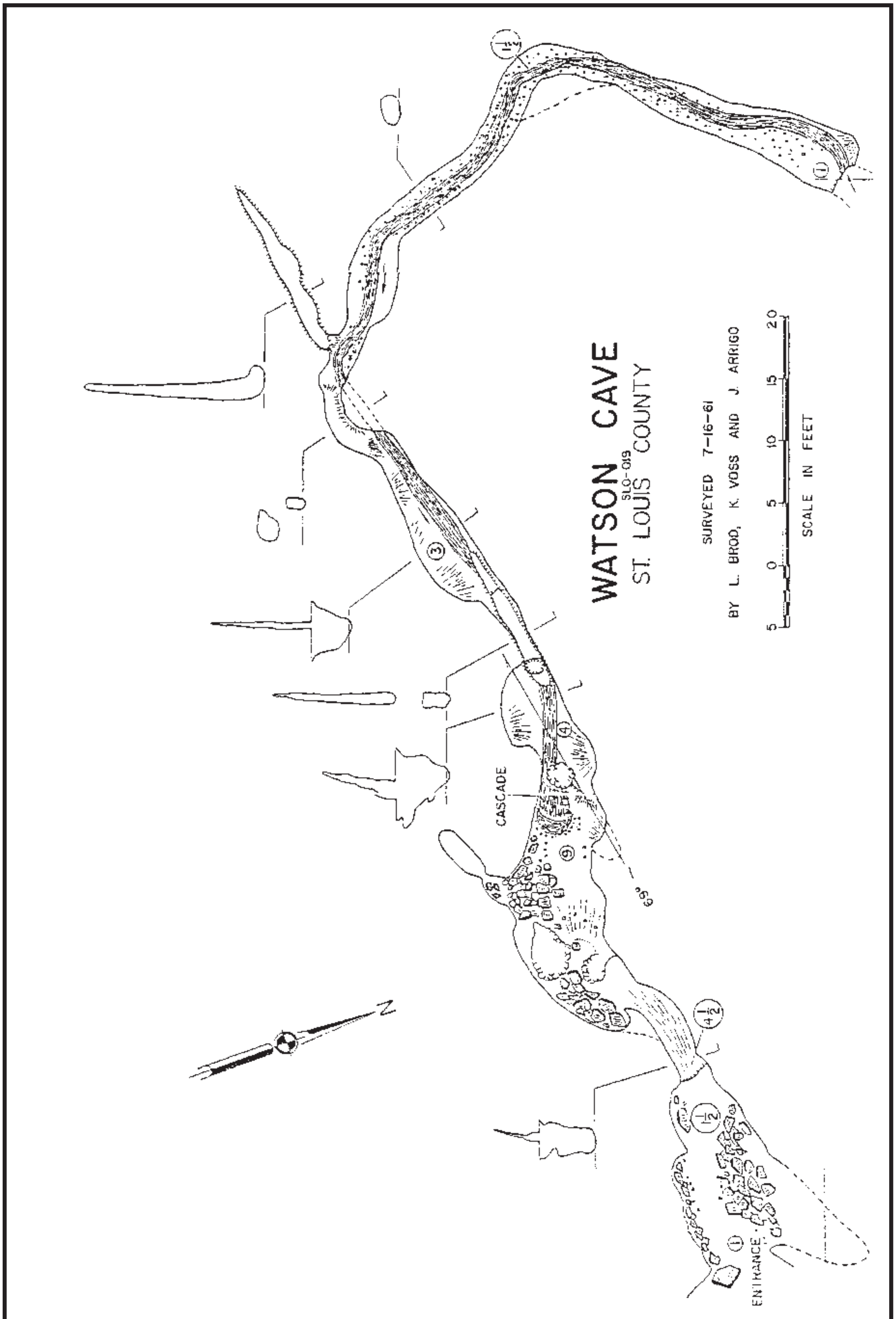

Figure 3 Watson Cave Map. Map by L. Brod and J. Arrigo.

Fair. If so, it was used only as foundation stones for temporary terra cotta constructions as no evidence remains of its use in any permanent structure in St. Louis' Forest Park. Quarry buildings burned in 1916, and for eighty years the property remained in private hands, used informally for picnicking, nature study, as "woods" by local children during the day and for partying by local teens by night (Baker 1995, Buckley and Buehler 1904).

In 1964 Lang Brod mapped Watson Cave, the small cave encountered during quarrying (Figure 3). This cave is approximately 35 m long. Ten meters

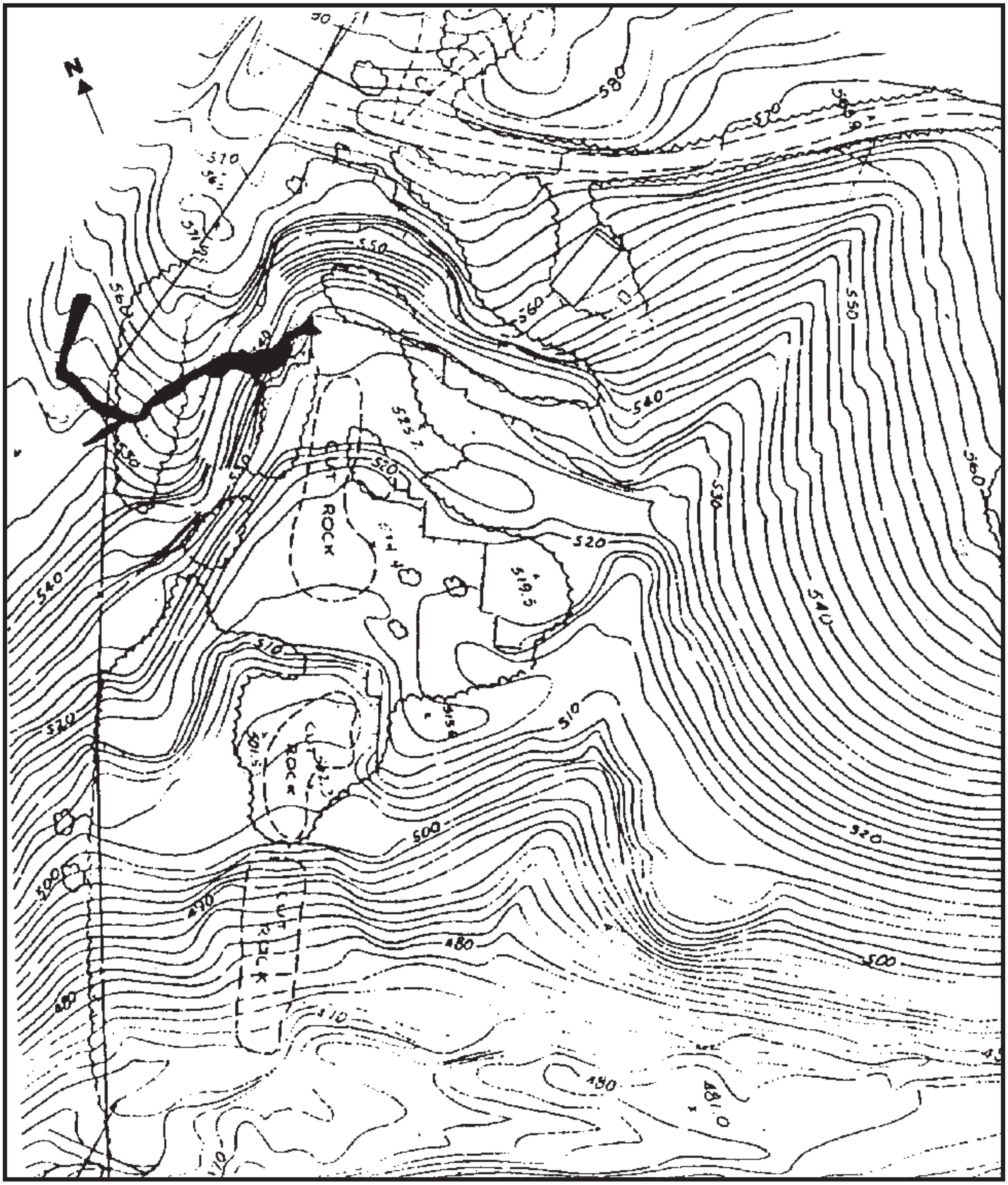

Figure 4 *Watson Cave overlay. I-270 lies just off map to the west; to the north is the Burlington–Santa Fe Railroad. Map by Tom Clifton.*

into the cave, the stream that runs the remainder of the cave sumps. Upstream of the sump, the cave continues to its terminus in a 15-cm-high passage admitting the stream. The cave is rather shallow, as indicated by the presence of tree roots. Most of the cave is developed along joints, before the sump, it is rarely over 60 cm tall, but beyond one encounters a one-meter high waterfall and passage up to almost three meters tall. The outflow of the sump is unknown. A large room, about three meters long and tall enough to sit in comfortably, exists at this point. Beyond the room, this tall passage is also extremely narrow, best described as a crevice with intermittently passable openings. Only the stream-enlarged bottom portion of the passage is sufficiently roomy enough for small adults (Brod 1964). The cave initially heads towards I-270, but turns northward, and instead pinches out (Figure 4). At approximately the elevation of Watson Cave in the northbound lane on I-270 is a concrete reinforcement structure partway up the rock wall, its purpose is unknown, but may have some relationship to a karst feature. A small, perennial stream tumbles down the property towards the Meramec River.

The Problem

In summer 2000, Miracle Design Group proposed to develop the old quarry as an 18-unit multifamily complex. The owners, Ernest and Dee Koestering, were in their 80s. They lived adjacent to, and had owned the 3.2-ha (8-ac.) quarry since 1962. The developer made the Koesterings an attractive offer—contingent on the city changing the zoning to permit multifamily development.

The Players

Ernest Koestering was a retired engineer and his wife, Dee, a homemaker. His home and the disputed site lay in a wooded part of Kirkwood, bounded on the west by I-270 and on the north by the tracks of the Burlington–Santa Fe Railroad. Because of increased suburbanization and land values, he had been approached several times, as recently as 1998, to sell the undeveloped parcel, but he had resisted, preferring the unused, forested, buffer zone between himself and the noisy interstate. Advancing age and financial consideration caused him to reluctantly consider the Miracle Design Group proposal.

A number of obstacles stood in the way of the property sale, chiefly that the property was not zoned for multifamily dwellings, and that other residents along the south side on South Signal Hill Drive, with wooded lots of 0.4 to 1.2 ha (1 to 3 acres), did not want to see a multifamily development. One of these residents, Ms. Linda Fenton, took it upon herself to make preservation of the quarry property her cause. Another neighbor, Jamie Meier, canvassed her neighbors not only to prevent the Kirkwood Planning and Zoning Commission from rezoning the property, but also to effectively lower the current zoning code to conform better to other properties in the area. Fenton also contacted Ron Coleman of the Open Space Council, a local greenspace advocacy group, for advice.

Linda Fenton was sympathetic to her neighbors, the Koesterings, and their wish to sell the quarry for a reasonable price, but equally determined to fight the housing complex, and to preserve the quarry. In order to have anything to preserve, the first step was to stop the rezoning, and the second, to find a compatible buyer for it. Her initial search for a conservation buyer failed. The property was at the same time too valuable and too worthless. Although birders had used it, an informal botanical survey only found species one would expect in an overgrown, abandoned lot.

Throughout this process, the Koesterings seemed of two minds on the quarry. Although both had a great love for the land, they entered into a preliminary contract for its sale. This made dealing with them during the entire process a sensitive issue. One respected their right to do as they pleased with the property, while at the same time encouraging them to consider conservation alternatives, and helping them find other buyers who did not propose to develop. An additional fact was that Dee Koestering's health was in constant flux during the year from August 2000 to her death in August 2001.

Among Fenton's Kirkwood acquaintances was Mr. Tom Clifton, whom she knew to be a caver with Meramec Valley Grotto. Tom enlisted the help of Tom Cravens, Meramec Valley Grotto founder, who also lived in Kirkwood, and who had corresponded with Mr. Koestering occasionally since 1970, and Jerry Vineyard, retired deputy state geologist, who had been contacted by Koestering in 1998 regard-

Figure 5 Location of the Meramec Highlands Quarry east of I-270 in Kirkwood, Missouri.

ing where the water in his cave stream went.

In August 2000, the Koesterings, Clifton, Fenton, a geologist, a botanist, the Mayor of Kirkwood, Mike Swoboda, and assorted neighbors visited the site to see if there were bats in the cave, especially any endangered species. None were found. Clifton was the only member of the party to enter the cave. Although they took maps of the cave and the verbal description, the others, carrying flashlights and dressed in casual outdoor wear, at least subliminally expected a large, walk-in cave, not a crawling entrance in the side of the quarry wall (Tom Clifton pers. comm.).

As trip participants discussed possible development, nine major hurdles to clear any change in zoning regulations became clear. These were:

- No sewer on property. The nearest sewer main would involve bringing sewer from across I-270. Septic systems were out of the question because of the topography and lack of topsoil over the bare bedrock.
- Water lines were available adjacent to the property, but again, laying waterlines directly on rock brought a new set of expensive engineer-

ing problems.
- I-270 had cut off the driving access to the property. A narrow, one-lane road existed along the railroad tracks, but it would have to be widened, filled and graded to be brought to code for that many residents.
- Because of the steep terrain, massive cut-and-fill would be needed to achieve anything resembling normal landscaping. Current residents were leery of the blasting needed to secure the housing units to the hillside.
- The tract is bounded by a railroad main line on the north (Figure 5). Families with children would not want to locate there, plus little could be done in terms of noise mitigation from the railroad.
- When I-270 was built alongside the Koestering's property, it consisted of two lanes north and two lanes south. The highway was now four lanes in each direction. What was once a twice-a-day noise annoyance during rush hour was now a 24/7 roar of noise. Noise mitigation would have to be done for the complex to attract suitable tenants.
- The developer planned to ask for a number of variances from city code because of the excessive cost to meet codes. The local residents were concerned that their new neighbors meet the same codes as they had to, and not be excused, in order to maintain local property values.
- The active perennial stream would have to be channelized or buried. No flow-monitoring records existed, so engineers would have to study the stream, incurring additional cost, not to mention the cost of the mitigation. The construction/engineering problems of the cave stream water (if the area over the cave were developed) were unknown.
- After meeting objections one through eight, the developer estimated that final cost of each unit to be near $800,000 under single-family zoning in order to obtain a decent return.

Although Kirkwood is reasonably well-to-do, over three-quarters of a million dollars per unit was greatly out of line even for the single-family housing with land adjacent to the property. He proposed to sell the attached-unit homes for $330,000 each, because he could double the number of units under the zoning change he sought (Tom Clifton, Linda Fenton, Jerry Vineyard, Murray Pounds pers. comm.).

The Plan

A three-fold plan enacted over the next year ensured that the property was, in the final assessment, saved in its semi-wild state. This plan consisted of (a) thwarting the proposed change of property zoning to multifamily housing based on the criteria just enumerated (b) determining actual cultural and natural resource values which existed on the property and (c) finding funding sources to acquire the property for conservation purposes.

The Results

The change of zoning from R-1 single family to 4–3 multifamily was denied on November 1, 2000, because of the efforts of Fenton and her neighborhood group. The outcome was also assisted by testimony from Clifton, information from the Missouri cave files furnished by Jerry Vineyard on the cave resources, neighborhood concern about extensive blasting and sinkhole creation in a karst area, and issues related to the surface and cave streams under a development scenario. The Missouri Cave Resources Protection Act was entered as evidence of the importance of caves into zoning hearings.

In the course of examining the site for cultural and natural artifacts and resources to preserve, a long length of original quarry chain was discovered. Later, an example of feathers and wedges were found intact in the wall—a preserved example of the mining methods used at the turn of the twentieth century. Jerry Vineyard found, in searching old books, that the quarry was a geological type locality for the Spergen Hill (Salem) Limestone, as well as the original example cited by the United States Geological Survey of the Meramecian Series of the Middle Mississippian strata in Missouri, which after the quarry was successfully saved, was used as the type locality for these ancient rocks nationwide (Lane and Brenckle 1977).

Clifton made a detailed examination of the cave on several occasions, with the intent to research water quality and biota there, including plans to gate the cave against teenage intruders—the ones who had left beer cans and other debris

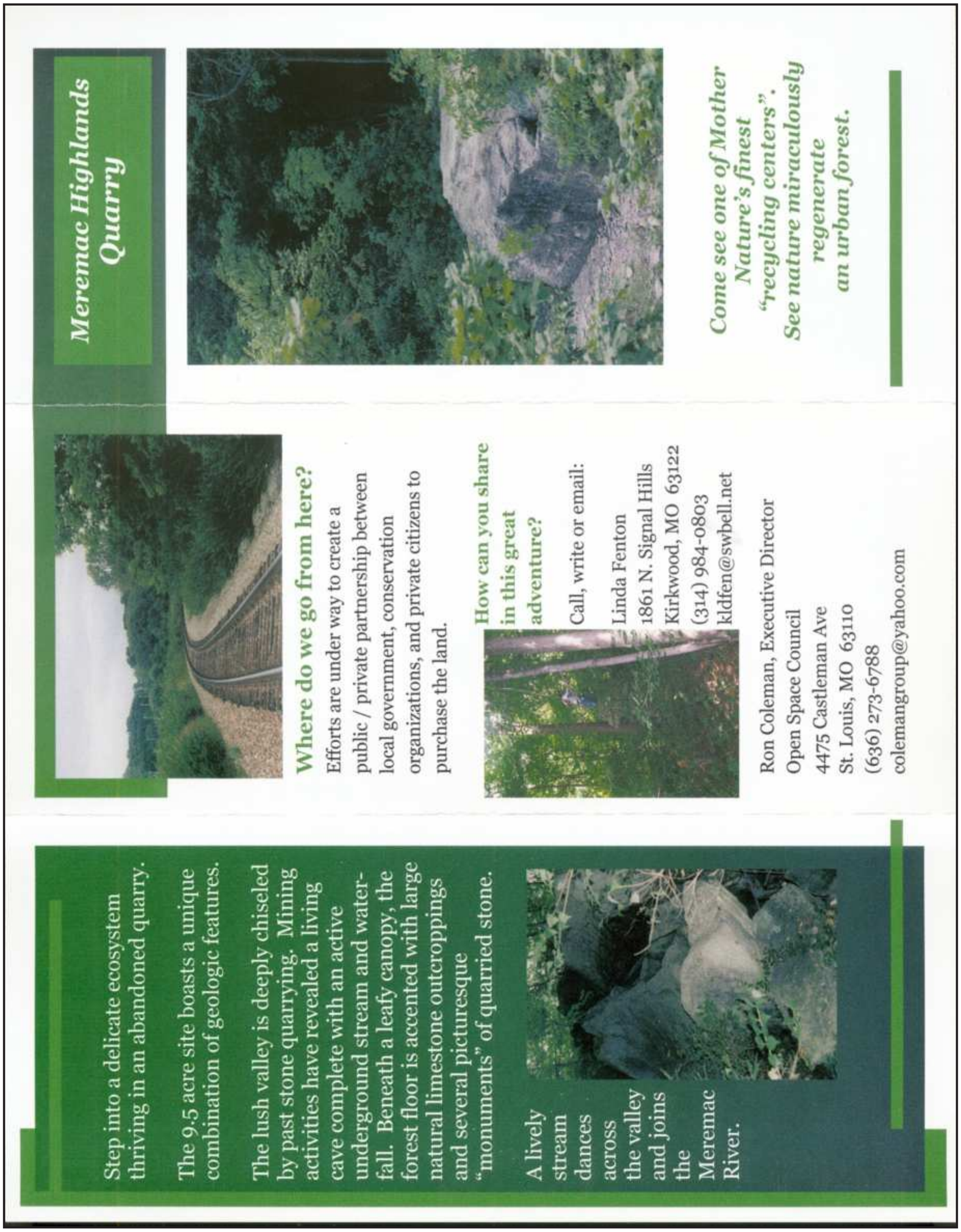

Figure 6 Brochure issued by Linda Fenton and the Open Space Council to encourage the formation of a public-private partnership.

down a passage so small a cave rescue would prove most difficult. Fenton, the local chapter of the Audubon Society, and the Webster Groves Nature Study group made extensive bird and botanical lists on the property. The property begged for preservation as a nature study area because of its essentially wild return to nature, including its use as a wildlife refuge.

Finding the Money

After the developer's attempt at rezoning failed, Fenton turned her efforts towards raising the money necessary to buy the property for conservation. Almost immediately, a neighbor put up $40,000 in a matching grant challenge, but this was a mere 8% of the fair appraised value of the half-million dollars generally expected for the property. The Kirkwood Parks Board was interested in the property, as it was one of the few remaining "wild" parcels in the city limits, but they did not have the funding. Even though Signal Hill and the adjacent community had come together to fight the zoning change, they were not too keen on the property becoming an attractive nuisance as a public park, either because of the infrastructure needed to make it one, or the additional traffic. Many of the same issues that were used to fight the housing complex were issues of concern to the nearby residents.

Fenton consulted Ron Coleman, and they envisioned a public-private partnership where private nature study groups, and some public grant-funding would preserve the land, but still control outside access. Brochures were printed up to pursue this idea, but funding was slow in coming, as were negotiations with the Koesterings, who believed that with public funding would come increased public access and an end to their solitude.

In August 2001, Mrs. Dee Koestering took a turn for the worse, and passed away on August 21. Reportedly, she told her husband to sell the property to the city before she died. Within a few weeks after her passing he offered not only the quarry, but also the 0.6-ha (1.55-ac.) tract containing his home to the City of Kirkwood for Dee Koestering Park at Meramec Highlands Quarry (Watkins 2003).

It took until November 15 for a final deal to be struck with Mr. Koestering, and another year for preliminary assessment and basic access to the park before it could be opened to the public. Although the exact breakdown of funding for the park was available to me, just under half ($207,000) of the $575,000 purchase price came from a Federal Land and Water Conservation Grant administered by the

Figure 7 The author with interpretive geological panels at the overlook shelter

Figure 8 The trail in the park is the same path picnickers have used for a hundred years.

Missouri Department of Natural Resources for the preservation of parklands and green space (City of Kirkwood 2003, National Park Service 2003).

Conclusion

Dee Koestering Park is managed as a nature study area, and will never be "manicured" into a typical city park. Access to the park is limited to ten parking spaces at the entrance. Only those with disabilities or explicit special permission are allowed to drive down the steep, one-lane road to the inner lot. A sheltered overlook of the quarry with historical and geological interpretive panels has been erected using private funds along a paved, handicapped-accessible trail.

Those hiking into the quarry and along the creek are following the old beaten trails established by a century of informal use. Watson Cave is now gated, access is controlled through application to the Kirkwood Parks Board. The preservation of this significant site including Watson Cave would not have been possible without the cooperation of the owners, the drive of the neighbors in wishing to preserve nature, the input from the cavers in furnishing data and the involvement of both government and nongovernmental conservation groups and conservation-minded citizens.

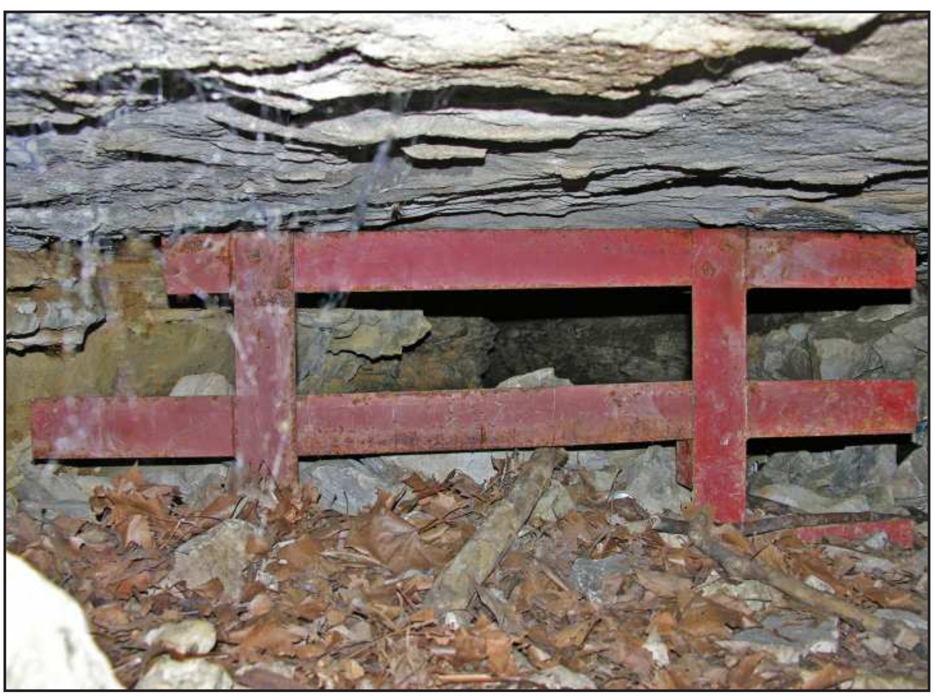

Figure 9 Watson Cave is now properly gated.

Acknowledgments

I am grateful for much information that came from discussions with Tom Clifton, Linda Fenton, Jerry Vineyard, and Murray Pounds, Kirkwood Parks and Recreation Director. Tom Clifton

also provided a folder containing correspondence and contemporary news clippings intended to inform Meramec Valley Grotto, as well as papers gathered for his disposition before the Kirkwood Planning and Zoning Commission. My knowledge of the park is from personal involvement in 2000–2001 as a member of Meramec Valley Grotto, and in 2004 when I was professionally involved to make geological interpretive panels and teachers' hand-out materials for the park. Thanks again to Tom Clifton and Linda Fenton for that opportunity.

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DETECTION PROBABILITIES OF KARST INVERTEBRATES

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Abstract

Protection of federally listed endangered troglobites in central Texas focuses on caves that are occupied by the species. The determination of occupancy is based on presence/absence surveys for those taxa. Under current U.S. Fish and Wildlife Service recommendations, three surveys are used as a standard to determine presence or absence, and certain environmental and seasonal conditions must be met.

We used survey data from 23 caves on Camp Bullis Military Reservation, Bexar County, Texas to test the validity of the survey protocols. Presence/absence matrices were created for three cave species, *Batrisodes uncicornis*, *Chinquipellobunus madlae,* and *Rhadine exilis*. Eleven environmental and seasonal covariates that have been suggested to affect detection probability were tested for fit to the detection data. *B. uncicornis* and *R. exilis* were determined to have constant detection probabilities of 0.1226 and 0.1875. *C. madlae* was found to have a survey specific detection probability (average $p = 0.2424$), and in no case was detectability tied to any of the measured covariates. Parametric bootstrapping was used to simulate the number of surveys needed to have a 5% chance of not detecting the species if they were present at the site. The number of surveys needed ranged from 10 to 22.

These results indicate that more surveys should be performed before determining absence from a site. The results also indicate that most of the time cave species are not available to be surveyed, and we hypothesize that they retreat into humanly inaccessible cracks connected to the cave.

Key words: cave ecology, cave management, endangered species, invertebrates, beetles, harvestmen, detection probability, Camp Bullis, Texas

Introduction

Detection probability (p), or detectability, is the chance that a karst invertebrate will be observed if the cave is occupied by that species. In order for a species to be observed it must be both available (e.g. not hiding in a humanly inaccessible crack) and seen by the researcher. Occupancy (Ψ) is the proportion of sites that are occupied, or the proportion of areas where the species is present. Failure to take into account detection probabilities when using species counts can lead to underestimating cave occupancy, since nondetections in survey data do not necessarily mean that a species is absent unless the probability of detection is one (MacKenzie et al. 2002, Bailey et al. 2004). If the probability of detection is less than one, then surveys should be designed to account for imperfect detection.

Cave organisms are small and live in an environment that is difficult to sample because of constricted crawlways, vertical drops, low oxygen levels, and an abundance of mesocaverns, or tiny cracks and voids connected to the cave, but inaccessible to humans. For the 16 species of federally-listed, terrestrial, karst invertebrates in central Texas, recovery is based on protecting habitat around caves known to contain the species, therefore estimating occupancy of caves is of paramount importance. Monitoring the populations in these caves and conducting surveys in new caves are listed as key components to the recovery strategy (USFWS 1994).

The U.S. Fish and Wildlife Service (2006) provides survey recommendations for these taxa and detail that permitted surveyors must have several years of experience with these or similar species under a permit holder. During the three surveys required to ascertain presence or absence of a species in a cave, certain environmental and seasonal conditions must be met. Thus far these conditions (number of visits, season, temperature, recent rain) have been determined based on nonquantified observations by researchers balanced with an estimation of observer impact on the environment (James Reddell and USFWS Bexar County Karst Invertebrate Recovery Team, pers. comm.).

Since newly found caves are rapidly being impacted by development, and the data from early counts of karst invertebrates are being relied upon for guidance of preserve designs, it is imminently important to estimate the utility of the recommended survey protocol with confidence. The focus of this study is to determine the detection probabilities for several terrestrial karst invertebrates, to assess whether certain environmental parameters affect detectability, and to use detectability to determine the number of surveys required to be confident in a determination of absence from a site.

Materials and Methods

Study sites. Caves on Camp Bullis Military Reservation, Bexar County, Texas were used for this study, and the raw dataset along with detailed information about each site is reported in George Veni and Associates (2006). Cave sites were subdivided into zones, and these individual zones are the survey units. Surveys were conducted three times per year, during the spring (May), summer (July 15 – August 15), and fall (October). These started in the fall of 2003 and included spring 2007, for a total of eleven sample events. Prior studies have used this method (Elliott 1994) and it is consistent with U.S. Fish and Wildlife Service endangered species survey recommendations (2006).

Detection probabilities, occupancy and number of surveys. The program PRESENCE (Proteus Wildlife Research Consultants, Dunedin, New Zealand) includes mark-recapture models modified by MacKenzie et al. (2002) for use with presence-absence data. It was used to analyze the fit of several models to the dataset. The first test was to determine whether our dataset, which included multiple years and seasons, could be considered "closed" during the period of the surveys, fall 2003 to spring 2007. "Closure" means the cave zone did not experience a change in occupancy by the species during the time interval of surveys, and it is an assumption of the occupancy models (MacKenzie et al. 2002). To determine closure three models were compared. The first model considered the detection probability as specific to each survey event, the second as specific to each season, and the third as constant across all survey events. The models were compared using Akaike's Information Criterion (AIC) and AIC weights (Burnham and Anderson 2002). Once the assumption of closure was validated, detection probabilities were modeled as either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates discussed below.

After model-selection analysis, we determined the number of surveys needed to have a 5% chance of not detecting the species at sites where they are present, based on estimated probabilities of detection. For the harvestman, *C. madlae*, we found that detectability varied with each survey. Therefore, we conducted a parametric, bootstrapping simulation obtaining 1,000 pseudosamples (Manly 1997). We used the formula

$$\prod_{i=1}^{s} (1-p_i),$$

where Π_i is the detection probability of the "ith" survey, *p* is the detection probability on survey *i* and *s* is the number of surveys (Jackson et al. 2006). For *Batrisodes uncicornis* and *Rhadine exilis*, whose detectability was constant across surveys, the calculations were based on the simpler formula

$$1-(1-p)^s,$$

where *p* is the detection probability and *s* is the number of surveys performed (formula 6.1 in MacKenzie et al. 2006). Simulations for each different number of surveys (2, 4, 6, etc.) were performed using the statistical software **R**, and consisted of 1,000 bootstrapped samples produced with a parametric and not a nonparametric bootstrapping algorithm. Then for each different number of surveys, the mean probability of failing to detect the species was calculated.

Covariates. Detection probabilities were modeled as either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates. Of these eleven covariates, four were unique to each cave site and seven were unique to each sample event. They were chosen based on personal observation, interviews with local cave biologists (James Reddell, Peter Sprouse), USFWS recommendations (2006), and other research (Schneider and Culver 2004). Site covariates included cave length, cave depth, size of floor search area, and size of wall search area. Seven sample covariates changed with each event and included four continuous variables: search time, in-cave temperature, in-cave relative humidity and surface air temperature. The remainder corresponded with USFWS survey recommendations and consisted of a yes/no determination for falling within the recommended surface temperature range, recommended sampling season and a recent rain event.

Species. *Batrisodes uncicornis* is a troglophile (not restricted to caves, but can spend entire life cycle in a cave), and an eyed pselaphid beetle (Figure 1) that occurs in caves throughout central Texas. This species is not endangered, but it is closely related to endangered *Texamaurops reddelli* and *B. texanus*. It is known to occur in nine caves containing 21 zones that were sampled 11 times.

Figure 1 Batrisodes uncicornis*, a tiny (2 mm), troglophilic beetle, from B-52 Cave, Bexar County, Texas.*

Chinquipellobunus madlae is a troglobitic (restricted to caves) harvestman (Figure 2) that occurs in caves throughout central Texas. This species is not endangered, but it is related to endangered *Texella cokendolpheri, T. reyesi,* and *T. reddelli* harvestmen. *C. madlae* is known to occur in 22 caves containing 61 zones that were sampled 11 times.

Figure 2 Chinquipellobunus madlae*, a troglobitic harvestman (2-3 cm), from Flying Buzzworm Cave, Bexar County, Texas.*

Rhadine exilis is a federally-listed, troglobitic carabid beetle (Figure 3) restricted to Bexar County, Texas. Survey results were used from 23 caves subdivided into 65 zones with 11 sample events.

Figure 3 Rhadine exilis*, an endangered, troglobitic, ground beetle (1-1.5 cm), from Banzai Mud Dauber Cave, Bexar County, Texas.*

Results

The assumption of closure was met for all taxa, indicating that species do not colonize a site or become extinct from a site within the study period. Lower AIC values indicated the data for *B. unci-cornis* were most consistent with constant detection probabilities and the data for the other two species varied by survey rather than being seasonal or constant. After closure was met, data from all years were used to test whether detection probabilities were either constant among surveys, specific to individual surveys, or influenced by one of eleven covariates. Of the three species, *C. madlae* was the only dataset found to have a clear best model, which was that the detectability was different for every survey. For *C. madlae*, the varying values of *p* allowed us to create 95% confidence intervals (Figure 4).

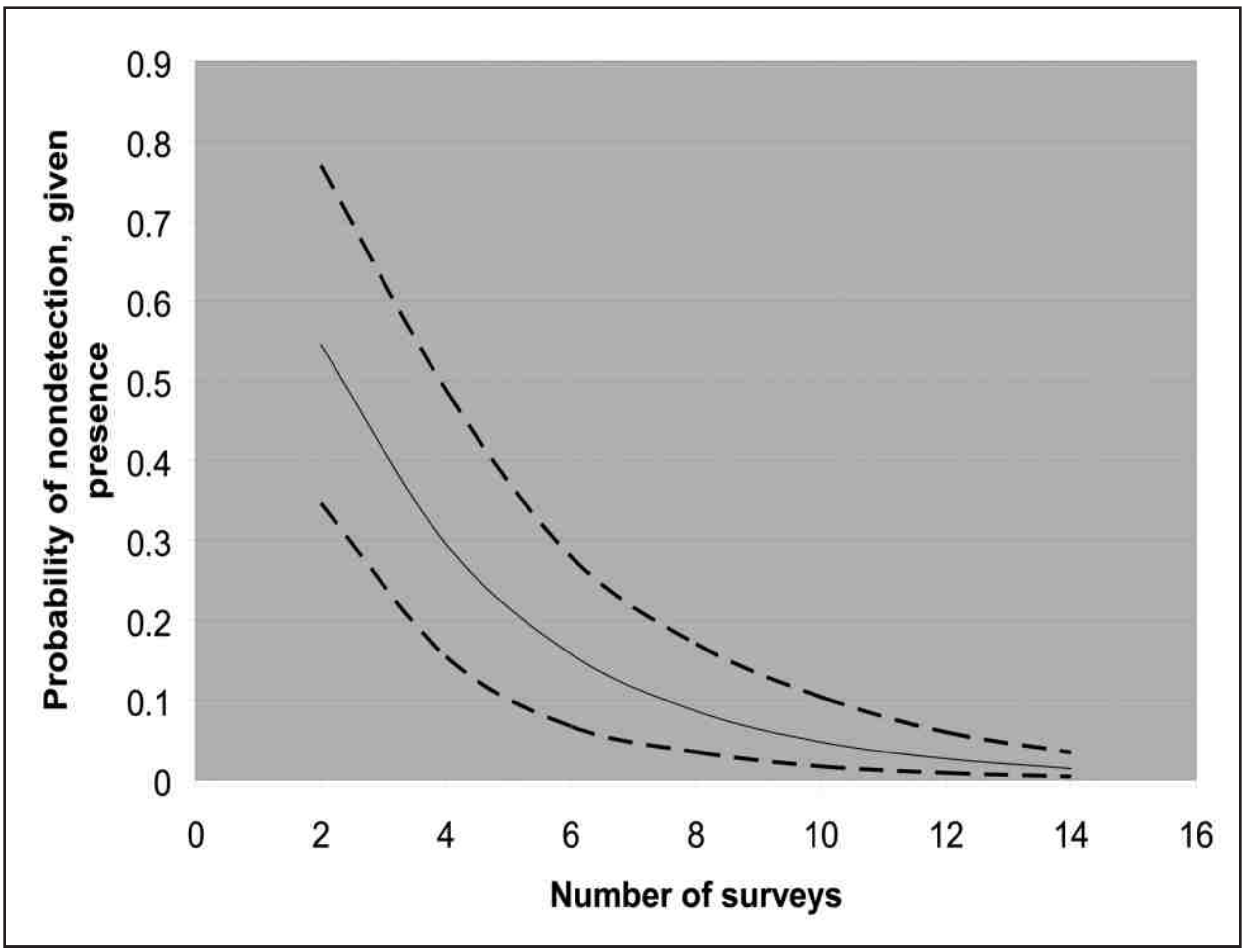

Figure 4 *Simulations using the survey-specific detection probabilities measured for C. madlae show that more surveys decrease the probability that this species will not be detected at sites where they are present. Upper and lower 95% confidence intervals are shown as dashed lines. These findings suggest that 10-12 surveys are needed to be 95% confident that C. madlae are absent from a surveyed site.*

Detection probabilities ranged from 0.0595 to 0.3769, with a mean of 0.2424, standard error of 0.0943 and coefficient of variation of 0.3887. The proportion of sites occupied (Ψ) was 0.85 with a standard error of 0.06. The other two species had several models that rose above the rest, but were not distinct enough to choose between, and in those cases the most parsimonious of the higher-ranking models, constant probability of detection, was chosen. In the case of *B. uncicornis*, the constant detection probability was 0.1226, the proportion of sites occupied (Ψ) was 0.45 with a standard error of 0.16. In the case of *R. exilis*, the constant detection probability was 0.1875, the proportion of sites occupied (Ψ) was 0.71 with a standard error of 0.07.

Parametric bootstrapping yielded the following recommended number of surveys for *B. uncicornis*—22, *C. madlae—10-12*, and *R. exilis*—14. These are the recommended number of surveys to conduct to reduce the probability of nondetection, given presence, to 5%.

Discussion

Many caves are surveyed to determine whether they are occupied by rare and endangered troglobites, and several researchers have examined accumulation curves and patterns of species richness in karst areas of West Virginia and Slovenia (Culver et al. 2004, Schneider and Culver 2004). These studies focused on determining the number of cave species in a region and how many caves would have to be sampled to obtain an accurate estimate of species richness for the area rather than for a single cave. Results included a lack of asymptotes or plateaus in species accumulation curves, with one explanation being that repeated visits are often necessary to collect all of the species found in a single cave (Schneider and Culver 2004). Culver et al. (2004) give an example of a new taxon being found after six visits, and two examples of new taxa being found after >100 visits to a cave. In the instance of Lakeline Cave, Williamson County, Texas, at least 45 biological surveys have been performed by experienced cave biologists of the entire cave (approximately 23 m long), and on approximately the 40th visit a new species of troglobitic pseudoscorpion was found. Clearly some species are commonly not available or not detected, however prior to this work no researchers have attempted to calculate detection probabilities or estimate the number of visits required to a single cave to find a troglobite.

The detection probabilities calculated herein suggest that modifications should be made to recommended survey techniques to confidently estimate occupancy. Even in taxa that are large and easy to see (*C. madlae*, Figure 2), in our analysis of caves where they are known to occur, the proportion of sites occupied was 0.85 and the detection probability averaged only 0.24. With 10-12 visits recommended to confidently determine absence for this taxon, many more should be required of smaller, slower-moving and more inconspicuous troglobites such as *Texella* species.

Suggestions about appropriate sampling conditions for cave fauna come from qualitative observations by cave biologists, and in Texas have generally included seasonal and weather conditions that are thought to make the interior of these shallow caves more favorable for finding cave species. In our lengthy list of possible covariates, however, none clearly demonstrated an association with detectability of these species. For one of three taxa, detectability definitively varied with each survey event, indifferent of all the covariates tested. For the other two taxa, the distinction was less clear and confounded by a small number of detections in the matrix of observation events. Patterns of species detections appear irregular, and more work needs to be done both on the environment and experimentally on the species to determine if the environmental variables we measure during these studies are actually related to detection probability. For example, dataloggers in caves can demonstrate if seasonal, temperature, or rainfall variation on the surface is reflected in the cave environment at different endangered species localities. The other critical component is to use experimental manipulation of the taxa to determine if they respond to the magnitude of changes that actually occur within the cave.

When the species analyzed herein are not available, the most obvious hypothesis is that they retreat into inaccessible cracks that are connected to the cave. These spaces, called mesocaverns (or sometimes called epikarst, voids, or unenterable caves), should then be considered a priority for conservation. Presently management focuses on caves and surface habitat immediately surrounding caves. Cave entrances and the surrounding surface area are important because they provide a nutrient source for cave ecosystems, but this suggests that a greater area of karst that is connected to caves may be where the species often reside. Knapp and Fong (1999) also concluded that the stygobites they studied occur primarily in a larger area of epikarst that is connected to the cave pools they could access, and considered the pools a small window into that habitat.

Acknowledgments

Jackie Schlatter (Chief of Natural and Cultural Resources, Ft. Sam Houston, Texas) provided permission to use the dataset from Camp Bullis Military Reservation and coordination of the funding to collect the data. George Veni (George Veni & Associates) was the principal investigator and coordinator for all the research at Camp Bullis during the time these data were collected, and he always encouraged analyses to further the knowledge of these little-studied systems. Cyndee Watson (USFWS) was involved in the project conception and provided many useful suggestions throughout the duration of the project. Rob Myers assisted with review and revisions of a draft version. James Reddell (Texas Memorial Museum) and Peter Sprouse (Zara Environmental LLC) provided suggestions of covariates to test. Kellie Cowan (Zara Environmental LLC) spent countless hours extracting and arranging the data for input into PRESENCE. William R. Elliott started monitoring cave species in central Texas and provided the framework for future research. Many people were involved in the in-cave data collection, including USFWS karst invertebrate permit holders Andy Gluesenkamp, Rob Myers, James Reddell, Marcelino Reyes, Peter Sprouse, Bev Shade and George Veni, and their observations and dedication created the large dataset used in this project, and that will certainly be used for years to come. Funding for the analysis and this report was provided by Texas Parks and Wildlife through the Endangered Species Act, Section 6 grant program of the U.S. Fish and Wildlife Service. In particular, Craig Farquhar (TPWD) did an outstanding job taking care of the administration of these funds. Matching funds and general support of the author were provided by Zara Environmental LLC and Texas State University.

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SUPERIOR KARST STEWARDSHIP THROUGH SUPERIOR DATA MANAGEMENT: THE KARST INFORMATION PORTAL

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Abstract

Effective stewardship of caves and karst areas requires access to and efficient analysis of a diverse range of information. Vital data are scattered throughout specialty mainstream journals, which even for a single project could include fields such as ecology, hydrogeology, contaminant transport, toxicology, engineering geology and law. Additionally, volumes of crucial information often lie in difficult-to-find gray literature. Management recommendations and decisions should be based on assessments of state-of-the-art information, but fall short when important patterns and relationships are overlooked.

The Karst Information Portal (KIP) offers a solution to these problems. Conceived in 2005 and launched in June 2007, KIP grew as a partnership among the International Union of Speleology, National Cave and Karst Research Institute, University of New Mexico, and University of South Florida. Key features complete or in development include:

- Federated searches of Web sites for more efficient and reliable location of key research papers and information,
- A searchable database of multidisciplinary karst information,
- A library of on-line karst papers, reports and theses,
- A collaborative international on-line workspace to post and evaluate images, maps, databases, and other published and unpublished information.

Like other virtual research portals, KIP will continue to grow as existing and future partners contribute information by plugging Web sites and databases into the network. KIP will not duplicate existing databases but will more efficiently access and process them with superior tools. Additional partners can help fulfill

KIP's potential in revolutionizing cave and karst stewardship through advanced and collaborative integration of data and ideas.

Key words: web-based karst information, bibliographies, databases, on-line literature, cave management

Introduction

The stewardship of karst areas and resources is a complex, multi-disciplinary task. Species management often depends on both broad and specific ecosystem and hydrological analyses. Protection of karst water quality and contaminant remediation can require understanding of intricate chemical reactions and biological attenuation processes, and the delineation of drainage basins and convoluted flow paths. Archeological materials require sensitivity to diverse cultural concerns. The potential for paleontologically significant deposits is evaluated relative to geological and other factors. Constructed management structures are engineered to preserve natural conditions despite occasional conflicting needs and on a landscape of uncertain stability. This all occurs concurrently relative to available information, human and resource needs, and impacts in surface, subsurface and legal/legislative environments.

Ultimately, successful stewardship depends in large part on access to karst-specific data and knowledge. This knowledge might come in the form of published scholarly articles, unpublished government or technical reports, cavers' maps and notes, or even oral histories. Regardless of form, much of the existing knowledge of karst resources is fragmented and scattered all over the world, in particular, important cave information is often maintained by amateur speleological clubs that may lack the resources or the inclination to make that data available to the wider karst community. Unless this knowledge can be integrated and linked, issues of environmental degradation related to karst will be difficult to address without significant duplication of effort.

The Karst Information Portal (KIP)—a joint project of the University of South Florida libraries, the National Cave and Karst Research Institute, the University of New Mexico, and the Union Internationale de Spéléologie (UIS), with significant support from the Dr. Kiran C. Patel Center for Global Solutions at the University of South Florida—was developed and implemented with the intent of addressing this problem. KIP is aggressively acquiring karst-related content, with an emphasis on gray literature and raw data that have historically proved to be difficult for researchers to locate and access.

What Is KIP?

Conceived in 2005 and rolled out in mid-2007, KIP's goal is to foster the integration of karst knowledge by providing a comprehensive, community-driven central repository of this knowledge, including gray literature, raw data, and published journal articles. It is both a web portal, in that it provides connections and links to information and data available elsewhere on the World Wide Web, and a database, in that it stores some data locally, which can then be downloaded by portal users. Researchers and community members contribute content to KIP's catalog via a browser-based form, they can also share information regarding events, deadlines, and current research between themselves. As of November 2007, KIP's catalog contained over 4,000 items, including journal articles, reports, abstracts, databases and bibliographic data.

This "one-stop" approach to information access has at least two immediately apparent benefits. First, it facilitates research by providing access to the existing body of karst literature, including the oft-elusive gray literature. Second, it ensures long-term electronic access to these information resources. Additionally, formerly catastrophic events, such as a library fire or flood, no longer pose the threat of depriving the karst community access to information stored on a library shelf.

How KIP Works

KIP (http://www.karstportal.org) is a browser-based, platform-independent application with a design goal of facilitating open access to quality karst-related information. Everything from the user interface to the underlying database has been organized in a way to make it easy for users to both discover and contribute information. Navigation within the portal is conducted via a series of tabs, each providing access to a different content group, and is facilitated by static links in the footer:

- The ***About*** tab contains a listing of project partners and an array of project documentation, including brochures and user manuals. The content displayed here is largely static.
- The ***News*** tab contains announcements of upcoming karst-related events, new publications on cave and karst science, and important research updates. These items are updated as they are forwarded to KIP administrators. Users can subscribe to an RSS feed (**R**eally **S**imple **S**yndication) that will deliver updates to them as they are made.
- The ***Resources*** tab contains the "information core" of the entire KIP project. This is where users may access the catalog, which contains databases, theses and dissertations, maps/GIS information, cave and trip reports, technical reports, images, periodicals, oral histories, proceedings and abstracts, among other items. Ultimately, KIP's goal is for most portal users to actively participate by contributing work or raw data to the catalog, where it can be readily accessed by other members of the cave and karst science community. All items contributed by users must first be vetted by KIP administrators, in order to guarantee that each item in the catalog meets or exceeds a minimum level of relevance to the karst community at large. Users also have direct access to current and archived content for several online karst-related publications, including *Speleogenesis*, *Journal of Cave and Karst Studies* and *Acta Carsologica*, among others.
- The ***Community*** tab provides access to features that are intended to build personal and professional linkages among members of the cave and karst communities. Most notably, users can use the ***Forum*** to initiate and participate in conversation threads on a wide range of karst-related topics. The Forum is open to all registered users of KIP.

KIP provides several methods for information search and retrieval. Most pages feature a context-sensitive "sidebar" that offers a list of related links. Additionally, items in the catalog are assigned tags to facilitate one-click searches for related items in the catalog. KIP also incorporates a powerful search utility that enables users to conduct federated (simultaneous multiple-source) searches of the entire portal, or to conduct a more focused search within a particular section of the portal (i.e., the catalog, the forum, or news). Searches for information outside the KIP are customized to focus on karst-related Web sites to maximize the likely relevance of the results. Searches may also be refined based on geographic location, document type, language of resource, or the inclusion of specific terms based on UIS Speleological Subject Classifications.

Most items stored locally on KIP servers are recent (i.e., generally less than ten years old). This is due in large part to the fact that many older resources have never been digitized. In cases where copyright issues can be successfully negotiated, older resources will be scanned and uploaded to the portal catalog, certainly, copyright holders can hasten this process by scanning and uploading the resources themselves. Several digitization projects are either in progress or under consideration, including digitizing back issues of the *NSS News*.

Users are strongly encouraged to register with KIP, a process that can be completed from the portal's main page. While it is not mandatory to register in order to access information within KIP, registration brings with it the ability to contribute to the collection and to participate in the community-based features of the portal. KIP managers consider the portal's collaborative and community-building aspects to be among its most important features, as more and more users register, these features will become more robust.

KIP's Collaborative, International Nature

KIP's collaborative nature and international reach make feasible its goals of a centralized access point to karst information and developing broad connections between people within the karst community. Several projects driven by or associated with KIP draw upon its collaborative features. Examples follow:

- The Karst Oral History project is a series of interviews, conducted with prominent figures in the world of cave and karst studies, which are transcribed and posted to the portal along with the raw audio recordings. The purpose of this project is to preserve the experiences and observations of major figures in the cave and karst community, in their own words, so that future students of karst might be able to benefit from them. As of November 2007, four oral histories have been conducted: Jeanne Gurnee, Dr. William Halliday, Dr. Alexander Klimchouk, and a joint interview of Drs. Elizabeth and William White.

- The Scanning Electron Micrograph (SEM) database contains over a thousand SEM images. This project was created by DSpaceUNM to collect and index SEM images of microbial organisms and related structures and make them available for international collaborative review and study. Interested researchers are able to examine all of the metadata, comment, and post their own images.
- Currently in the planning stages, the Great Karst Trail is an effort to build an online trail system in which users contribute locations of trails in karst areas worldwide. This system will also be interactive, as each trail segment will be assigned links to research articles, images, or any other relevant information. The Great Karst Trail will also incorporate a *wiki* (a web-page-generating database that can be expanded and edited by users), designed to permit KIP users to comment on or refine information about the trails contained therein.

The Role of KIP in Cave and Karst Management

Cave management is only one segment of the larger karst community, the broader focus of KIP reflects that diversity. Given that, cave and karst managers might wonder how KIP can help advance the level of knowledge and understanding within their discipline.

First, the number of items in the catalog that address management-related issues is growing steadily. As of November 2007, searching the word "management" in the KIP catalog returned 217 records, a search on the phrase "cave management" returned 51 hits, while 28 records were returned for a search on the phrase "management plan." In many cases, direct access to these resources is available. When direct access is not available, each record returned provides bibliographic information for the resource in question, so the KIP user may locate it on his or her own. Examples of directly-accessible, management-themed resources within KIP include an examination of bat hibernacula in the karst of central Manitoba (Bliecki 2003), discussion of cave protection in national parks (Kerbo 2002), changing management perspectives at Carlsbad Caverns National Park (Burger and Pate 2001), the role of GIS technology in cave management (Olson 2001), and New Zealand's federal karst management guidelines (New Zealand Dept. of Conservation 1999). This is not a comprehensive listing of directly-accessible resources, but a representative, random sample of cave-management-related resources within KIP. The number of government publications, journal articles, conference proceedings and theses and dissertations addressing management issues is growing steadily as word about KIP gets out among the karst community. In particular, the KIP management team is hoping to increase the number of conference proceedings stored in or accessible from the portal. Proceedings can be notoriously difficult to access online. Currently KIP is in the process of adding proceedings from the National Cave and Karst Management Symposium (NCKMS): as of May 2008, materials from the 1999 through 2005 NCKMS proceedings are available directly through the portal.

Second, the diversity of karst-related information contained within KIP is often indirectly relevant to cave management issues. Karst systems are not closed systems, for that reason, cave management issues do not exist in isolation. In addition to the cave management-specific information available, KIP brings together an array of literature and data from other branches of karst research that can shed light on management-related issues (for example, land use in karstic terrains).

Finally, KIP works to facilitate information sharing and to open lines of discussion among the cave and karst management and science community, regardless of where users are located. Because KIP works across international boundaries, there is no reason that the international nature of cave information should continue to pose significant challenges to researchers. KIP also provides one-stop access to all types of cave and karst management information: examples currently contained in KIP include theoretical ideas of resource management, up-to-date first-hand knowledge of cave systems (extent, conditions, location, etc), and examples of existing approaches to cave management in diverse areas throughout the world.

Conclusions

KIP is an international, collaborative, browser-based tool linking karst researchers and cave enthusiasts with data, information and each other. Its benefit to cave management professionals is threefold: it provides access to management-specific information, to other related information that can help facilitate the growth and development of new ideas and approaches, and to other professionals who may be able to provide insight into solving the problems and challenges of cave management.

Put simply, KIP's ultimate contribution to cave management studies are to make it easier to determine what works, what does not work, and what might work by providing a centralized tool with which to mine the past experience of an entire community of experts. However, as with any collaboration-based project, the overall effectiveness of KIP as a tool to accomplish this significantly depends on the participation of the cave and karst community, through the content it will provide.

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ABSTRACT: SEASONAL VARIATION OF STABLE CARBON ISOTOPES IN CENTRAL MISSOURI CAVE WATERS

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Analysis of stable isotopes and major ions in cave waters in Central Missouri was performed to identify processes that may affect the use of stable carbon isotopes in speleothems as a paleoclimate proxy. Preliminary analysis discovered significant seasonal variation of carbon-13 $\delta^{13}C_{DIC}$ in cave streams, rimstone pools, and drip water. Variation in the amplitude of $\delta^{13}C_{DIC}$ appears to be constrained by the number of cave entrances and cave entrance proximity. Seasonal variations in carbonate growth of speleothems coupled with changes in cave entrance geometry could have significant impacts on interpretations of stable isotope signatures found in speleothems and resulting paleoclimate models.

ABSTRACT: A DECADE OF PALEOCLIMATOLOGICAL STUDIES IN CREVICE CAVE, MISSOURI

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Crevice Cave in Perry County, Missouri is a world-class site for paleoclimatological studies. The cave contains a wide assortment of speleothems, many broken by natural processes, which are useful in reconstructing past variations in temperature, vegetation, seasonality, and flooding. The time frame of possible inquiry extends back from present for nearly 400,000 years, with resolution varying from centuries to seasons depending on the proxy and technique being utilized. The chronology of the speleothem record is established by high-precision U/Th dating. Highlights of the paleoclimatic record in Crevice Cave include:

- The first explicit demonstration of replication of stable isotope profiles among multiple speleothems.
- An outstanding carbon isotope history during past interglacial/glacial cycles that shows the response of mid-continental vegetation to changes in global climate.

- Detailed oxygen isotope variations during the last glacial period that can be rigorously compared to ice core records from Greenland.
- Development of a new proxy for flooding, obtained from sediment laminae preserved in stalagmites.

ABSTRACT: SPELEOGENOMICS: A PROPOSAL

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The many ways in which cryptobiotic (*sensu* Peck 1990) species have adapted to become light-deprived biota of crevices, caverns, caves and karst arguably count as prime manifestations of the body-plan-molding-power of the evolutionary process. Troglobitic species represent the extreme end of multiple independent solutions to conquering adaptive challenges, such as readjusting water-content regulation to constant humidity and enhancing the sensitivity of tactile and olfactory senses for successful search of food and prey. Much attention has been paid to such species by comparative morphology and physiology. These disciplines recently have been complemented with comparative developmental genetics. Seminal studies in the Mexican cavefish *Astyanax* revealed a surprising trade-off in the development of sensory over visual primordia (Yamamoto et al. 2003). The recent analysis of the genome of the cryptobiotic red flour beetle, *Tribolium castaneum*, unraveled an unexpectedly drastic reduction of visual receptor genes correlated with massive expansion of genes encoding olfactory and gustatory receptors (Consortium). These findings expose dramatic gene regulatory and genomic consequences that can come along with cryptobiotic adaption.

How general is genomic trade-off between visual and olfactory genes in cryptozoic species? Which changes in the genetic control of development are responsible for the often-observed reduction or loss of visual organs? These questions can now be comprehensively addressed by comparative genome sequencing. As sequencing technology continues to become increasingly more affordable, the thesis is posed that the time has come to study cryptobiotic organisms by comparative genomics. Advancing the resulting field of "speleogenomics" would critically depend on the expertise of the speleological community. Understanding the uniqueness of troglobite genomes in turn is likely to stimulate ecological research and to enhance public understanding for conservation efforts.

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Abstract: Karst Collapse in Missouri: Geology and Risk Assessment

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Over 170 karst collapses were documented by the Missouri Department of Natural Resources between 1970 and 2007. A significant number of the collapses occurred in populated areas and several resulted in loss of property. Historically, several sewage lagoons have failed by karst collapse resulting in significant groundwater contamination. The Missouri Department of Natural Resources evaluates karst collapse potential based on a combination of eight factors. Geospatial analysis and geologic investigations of collapse settings in Missouri indicate the current evaluation technique is only marginally adequate and is most applicable in the Salem Plateau province. A new evaluation technique has been developed based on geologic setting in combination with other factors and is the basis for new collapse potential maps.

Abstract: Recent Advances in Bat Gates

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Recent changes to bat-friendly, low-airflow-loss cave gates have made them easier to build, more secure, and have enabled the construction of gates in locations once considered ungateable.

Abstract: Fecal Bacterial Contamination of a Karst Watershed in Central Missouri

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The Bonne Femme watershed of Boone County, Missouri, has a varied surface geology that includes karst topography with losing streams that are an especially vulnerable setting for groundwater contamination. The study objective was to compare fecal contamination and detection of specific, pathogenic, water-borne bacteria within the major subwatersheds, and relate this contamination to land use and hydrology. Ten subwatersheds were sampled weekly, for one month per quarter-calendar year since 2003 for fecal coliforms, *E. coli*, enterohemorrhagic *E. coli* O157:H7, *Salmonella*, and *Shigella*. Fecal coliform and *E. coli* enumerations were done by the membrane filtration techniques, and pathogen-specific analyses were performed through culture enrichment of water samples followed by DNA extraction of bacterial growth and PCR using pathogen-specific primers. Under low-flow conditions, fecal coliforms and *E. Coli* levels were typically less than 1000 cfu/100 mL, but many sites exceeded state and federal whole body contact limits in the second and third quarters of the year. Under high flow conditions, most sites exceed 10,000 cfu/100 mL, and whole body contact limits were always exceeded. *Salmonella* and *Shigella* were detected in at least two streams in each quarter of 2005 and 2006; *E. coli* O157:H7 was detected in at least one stream each quarter since second quarter 2005. In general, fecal bacterial contamination was significantly correlated to stream discharge and time of year, but it was not significantly correlated to land cover or to physico-chemical properties of the stream water within the subwatersheds. Site-specific causes explained the observed levels at the three sites with the highest fecal bacterial contamination.

Abstract: What, If Anything, Is a Cave?

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A point of great sensitivity and often controversy among cavers is the dissemination of cave entrance locations. When a caver asks "Where is the cave?" they generally mean "Where is the cave entrance?" This shorthand expression can lead to serious miscommunication and friction between cavers and land managers.

Land managers or agency personnel who have responsibility for cave resources and protection will often ask cavers for cave locations. The land managers need to know primarily where the appropriate management unit is located, which almost always is a much larger area than an entrance. Everyone tends to use the word cave, but almost no one actually is referring to a cave as such. Good relations and trust among cavers and government and nongovernmental organizations can be much better fostered with the use of more precise language and using the sharing of less sensitive management unit information, such as recharge areas, as a starting point for building trust.

ABSTRACT: MANAGING PALEONTOLOGICAL RESOURCES IN CAVES

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Caves typically contain a wealth of paleontological resources that hold important clues to past climates and ecosystems. These resources range from invertebrate and vertebrate remains to animal trackways, and from dung deposits to speleothems. Unfortunately these irreplaceable resources often go unrecognized and thus management protocols are generally lacking. The first step in managing such cave resources is assessment and inventory. This involves a survey to recognize and identify these resources, a photographic record of each site, and a map with accompanying notes that pinpoint and discuss the localities. The second step is sampling and advanced assessment of known sites. This is a continuation of the first step but requires a more advanced research component to establish the overall significance of the localities. This research often includes sampling, salvage of fossil remains, and follow-up laboratory work. The third and final step in the management process is monitoring and protecting the known localities. To better demonstrate the significance of paleontological resources in caves, and the importance of their management, we provide examples from Powder Mill Creek Cave, a well-known system managed by the Missouri Department of Conservation.

ABSTRACT: "CAVES: LIFE BENEATH THE FOREST"

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While caves prove to be fascinating for the brave of heart, the harsh conditions in them can make their recesses difficult and uncomfortable for many people to explore. As a result, it is unlikely that significant numbers of our public will ever have a chance to see the remarkable adaptations that life has made to survive in this inhospitable environment. This education initiative is geared at educating and engaging children, as well as adults, about the intriguing life forms that exist in the remarkable karst topography that stretches across the United Stated.

But, how do you get the public excited about the array of bizarre creatures living in caves, especially millipedes, spiders, and isopods? The Hoosier National Forest, Indiana Karst Conservancy and National Speleological Society sponsored a cave biology documentary/webumentary produced by Ravenswood Media of Chicago, Illinois, "Caves: Life Beneath the Forest." The goal of this program is to emphasize the importance of cave conservation by giving the general public a chance to see creatures that they will likely never encounter on their own. By engaging the public, the sponsors hope to instill in them an appreciation for caves and cave species.

To help get the word out, showings of the film are given across the country, and it is being worked into various education and outreach programs such as Project Underground (next page). A special showing of this video was presented during the poster session at this Symposium.

For more information on the production, including various clips and availability, see http://www.caves.org

ABSTRACT: KARST AND CAVE STEWARDSHIP: AN EXPLORATION OF CURRENT AND FUTURE EDUCATIONAL AND RESEARCH NEEDS

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Karst is a landscape characterized by disappearing streams, sinkholes, and subsurface drainage, often in the form of caves; although, not all caves are found in karst environments. Once a rural environment, it has increasingly become

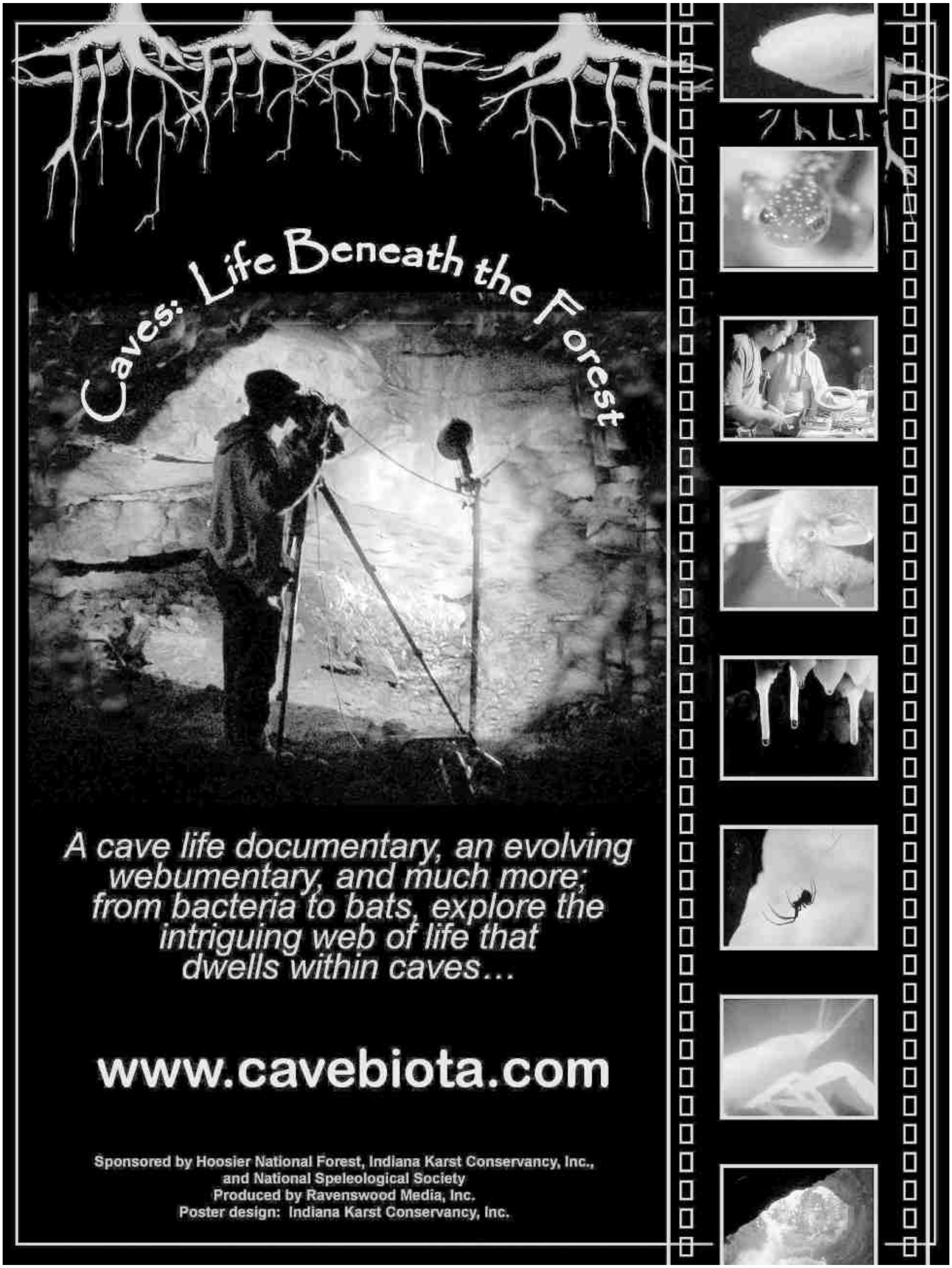

Figure 1 *Poster for "Caves: Life Beneath the Forest."*

associated with suburban and urban needs and environments. Throughout the world, karst and cave concerns include water access, pollution transport, tourism, and research, yet few land managers and policy makers understand what karst is. Worldwide, karst and cave education is extremely limited, and only two universities have established well-developed cave and karst programs. The lack of understanding about karst and caves stewardship results in lack of understanding of educational needs and even research funding. Karst and cave stewardship requires a multi-disciplinary approach as well as local, national, and international cooperation.

ABSTRACT: THE POTENTIAL EXTENT OF THE JEWEL CAVE SYSTEM

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With over 217 km (135 mi.) mapped, Jewel Cave is currently the second longest cave in the world. Research has shown a direct relationship between airflow at the entrance and the prevailing atmospheric pressure. Herb Conn used this barometric airflow to estimate a total minimum volume of 113 million m^3 (4 billion $ft.^3$), or 6,400 km (4,000 mi.) of average-sized cave, only 3–4% of which is presently documented.

This study estimates the extent of still-undiscovered portions of the cave system based on the following existing information: 1) thickness and distribution of the Madison limestone, 2) potentiometric surface of the Madison aquifer, 3) location and extent of potential geological obstacles, 4) the three-dimensional distribution of Wind Cave and Jewel Cave within the host rock, and 5) the "cave density" at Wind Cave and Jewel Cave.

The resulting geospatial model delineates the maximum geographic extents of the two caves. Most of Jewel Cave's volume extends toward Wind Cave, and vice versa. The overall cave-to-limestone ratio is well within the range of known "cave density" values for each cave. These data support the possibility that the two volumes could be part of a single large cave system, but a physical air trace is needed to prove an air connection.

Outlining the potential extent of the proposed Wind/Jewel cave system is a valuable tool for resource protection. It strengthens the rationale for adaptive surface use, pursuit of land purchases and exchanges and good-neighbor relationships.

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