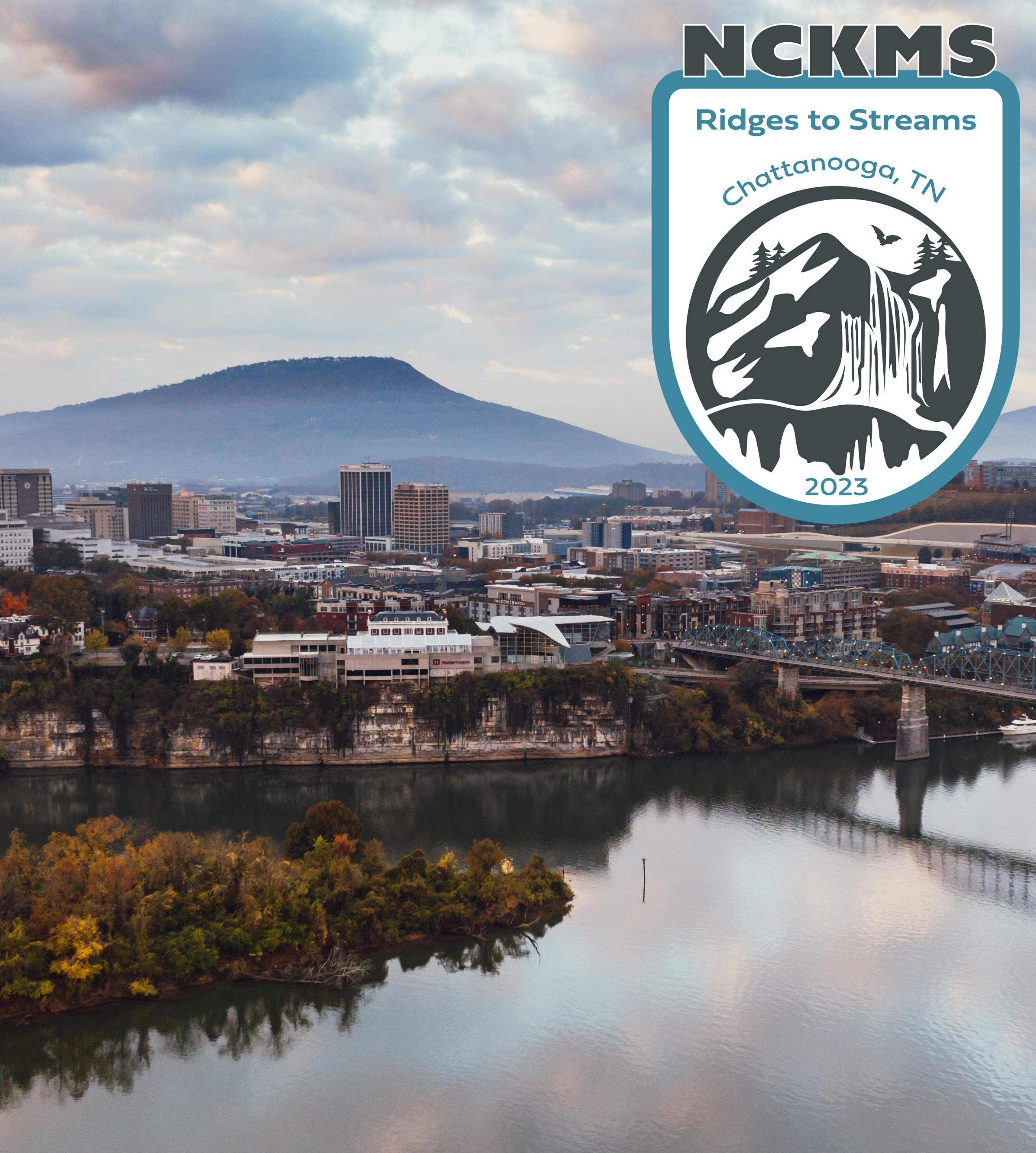

NCKMS

Ridges to Streams

Chattanooga, TN

2023

25th National Cave and Karst Management Symposium Proceedings

6 –10 November 2023 — Chattanooga, Tennessee

National Cave and Karst Management Symposium

Proceedings of the Twenty-Fifth Symposium

NCKMS: Ridges to Streams

November 6 - 10, 2023

Chattanooga, Tennessee

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Front Cover: The City of Chattanooga showing the Tennessee River and the northern end of Lookout Mountain. Photo courtesy of the Chattanooga Tourism Company.

Back Cover: Various scenes at the Symposium. Photos by Dave Jackson, Kyle Lassiter, Meredith Weberg, and Eugene Vale

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Foreword

Welcome to Chattanooga and the 2023 NCKMS

On behalf of Southeastern Cave Conservancy, Inc., we are excited to be hosting the 2023 National Cave and Karst Management Symposium in Chattanooga. We have an exciting and educational week planned and are greatful to our presenters who are the backbone of what makes NCKMS so valuable. Thanks to Kyle Lassiter and Ben Miller for working so hard to solicit and organize the presentations into six sections. Outside the presentation hall, you will experience a variety of what the Chattanooga and tri-state areas offer. Ben is not only leading a dye tracing workshop but will be leading the Northern Tier field trip. Matt Niemiller will lead the Southern Tier field trip and is also our banquet speaker on Thursday night. We are all looking forward to our evening social programs at Oddstory Brewery, Outdoor Chattanooga, and Ruby Falls on Lookout Mountain. In addition to your registration, the Symposium is supported through the generosity of our co-sponsors. Several have displays in the meeting area, so please stop by and thank them for supporting NCKMS. Emily P. Davis has done a great job of communicating with our individual, corporate, and nonprofit co-sponsors.

Emily is also helping lead the Speleothem Repair workshop with Val Hildreth-Werker on Wednesday. SCCi Office Manager Courtney Parker has been working behind the scenes to make things happen and assisted with arranging the venues and caterers.

We are so glad to see you, and enjoy the week!

John L Hickman
Chair, 2023 National Cave and Karst Management Symposium

NCKMS 2023 Host

Southeastern Cave Conservancy, Inc.

NCKMS 2023 Staff

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Emily P. Davis	Organizing Committee Co-chair & Sponsorships
Kyle Lassiter	SCCi Chair & Program Co-chair
Ben Miller	Program Co-chair, Field trip Leader & Workshop Leader
Courtney Parker	SCCi Office Manager, Logistics & More
Matt Niemiller	Field Trip Leader & Banquet Speaker
Brian Ham	Field Trip Leader & Workshop Leader
Val Hildreth-Werker	Speleothem Repair Workshop
Chrissy Richards	Field Trip Driver
Katie Miller	Field Trip Driver
Jason Richards	Field Trip Cameo Cave Diver
Makaria Doggett	Field Trip Assistant
Kris Green	Field Trip Assistant
Ray Knott	SCCi Executive Director & Registration Volunteer
Buck Meyer	Registration Volunteer
Patty Springer	Registration Volunteer
Bill Stringfellow	Registration
Amber Lehmann	Logo Design
Chattanooga Grotto Members	Monday Meet-and-Greet Social Hosts
Session Chairs:	Ben Miller, Hydrology of Karst Landscapes
	Steve Samoray, Bats and WNS Panel Discussion
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	Jerry Lewis, Cave and Karst Biological Studies
	Amy Hourigan, Education and Karst Studies

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Limaris Soto	U.S. Forestry Service
Dave Foster	American Cave Conservation Association
Ben Miller	U.S. Geological Survey

Workshops

Workshop 1: Sustainable Tourism Solutions in Cave and Karst Biosphere Reserves

Webinar presented by CaveMAB Network

Facilitated by Lee Anne Bledsoe (Western Kentucky University)

Workshop 2: Dye Tracing Workshop

This workshop will be a full day workshop which will cover the basics of groundwater tracing in karst systems using fluorescent dyes. The morning will consist of a series of lectures and presentations detailing the methods and materials utilized in karst groundwater tracing. Additionally, several case studies will be discussed which will help to understand how these techniques may be applied to different karst systems to help both map karst groundwater flowpaths and delineate recharge areas for springs and caves. The class will transition to the field in the afternoon to a nearby karst area where the techniques discussed in the morning will be applied. The field component will require participants to hike on potentially steep terrain in areas lacking trails and through forested areas with potentially thick vegetation. Each participant should wear proper field clothing and should bring a small pack with water, food, and a field notebook.

Led by Ben Miller (U.S. Geological Survey) and Brian Ham
(Tennessee Department of Environment and Conservation)

Workshop 3: Tour of Tennessee Aquarium Conservation Institute and presentation on research in Key Cave, Alabama on Alabama Cavefish and undescribed Cave Shrimp and two rare Cave Crayfishes.

The warm waters of the southeastern United States are home to an amazing diversity of animals and habitats. The Tennessee Aquarium Conservation Institute, TNACI, works to protect and sustain the region's natural treasures and bring people of all ages closer to nature. Help us celebrate and care for these riches in our backyards. The Instiute is currently working with two legal NGOs on trying to get Key Cave National Wildlife Refuge to better manage the recharge area for Key Cave, the only home to the Alabama Cavefish, and one of only two caves in the United States with two species of Cavefishes (also Southern Cavefish). Also, home to a new undescribed Cave Shrimp and two rare Cave Crayfishes (Alabama and Phantom). Will include a PowerPoint to show all of the cool photos of these wonderous critters.

Led by Staff of the Tennessee Aquarium Conservation Institute

Field Trips

Trip 1: Southern Tier Cave & Karst

Trip Leader: Matt Niemiller

Synopsis: Attendees will visit four unique caves along the Tennessee Valley in Alabama. Sites include Sauta Cave, managed by the USFWS; Cathedral Caverns, managed by the Alabama Department of Conservation and Natural Resources; Stephens Gap Preserve, managed by the SCCi; and Russell Cave, managed by the NPS. Each sites takes a different method on how to manage its resource. Representative from the managing organizations will speak to strategies, and Dr. Niemiller will include interested biological features at each site.

Trip 2 : Northern Tier Cave & Karst

Trip Leaders: Ben Miller and Brian Ham

Synopsis: Travelling through the Cumberland Plateau of Middle Tennessee, attendees will visit both Karst features and caves. Sites include Jasper Big Spring, source of the Town of Jasper water supply; Big Mouth and Big Room Caves, operated as The Caverns concert venue and commercial cave; Grundy Big Spring, major tributary to the Collins River; and Cumberland Caverns, one of Tennessee's longest caves operated as a commercial cave. Differing management methods will be discussed as well as unique geological and hydrological features of each.

Trip 3: Speleothem Repair Workshop

Trip Leaders: Val Hildreth-Werker and Emily P. Davis

Synopsis: The workshop will consist of a brief classroom session at the hotel, followed by in-cave repair at a nearby cave. The main formation area where the workshop will take place is dry, walking borehole, so only basic caving equipment is needed.

Oral Presentations

Hydrology of Karst Landscapes Session

Chair: Ben Miller

Karst Research Synergy in Tennessee

Ham, Brian[1]; Miller, Ben[2]

[1] Tennessee Department of Environment and Conservation, 312 Rosa Parks Boulevard, 11th Floor, Nashville, Tennessee

[2] Ben Miller, United States Geological Survey, 640 Grassmere Park, Suite 100, Nashville, Tennessee

Abstract

Two recent projects between Tennessee Department of Environment and Conservation and the United States Geological Survey have focused on karst research to protect areas of high conservation value and springs used as a drinking water source. Dye tracing has been conducted in 7 communities across TN to delineate groundwater recharge areas for these karst springs that serve as a source for public water systems. This information will be used to assess and potentially modify source water protection areas for these springs. Additionally, GIS analysis is being conducted to identify areas of high karst conservation value. Dye tracing is also being conducted in these high resource value areas to better understand groundwater flow hydrology and help inform management of these lands. A summary of dye tracing results and the path for the next five years will be presented.

Identifying Contributing Areas for Tennessee Community Drinking-Water Springs with Dye Tracing

Hourigan, Amy M.[1]; Miller, Benjamin V.[1]; Ham, Brian[2]

[1] United States Geological Survey, 640 Grassmere Park, Ste. 100 Nashville, Tennessee 37211
[2] Tennessee Department of Environment and Conservation, 312 Rosa L. Parks Avenue, 11th Floor, Nashville Tennessee 37243

Abstract

Karst aquifers and springs are important drinking-water resources in Tennessee. Sixty-six community and non-community public water systems within the state use springs as a water source. These groundwater systems are characterized by rapid recharge from the surface with little to no filtration, resulting in high susceptibility to contamination. Additionally, contributing areas and groundwater flow paths are unpredictable in karst landscapes. To protect these resources, public water systems are required to identify the area that contributes to the water supply and delineate a source water protection area (SWPA). SWPAs are boundaries for contributing areas that are often estimated, rather than determined by a formal study. The U.S. Geological Survey (USGS), in partnership with Tennessee Department of Conservation (TDEC), is investigating contributing areas to karst springs, particularly those used as sources of drinking water. Potential vulnerabilities within the systems were evaluated based upon maturity of karst development, underlying geology, and uncertainties related to estimated contributing areas. Since fall 2021, seven communities have been a part of this five-year project. Fluorescent dye traces were conducted in late 2021 in Cowan, Jasper, Vanleer, and Woodbury, with Caryville, Lafayette, and Morristown added in 2023. These investigations have revealed contributing areas, both inside and outside current SWPAs and identified hydrologic interaction between topographically separate basins. Results from these studies provide public water systems with information to help better manage their drinking water resources.

A Comparative Sudy of Mesh and Filter Fabric Charcoal Receptors for Fluorescent Dye Detection

Bledsoe, Lee Anne[1]; Veith, Gracie[1]; Singer, Autumn[1]; Arpin, Sarah M.[2]; Tobin, Benjamin W.[2]; Hemenover, Will[1]

Crawford Hydrology Laboratory, Department of Earth, Environmental and Atmospheric Sciences, Western Kentucky University, Bowling Green, KY 42101

Kentucky Geological Survey, University of Kentucky, 228 Mining and Mineral Resources Building, Lexington, KY 40506

ABSTRACT

Fluorescent dye detection using activated charcoal has been common practice in groundwater tracing for over 40 years. Charcoal receptors are typically constructed with fiberglass mesh screening for maximum charcoal surface area contact. More recently, filter fiber 'milk socks' are being used under the assumption that there is no influence on dye detection. Experiments by Crawford Hydrology Lab (CHL) and the Kentucky Geological Survey (KGS) found no considerable difference in dye concentrations between the two in a controlled setting. In tracer studies however, charcoal receptors are exposed to uncontrolled variables. Milk socks can reduce removal of charcoal dust interference, may unfavorably provide a more stable substrate for sediment and biota, and are designed for warm liquids in high flow conditions. Prior field tests using exclusively milk socks revealed potential implications to tracer studies.To assess potential differences, CHL conducted two multi-dye tracer tests. Mesh bag and milk sock receptors were deployed simultaneously along known or anticipated flow paths. Qualitative results show higher dye concentrations on charcoal deployed in mesh bags in 82% of the samples, with 51% exhibiting concentrations more than double that found in milk socks. There was no difference in overall interpretation of tracer test results between mesh and milk sock receptors. However, there were three samples where positive detections for Tinopal were missed by the milk socks in relatively low flow conditions. While milk socks offer field researchers a cost and time-effective option, receptors should be pre-rinsed for reduced charcoal fluorescence interference and caution should be used in dye selection when tracing in low flow conditions.

INTRODUCTION

Groundwater tracing using fluorescent dyes relies on adsorption of the fluorescent tracer onto the surface of activated coconut charcoal. Charcoal receptors are passive, cumulative sampling devices used to determine groundwater flow direction and estimated time of travel by establishing a point-to-point hydrologic connection. Simply put, results indicate either that dye is present on the charcoal or it is not (non-detect). This qualitative method was developed in the early 1970s primarily for investigating karst aquifers where groundwater flow regimes are decoupled from surface topography and cannot be easily modeled or predicted. Fluorescent dyes are introduced into an aquifer via natural features such as sinkholes, swallets or cave streams, or man-made features such as wells or soil pits. Charcoal receptors are deployed at down-gradient resurgence points (e.g., springs, wells, surface streams) to 'receive' or collect the dye(s).

Historically, charcoal receptors have been constructed of a 2-inch by 4-inch fiberglass screen packet loosely filled with 5-15 grams of activated coconut charcoal (Figure 1). Mesh was selected for maximum surface area contact with the water source being monitored. The packets, or receptors, are secured by either machine-sewn, heavy-duty, nylon thread, plastic cable ties, staples, metal wiring, heat-sealed, or some combination thereof (Currens 2013, Aley and Beeman 2015, CHL 2016, Ewers 2023). In the field, charcoal receptors are tethered to a weight and/or a stable bank-side feature and deployed to maintain position in stream or spring flow to avoid burial or sedimentation and deter biological activity.

In recent years, researchers began using filter fiber 'milk socks' manufactured for the dairy industry in place of mesh bags, citing the ease of receptor construction, and therefore lower cost, as well as increased durability in high velocity conditions. The milk socks are long tubes of non-woven, polyester material that can easily be cut into short sections and the tube ends stapled to create packets for charcoal receptors construction (Figure 1). However, the transition to milk socks assumes there is no dif-

Figure 1. Milk sock and mesh bag receptor pictured side-by-side at Blue Hole #1, Lost River Cave, Kentucky (left) and in KGS lab experiments (right).

ference or influence of receptor materials on dye detection despite the lack of comparative testing.

Mesh bags and milk sock receptors have each been used successfully in a variety of karst environments across numerous studies. Charcoal receptors that have not been rinsed or exposed to sufficient flow exhibit a fluorescence profile with peaks at approximately 500 nm and 560 nm, wavelengths that are close to or overlap with commonly used dyes, fluorescein and rhodamine WT respectively (Ewers 1994, Aley and Beeman 2015). When deploying receptors into monitoring wells or locations where very low flow conditions are expected, it is standard practice to pre-rinse receptors to remove the fine charcoal dust to avoid potential fluorescence interference but is not standard practice when monitoring karst features. During an external client study using exclusively milk sock receptors, CHL observed fluorescence profiles that resembled unrinsed or poorly rinsed charcoal. These observations raised initial concerns about charcoal interference when using milk sock receptors as well as milk sock performance in low flow conditions as not all dyes injected were recovered during that trace.

To investigate potential differences of receptor materials on dye recovery, CHL and KGS ran independent benchtop experiments exposing both mesh bag and milk sock receptors to known concentrations of fluorescein (Acid Yellow 73), eosine (Acid Red 87) and Rhodamine WT (Acid Red 388) dyes in deionized water solutions. Our hypothesis was that there would be no difference between the overall results (positive or non-detect) but that concentration values could vary between materials, between dyes, and/or between laboratories. A subsequent field test was conducted to assess how uncontrolled variables might affect dye recovery on milk socks versus mesh bags.

METHODS

Laboratory Experimental Design

Benchtop tests were conducted independently at both CHL and KGS, using similar but not identical experimental design and methodology. CHL, founded in 1979, is located on the main campus of Western Kentucky University in Bowling Green, Kentucky and follows protocols developed by Dr. Nicholas Crawford which have been subsequently enhanced over the years through additional research and improved instrumentation (CHL 2021). Likewise, KGS has been groundwater tracing since the mid-1980s, and their laboratory program developed under the direction of Jim Currens. Currens authored *Kentucky Geological Survey Procedures for Groundwater Tracing Using Fluorescent Dyes* (2013), an industry reference for fluorescent dye tracing. CHL and KGS laboratory methods and positive detection criteria are very similar and both labs agreed on minor sample processing differences as inconsequential in comparative testing a qualitative method. Those slight differences in CHL and KGS analytical methods are outlined in Table 1 below. These laboratory tests served as an initial assessment of potential differences of receptor materials on fluorescent dye detection in a controlled setting.

Crawford Hydrology Laboratory

Following standard CHL protocol, serial dilutions of fluorescein and rhodamine WT in deionized water were created at 0, 0.1, 1, 10, and 100 parts per billion (ppb) (CHL 2016). Solutions were analyzed to confirm target concentrations. Mesh bags were constructed of fiberglass screening, machine-sewn with heavy-duty nylon thread on three sides. Filter fabric milk sock tubes were cut in ~2.5-inch squares and one end stapled. Both types of receptors were then filled with six grams of activated coconut charcoal, stapled closed, and rinsed under a pressurized stream of deionized water until water ran clear of any visible charcoal dust, approximately 30-45 seconds. Each receptor was then individually placed in a 100 ml dye solution of known concentration (Figure 2). Receptors were fully submerged, and the solution agitated by swirling the containers five times in each direction. Receptors were stored in the dye solutions for seven days in the dark at room temperature. Both mesh bags and milk socks were then carefully removed from dye solutions and processed in normal CHL fashion (rinsed 30 seconds with tap water and oven dried overnight, Figure 2). Each receptor was split into three 2-gram subsamples during weighing, then eluted for 30 minutes using Smart Solution, a 5:2:3 mixture of n -propanol, ammonium hydroxide, and deionized water. Elution using a basic solution is necessary to desorb the dye the activated charcoal (Smart and Simpson 2002).

Samples (elutant consisting of dye and Smart solution) were analyzed for fluorescence using synchronous scanning on a Shimadzu RF-6000 Spectrofluorophotometer. CHL uses an excitation scan of 350-625 nm, a scan speed of 6,000 nm/min, excitation slit width 3.0 nm, and an emission slit width 5.0 nm. Sensitivity settings were modified pending dye intensity. LabSolutions software was used to calculate the area under the emission curve and identify the peak center wavelength (Figure 3). CHL criteria requires a peak center +/- 5nm from laboratory standards for positive confirmation of dye type. Dye concentrations are derived from a calibration curve based on emission peak area of known laboratory standards (*u*g of dye/liter of Smart solution). Results were entered into an Excel spreadsheet and quality checked before sharing with KGS collaborators for comparison.

Kentucky Geological Survey

Following the procedures of Currens (2013), KGS created dilutions of fluorescein, eosin, and rhodamine WT in deionized water with concentrations of 0, 1, 5, 10, 50, and 100 ppb. Mesh screening and milk sock filters were used to construct receptors

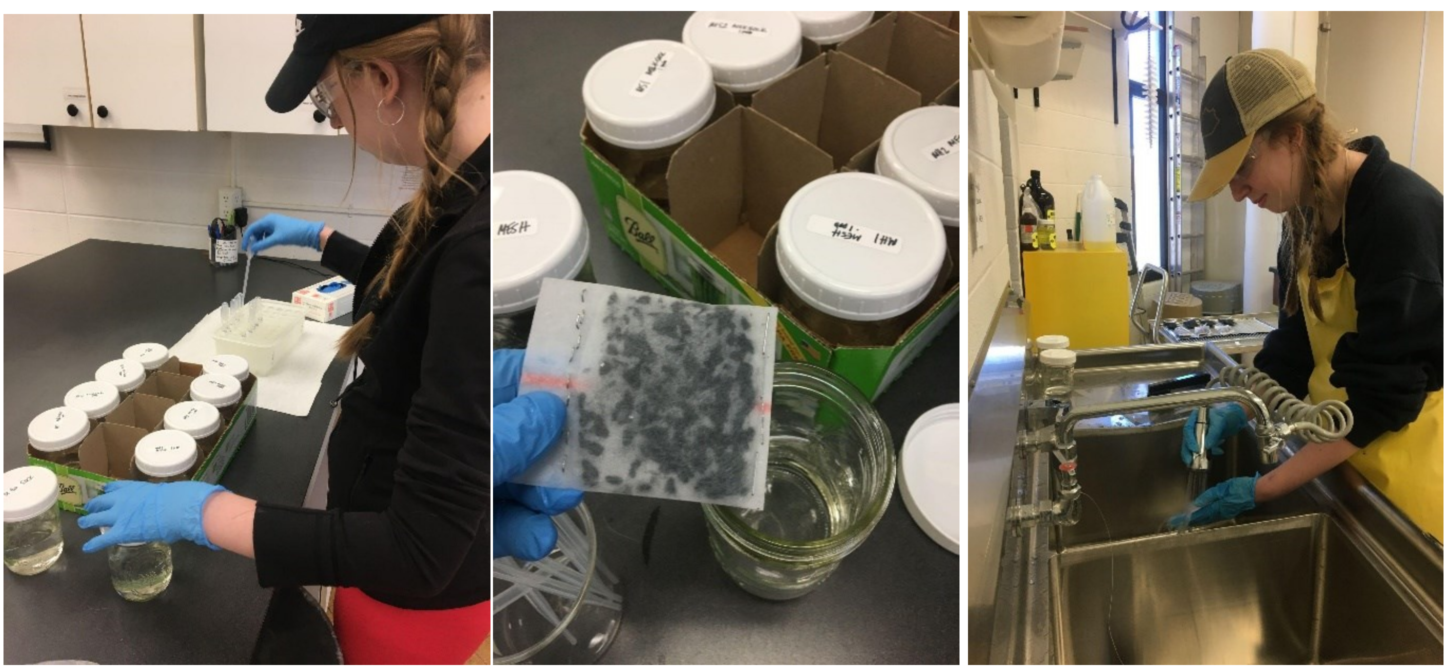

Figure 2. CHL preparation of mesh bag and milk sock receptors for benchtop testing.

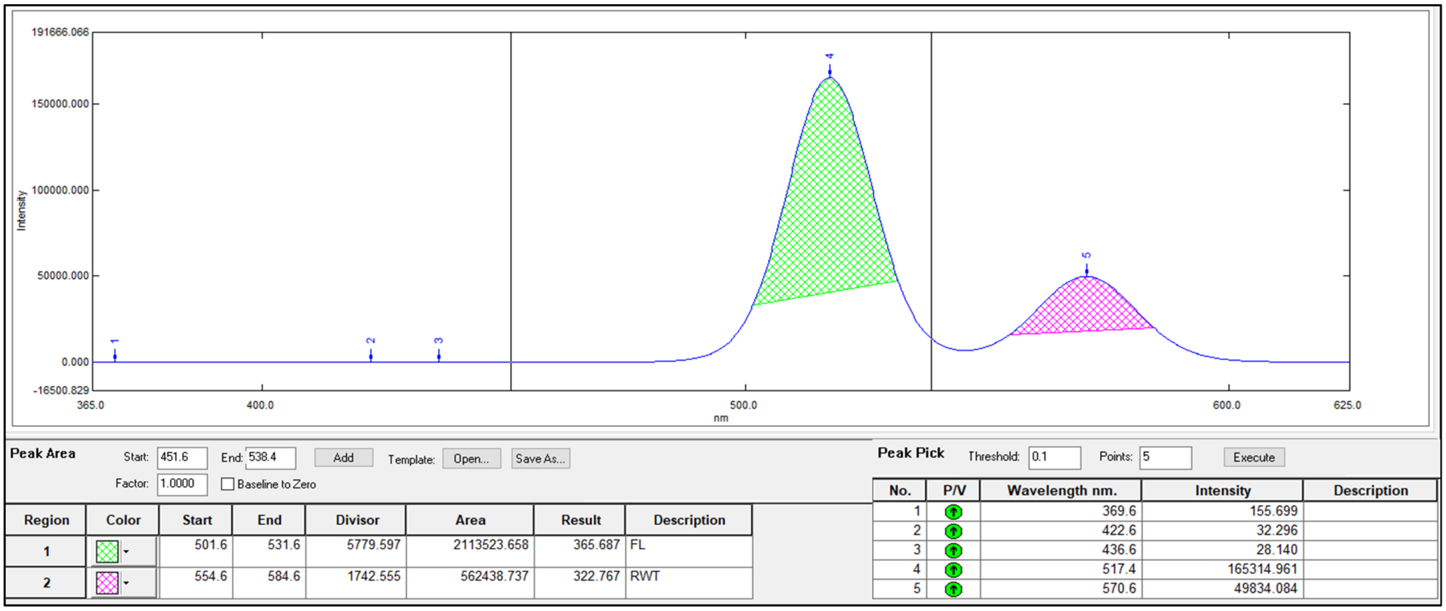

Figure 3. Data scan of mesh bag receptor showing fluorescein (FL) and rhodamine WT (RWT) emission curves. Table lower left of the figure shows calculated dye concentrations, lower right identifies peak center wavelengths and relative intensity.

of equal dimension, each containing 5 g of activated charcoal and secured with staples. Six pairs of receptors were placed in weighing trays (one per tray) with 45 mL of each standard and soaked for 18 hours. After the receptors were dried thoroughly (at least 48 hours), each was split into three 1.5-gram subsamples and transferred into a plastic cup and soaked in 3 mL of Smart Solution for 20 minutes. The elutant was then transferred to labeled cuvettes for analysis. The elutant was analyzed using Aligent Cary Eclipse spectrofluorophotometer. KGS uses a scan of 400-605 nm, a scan speed of 6,000 nm/min, excitation slit width 3.0 nm, and an emission slit width of 5.0 nm. KGS criteria requires a peak center +/- 5nm from laboratory standards for positive confirmation of dye type. Dye concentrations are derived from a calibration curve based on emission peak intensity of known laboratory standards (ug of dye/liter of deionized water). Results were entered into an Excel spreadsheet and quality checked before sharing with CHL collaborators for comparison.

In summary the differences in methodology for the benchtop tests included a variety of lab specific procedures (summarized in Table 1). These differences are known to cause different observed concentrations in dye but were assumed to not have an impact on the ability of each dye receptor material to adsorb the dyes.

Parameter	**CHL**	**KGS**
Spectrofluorophotometer	Shimadzu RF-6000	Aligent Cary Eclipse
Total amount of charcoal per receptor	6 g	5 g
Analysis temperature	30 C	Room temperature
Amount of charcoal eluted	2 g	1.5 g
Eluant soaking time	30 minutes	20 minutes
Dye standard base	Smart solution	Deionized water
Calibration curve	Fluorescent peak area	Fluorescent peak intensity
Dye soaking time	150 hours	18 hours

Table 1. *Summary of different lab methodologies between Crawford Hydrology Lab (CHL) and the Kentucky Geological Survey (KGS) for lab test..*

Tracer Test Design

Following laboratory testing, two separate multi-dye tracing efforts were undertaken by CHL; a repeat trace using fluorescein and rhodamine WT in the Lost River Basin, Bowling Green, Kentucky in early May 2023 and both in-cave and surface to spring tracing in Mammoth Cave National Park (MACA), Kentucky. In May and early June 2023, tinopal, eosine, and rhodamine WT were injected at locations in Great Onyx Cave proper, sulphorhodamine B at a sinking spring in the Great Onyx Basin, and fluorescein at a sinking spring in the Holton Hollow Basin (Figure 4). These locations were selected according to previously established point-to-point connections within each basin such that dye recovery at monitoring locations was certain and to expose receptors to a range of flow conditions and therefore a range of dye concentrations.

CHL has established protocols for the handling of dyes and materials during all stages of fieldwork activities to ensure that no fluorescence measured from the samples is attributable to any source aside from the introduced tracer. Appropriate personal protective equipment and engineered controls in sampling procedures reduce the potential for cross-contamination. Clean gloves were used to exchange receptors, which were placed into individually labeled zip-closure bags, stored in a cooler, and transported to the laboratory for processing and analysis.

The monitoring period for the multi-tracer test within the Lost River Basin was approximately two months, extending from late April to late June 2023 and included a total of four sample collection events at two monitoring locations. The tracer tests in the Great Onyx and Holton Hollow Basins occurred over a longer period since the project design included staggered injections. Post-injection sampling lasted approximately three months, beginning in early May, and concluding in early August 2023. Twenty-three sample pairs were collected during sampling efforts at Mammoth Cave across 10 locations.

Statistical Analysis

Benchtop Testing

Results of the benchtop experiments conducted by both CHL and KGS (Figure 5) were combined for statistical analysis in the program R (R Core Team, 2022) using the 'lme4' package (Bates et al., 2015). The dye concentration was used as a response variable in a mixed-effect regression model, and the material, concentration of the standard, and dye were used as predictors. The dye was included in models as both an additive and an interactive variable to account for potential effects of differing adsorption and mobility of each dye through the receptor material. Since laboratory methods were known to be different, 'lab' was incorporated as a random effect in the model. The concentration of the standard is a quantitative predictor; all other predictors were categorical.

Tracer Tests

Each mesh and milk sock receptor was split into triplicate samples and analyzed for all five dyes with the exception of the Lost River samples, as only fluorescein and rhodamine WT were introduced in that basin. There were thirty-one milk sock-mesh bag pairs collected during field testing. Each sample pair was considered per dye in these analyses, meaning one milk sock-mesh bag receptor set could produce five sample pairs (data points) if one or the other was positive for all five dyes.

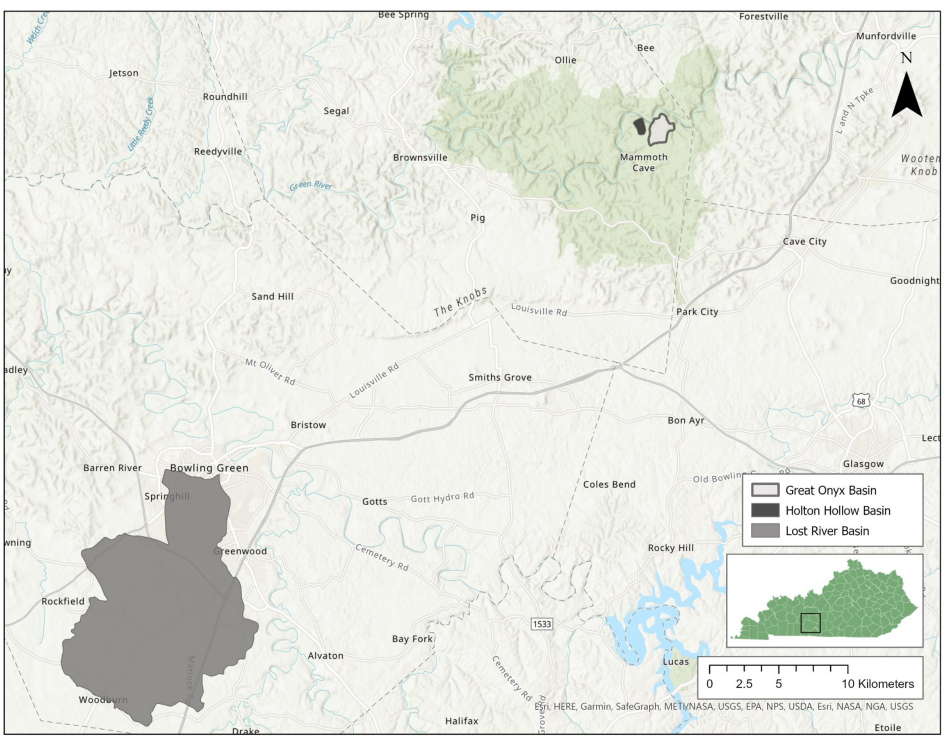

Figure 4. Map of study area with inset showing where in Kentucky the study area is located.

CHL criteria for positive detection identified 126 data pairs (results in triplicate) which were statistically analyzed in SigmaPlot 15.0. Descriptive statistics were explored and graphed for visual comparison of data range and mean. Raw and averaged data sets failed Shapiro-Wilk normality testing. Standard techniques to normalize data using log functions did not result in normal distribution either so the Mann-Whitney Rank Sum, a nonparametric test, was applied. This test does not require normality or equal variance but rather ranks all the observations from smallest to largest without regard to which group each observation comes from. The ranks for each group are then summed and the rank sums compared for statistical difference (Alsoft 2023).

RESULTS

Benchtop Testing

Mixed-effect modeling shows that the results of the laboratory analysis were driven entirely by the standard concentration of dye the receptors were soaked in ($p < 0.0001$). In a controlled laboratory setting, the receptor material, mesh or milk sock, does not affect the concentration of dye recovered (Figure 5). The type of dye also had no effect on the dye recovered.

All 126 data pairs (triplicate results for all five dyes) were statistically analyzed in SigmaPlot 15.0. Descriptive statistics and box plots are shown in Figure 6 and summarize all data collected.

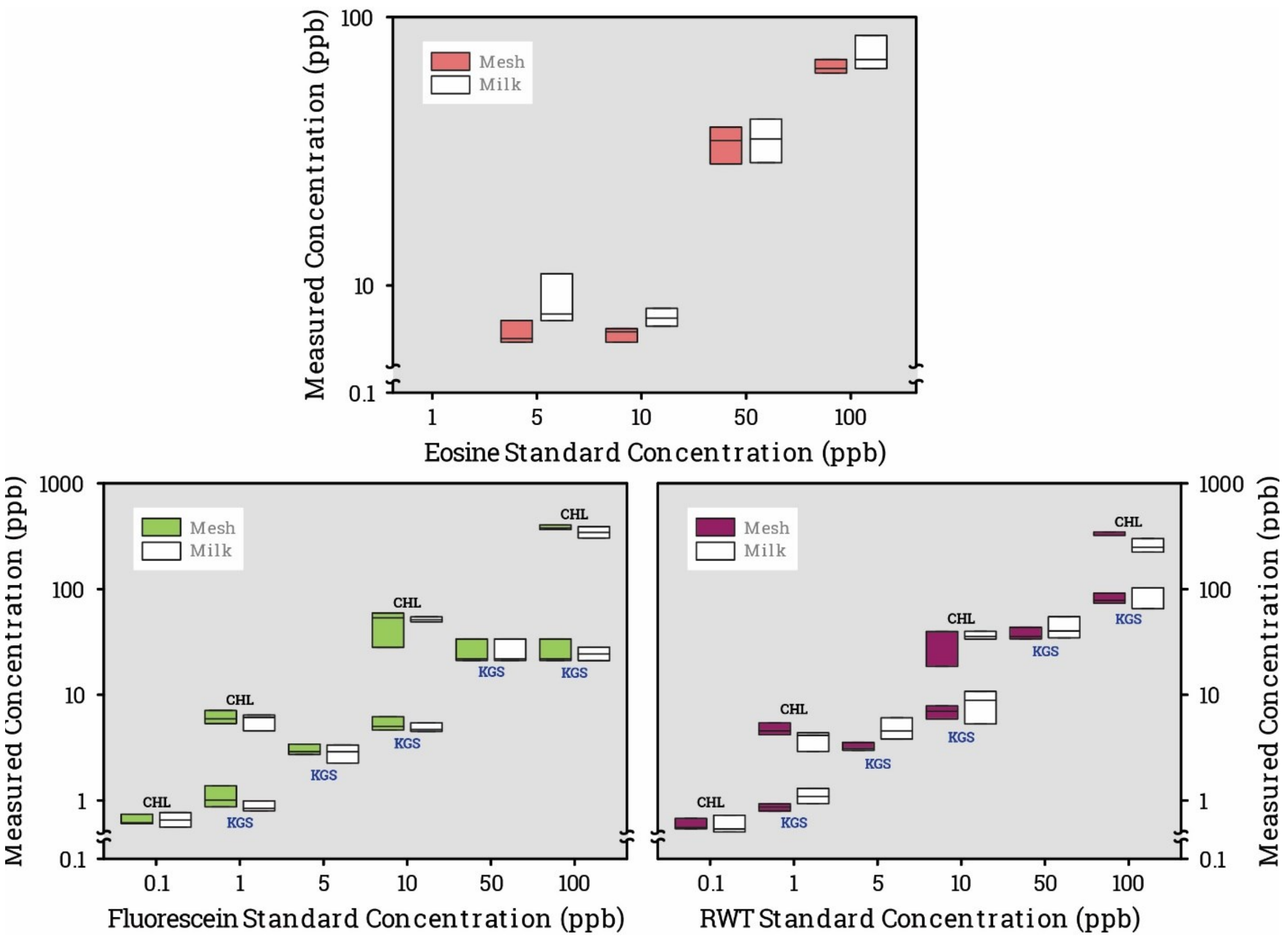

Figure 5. Box plots show the distribution of the benchtop experiment results. Due to differences in methodology, the concentrations of dye measured by CHL are consistently higher than at KGS. In the controlled laboratory environment, the type of material used to construct the dye receptors had no effect on the concentration of dye detected.

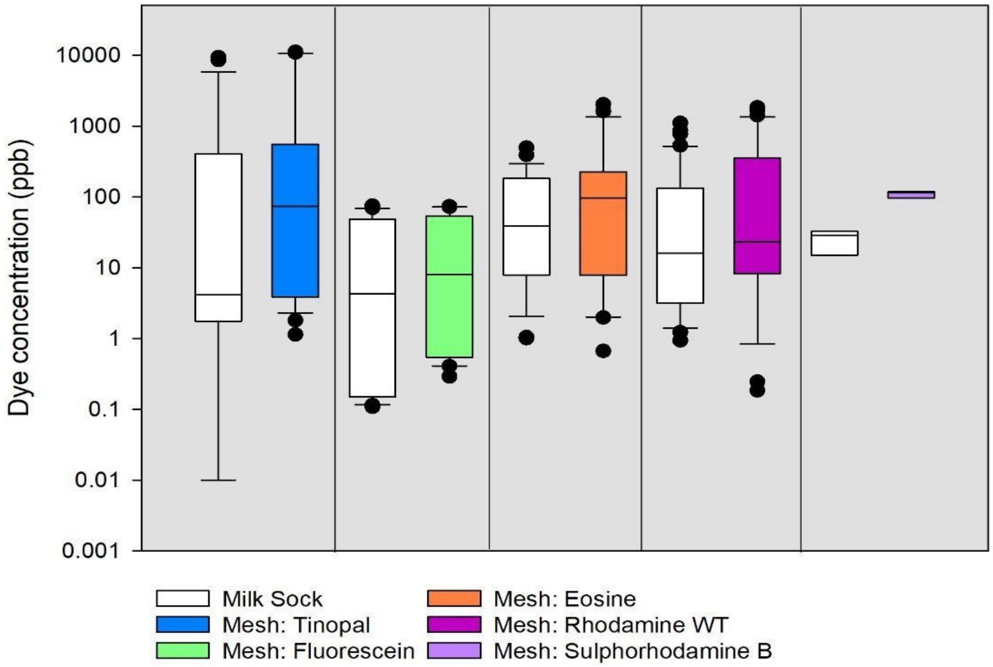

Figure 6. Box and whisker plots (log scale) summarize all data available for each receptor type per dye. Milk sock plots (white) precede mesh bag plots for each dye (by color). Horizontal line in the middle of each box represents the median value, the bottom and top of each box are the 25th and 75th percentiles and the very bottom and top of the "whiskers" that stick out below and above the boxes are the 10th and 90th percentile values. Small circles represent outliers.

Overall results show higher dye concentrations on charcoal deployed in mesh bags in 82% of the samples, with 51% exhibiting concentrations more than double that found in milk socks. There were three sample pairs from three separate monitoring locations where tinopal was non-detect in the milk sock receptor but positive in the mesh bag receptors. Statistical analysis indicates that there is a significant difference in dye concentrations between milk socks and mesh bags (Table 2). These results suggest that, while positive results were observed at all the same sampling sites in both types of receptors, mesh bag receptors adsorb a larger amount of dye than milk socks. Since the tinopal trace resulted in the only non-detect/positive receptor pairs and is known to have decreased adsorption onto charcoal compared to all other dyes, visual interpretation of samples exposed to a long-wave ultraviolet (UV) light was utilized as a secondary analysis method. Tinopal is an optical brightener and fluoresces under UV light at wavelengths visible to the human eye. Before charcoal became the industry standard, cotton dye receptors were commonly used in groundwater studies due to the low cost and ease of identifying dye presence. Though milk socks are made of polyester and no adsorption onto the material was expected, CHL visually analyzed receptor pairs for the presence of tinopal as a possible reason for reduced dye concentrations in the milk socks receptors. No fluorescence was observed.

Table 2. Mann-Whitney Rank Sum Test: Field Results

Group	N	Missing	Median	25%	75%
MESH BAG	126	0	39.978	5.873	241.839
MILK SOCK	126	0	21.578	2.883	152.312

Mann-Whitney U Statistic= 6682.500

T = 17194.500 n(small)= 126 n(big)= 126 (P = 0.030)

CONCLUSIONS

Results indicate that milk socks may be a practical alternative for charcoal receptor construction under certain field conditions. While differences exist in the lab procedures between CHL and KGS, results suggest that even when differences in lab procedures are accounted for, dye packet material results in no difference in the relationship between expected dye concentration and receptor dye concentration. While there was some variability, in a controlled setting, milk socks and mesh bags worked equally as well in adsorbing dye, regardless of the type of dye used.

Field results showed a different pattern. Milk socks consistently showed lower concentrations when compared to mesh bags at the same site. This suggests that there are differences in how water and dye move through the two materials in different hydrologic environments. A variety of factors have the potential to impact dye concentration between these two materials: dye type, flow rate, sediment accumulation, and biological activity all have potential to impact adsorption. Milk socks are generally designed for higher flow velocities, suggesting that less water and associated dye may interact with charcoal in low flow conditions.

Milk socks also have the potential to accumulate more sediment and provide a better substrate for biological growth, both of which reduce water flow into the receptor. Observed during continued client use of milk socks is that the filter fiber tends to accumulate more sediment and organic materials whereas fiberglass mesh allows fine sands and silts to flow through, complete burial notwithstanding. As such, milk socks increase laboratory processing time, meaning more effort is required to wash sediment and organic materials from the receptors and drying time is doubled compared to mesh bags. While milk socks do eliminate direct contact of sediment and charcoal, it is still uncertain if sediment could clog the filter fabric and inhibit dye detection. Observations and field test results indicate this could be an additional concern for milk sock use in low concentration, low flow conditions and warrants additional field testing. Regardless of dye packet material, conducting a thorough karst hydrogeologic inventory prior to initiating dye traces is highly recommended to better understand flow conditions which may be valuable in selecting dye packet material.

ACKNOWLEDGMENTS

The authors would like to acknowledge the prior research contributions and financial support from partner organizations that made this study possible: the Cave Research Foundation, Western Kentucky University (WKU) Applied Research and Technology Program, WKU Karst Field Studies, WKU Gatton Academy of Science and Mathematics, Mammoth Cave National Park, and Lost River Cave and Valley.

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Seepage Investigations and Dye Tracing in the Big Creek Watershed Near Buffalo National River, Arkansas

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ABSTRACT

The Buffalo National River in northwestern Arkansas preserves a range of karst features and landscapes. Big Creek in Newton County, Arkansas is the fifth largest tributary to the Buffalo River by land area (91 mi^2). The creek is comprised of two primary streams, Big Creek and the Left Fork of Big Creek (LFBC), both of which have significant reaches underlain by Mississippian Boone Formation, a commonly karstified limestone. From October 13-14, 2020, a seepage investigation was conducted in the Big Creek watershed to determine where losing and gaining reaches of the streams were located during base flow conditions. The study focused primarily on the two main streams in the watershed; however, 26 tributaries were visited for potential measurements. The seepage investigation resulted in a total of 13 discharge measurements along the main stem of Big Creek and the LFBC and 48 zero-flow observations at tributaries and dry reaches of the main streams. After the seepage investigation, a network of 27 monitoring sites were established for charcoal packets used in the detection of fluorescent dyes. On October 15, a dye injection was conducted along LFBC in a flowing reach upstream from a sink point. The dye was detected 2.9 miles downstream from the injection site at the next gaining stream reach and at subsequent monitoring sites downstream from the initial recovery site. This study will be used by agency personnel to better understand the karst processes in the Big Creek watershed and how these processes may impact water quality and quantity in the Buffalo National River.

Fate and Transport of *E. coli* through Appalachian Karst Systems

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ABSTRACT

Karst waters serve as important water sources in rural Appalachia and are well-connected to surface waters, making them susceptible to anthropogenic contamination, including fecal indicator bacteria which represent a public health risk. This work designed and implemented a watershed-scale monitoring program for a 26 km^2 sinking stream system in southwest Virginia to determine the fate and transport of *E. coli* in the system. This hydrologically complex watershed is predominantly agricultural and includes multiple surface water sinks that enter Smokehole Cave and emerge at Smokehole Spring. Bacteriological sampling, hydrologic measurement, and dye tracing were conducted at surface sites and within Smokehole Cave. Field data was synthesized to: 1) examine variations in *E. coli* concentrations in the watershed during varying flows/seasonal conditions; and 2) calculate *E. coli* growth/decay coefficients for the karst system during different flow/antecedent conditions. *E. coli* concentrations at Smokehole Spring consistently peaked days after peak hydrologic stage. Flow conditions and storm event response were the largest drivers of *E. coli* transport through the system. Dye trace results revealed that water from sinks can be stored or move slowly through the system, resurging during storm events. *E. coli* was calculated to decay within the karst system, with a half-life of about 5-120 days which is longer than the travel time of water through the cave of approximately 0.5-2 days. Findings indicate that *E. coli* transport in Appalachian karst systems is hydrologically driven, and targeted land-management practices should be explored to decrease *E. coli* loadings in karst waters.

New guidance for stormwater management in karst for Virginia

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Abstract

Managing runoff during and following land development is challenging in karst areas, where land disturbance and terrain modification pose risks to karst and vice versa. Stormwater runoff can introduce excess sediment, chemical, and biological contaminants into karst systems, many of which supply drinking water, support surface water flows, and/or comprise habitat for rare, threatened, or endangered species. Excessive sediment in stormwater runoff to karst features can plug karst conduits, resulting in back flooding of properties. Sinkholes induced by development related changes to surface flows and soil moisture can swallow buildings and vehicles, and short-circuit stormwater management infrastructure. Virginia's cave conservation community has raised concerns regarding this since the early 1970s, with widespread awareness among agencies and citizens since the mid-1990s. In 1999 the Virginia Department of Conservation and Recreation (VDCR) published "Technical Bulletin No. 2. Hydrological Modeling and Design in Karst". However, changes in regulations and shuffling of permitting responsibilities between and across agencies thwarted progress. Karst was addressed directly in state regulations in 2011. VDCR developed a draft guidance document for compliance. In 2013 permitting shifted to the Department of Environmental Quality (VDEQ) which kept the unfinished guidance available online. To assist VDEQ in development of a comprehensive stormwater management handbook, we developed an improved guidance document to both protect karst and aid developers in compliance with state and federal laws, including EPA's Safe Drinking Water Act, which treats sinkholes receiving stormwater runoff as Class V underground injection wells and falls under federal rather than state primacy in Virginia.

Introduction

Land disturbance in karst associated with construction projects can result in significant negative impacts to caves and karst, and to associated karst waters that provide drinking waters for humans and livestock, as well as habitat for subterranean and surface aquatic species. Separate regulations govern construction activities (erosion and sediment control) and post-construction drainage (stormwater management). After the passage of the Virginia Erosion and Sediment Control Law in 1973, regulatory responsibility in Virginia has been shifted between and shared among agencies including the Virginia Department of Environmental Quality (VDEQ), the Virginia Department of Conservation and Recreation (VDCR), local Soil and Water Conservation Districts, local governments, and the United States Environmental Protection Agency. Permitting authority was consolidated in VDCR in 2004, then transferred to VDEQ in 2013.

Legal protections for caves in Virginia were first enacted with passage of the Virginia Cave Protection Act of 1966. A new, more comprehensive Virginia Cave Protection Act was enacted in 1979, and it included establishment of the Virginia Cave Board with members appointed by the Governor (Lera, 2009). The Cave Board's charter included not only protection of caves, but also the power to "serve as an advisory board to any requesting state agency on matters relating to caves and karst" (Code of Virginia § 10.1-1002.A.2) and the duty to "study any matters of special concern relating to caves and karst" (Code of Virginia § 10.1-1002.B.6). Thus the Virginia Cave Board was established as an entity that could weigh in officially on matters of karst in relation to erosion and sediment control and stormwater management.

The Virginia Karst Groundwater Protection Program began in the VDCR Division of Natural Heritage (VDNH) in 1994, funded by an EPA Section 319 Clean Water Act - Projects of Statewide Importance grant. Federal Section 319 funds funded this Program through 2008, after which it became the Virginia Karst Program, funded by a combination of state general funds and private, state, and federal grants and contracts. Due to the heavy involvement of VDCR in land disturbance regulation prior to 2013, the Karst Program emerged as the primary Virginia agency with expertise in stormwater management in karst.

During the 1990s and early 2000s, various entities produced guidance on the management of stormwater in Virginia's karst.

The Cave Conservancy of the Virginias (CCV) produced "Living on Karst - a reference guide for landowners in limestone regions" in 1997, in collaboration with the VDNH Karst Groundwater Protection Program (CCV, 1997). This document drew attention to the challenges of controlling erosion and sediment and managing stormwater runoff in karst. In 1999, VDCR released "Hydrological Modeling and Design in Karst", Technical Bulletin No. 2 of the Virginia Stormwater Management Handbook (VDCR, 1999). A large portion of Technical Bulletin 2 was derived from the work of John Laughland from adjacent Jefferson County, West Virginia (e.g. Laughland, 1999). The Chesapeake Stormwater Network (CSN) produced "Stormwater Design Guidelines for Karst Terrain in the Chesapeake Bay Watershed (CNS Technical Bulletin No. 1)" in 2008 (CSN, 2008), with version 2 released in 2009 (CSN, 2009). The VDCR Karst Program contributed significantly to this document, as did consultants from the private sector working in Virginia.

What should have been an important regulatory change occurred at the federal level in 1999, when EPA officially classified sinkholes "improved" to receive stormwater runoff as Class V underground injection wells subject to regulation under the Underground Injection Control program within the US Safe Drinking Water Act of 1974 (USEPA, 1999). States had the option to regulate Class V wells, or to let EPA retain primacy. Virginia chose not to assume primacy over Class V injection wells. While this does not absolve developers of a legal requirement for compliance, the reality has been that in Virginia EPA resources are insufficient to regulate improved sinkholes, and to this day the vast majority of sinkholes in Virginia that receive stormwater runoff from developed lands are not even inventoried, much less registered with EPA. A switch to state primacy over Class V wells in Virginia could significantly improve the state's ability to prevent or respond to degradation of these sensitive receptors, the contamination of which can produce locally disastrous effects on drinking water quality.

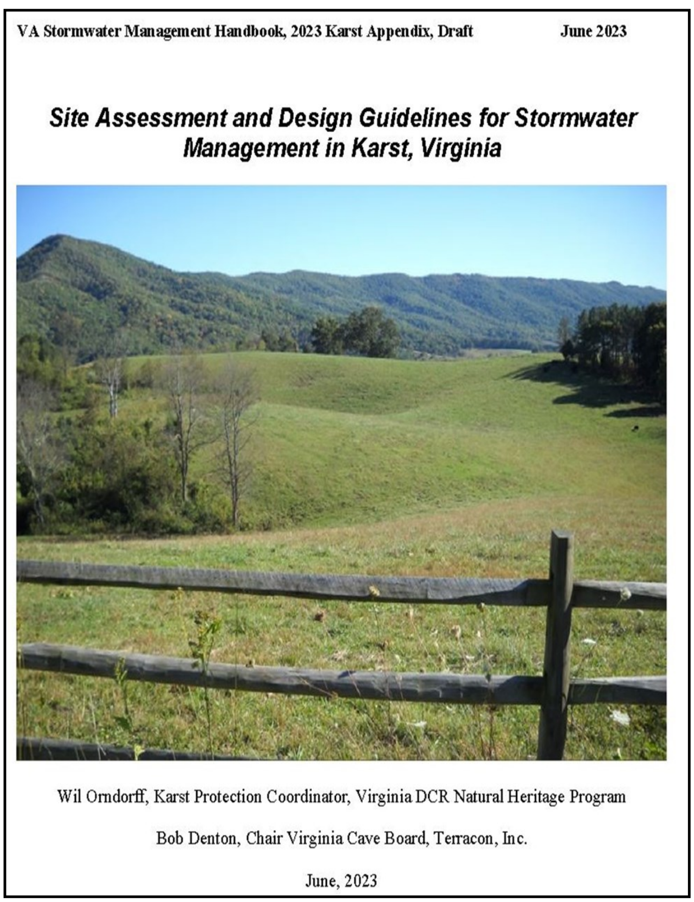
An important regulatory change occurred at the state level in 2011 when karst specific language was introduced into the Virginia Administrative Code. This language merits quoting herein, with code references (9VAC25-875-650B and C; 9VAC25-875-20) current as of 1 July, 2024. Note that BMP stands for Best Management Practice.

> *"9VAC25-875-20. Definitions…*
>
> *"Karst area" means any land area predominantly underlain at the surface or shallow subsurface by limestone, dolomite, or other soluble bedrock regardless of any obvious surface karst features.*
>
> *"Karst features" means sinkholes, sinking and losing streams, caves, large flow springs, and other such landscape features found in karst areas."*
>
> …
>
> *"Watershed" means a defined land area drained by a river or stream, karst system, or system of connecting rivers or streams such that all surface water within the area flows through a single outlet. <u>In karst areas</u>, the karst feature to which water drains may be considered the single outlet for the watershed.*
>
> …
>
> *"9VAC25-875-650. Stormwater management impoundment structures or facilities.*
>
> *B. Construction of stormwater management impoundment structures or facilities may occur in karst areas only after a study of the geology and hydrology of the area has been conducted to determine the presence or absence of karst features that may be impacted by stormwater runoff and BMP placement.*
>
> *C. Discharge of stormwater runoff to a karst feature shall meet the water quality criteria set out in 9VAC25-875-580 and the water quantity criteria set out in 9VAC25-875-600. Permanent stormwater management impoundment structures or facilities shall only be constructed in karst features after completion of a geotechnical investigation that identifies any necessary modifications to the BMP to ensure its structural integrity and maintain its water quality and quantity efficiencies. The person responsible for the land-disturbing activity is encouraged to screen for known existence of heritage resources in the karst features."*

The new language in the code (not limited to karst issues) necessitated updating the Stormwater Management Handbook, a process that VDCR had started when regulatory authority passed from VDCR to VDEQ in 2013. VDCR's draft handbook included “Stormwater Design Guidelines for Karst Terrain in Virginia (Appendix 6-B)” (VDCR, 2013), based largely on CSN Technical Bulletin 1. As of May 3, 2024, the 2013 draft Stormwater Management Handbook, developed mostly by VDCR, was still available at https://www.deq.virginia.gov/our-programs/water/stormwater/stormwater-construction/handbooks.

Inclusion of karst in the development of the Virginia Stormwater Management Handbook (2024)

Further development of stormwater guidance documents by VDEQ would not occur for nearly a decade, and VDEQ staff continued to consult frequently with the VDCR karst program in addressing karst-related stormwater issues. In June of 2022, VDEQ Director Mike Rolband attended a Virginia Cave Board meeting with several of his staff and expressed interest in guidance from the Board on issues related to caves, karst, and stormwater management. Rolband explained to the Board that VDEQ had initiated development of a new Stormwater Management Handbook that would address both Erosion and Sediment Control (Construction) and Stormwater Management (post-Construction), realizing that erosion and sediment control measures during construction are commonly integrated into post-construction stormwater management. Realizing that development of the new stormwater management handbook would take at least two years, in 2022 VDEQ released Guidance Memo No. 22-2012, “Stormwater Management and Erosion and Sediment Control Design Guide”, in which the word “karst” appeared 60 times. Also in 2022, work began on the new “Virginia Stormwater Management Handbook”, with a target roll-out of July, 2024.


VA Stormwater Management Handbook, 2023 Karst Appendix, Draft June 2023

Site Assessment and Design Guidelines for Stormwater Management in Karst, Virginia

Wil Orndorff, Karst Protection Coordinator, Virginia DCR Natural Heritage Program

Bob Denton, Chair Virginia Cave Board, Terracon, Inc.

June, 2023

Figure 1. June, 2023 Initial Draft of the karst guidance appendix for the 2024 Virginia Stormwater Management Handbook

The development of the new handbook was a complex endeavor, with dozens of stakeholders from local governments, state agencies, and the private sector meeting monthly for over a year to provide content and feedback to Arcadis, Inc., the contractor hired by VDEQ to manage the process. Virginia Cave Board Chair Bob Denton and VDCR Karst Protection Coordinator Wil Orndorff, co-authors of this paper, both served on the Stakeholder Advisory Committee, making sure that karst specific concerns were addressed throughout the handbook. Realizing the limited expertise on karst that Arcadis was devoting to the project, VDEQ agreed in March of 2023 to let Denton and Orndorff take the lead in developing the karst specific guidance portion of the document (Figure 1), which appears as “Appendix E - Site Assessment and Design Guidelines for Stormwater Management in Karst” and which is effective as of July 1, 2024.

VDEQ intends to maintain the Virginia Stormwater Management Handbook as a living document, with regular updates in response to user feedback provided through an online system hosted by enCodePlus (www.encodeplus.com):

https://online.encodeplus.com/regs/deq-va/index.aspx

Links to the Virginia Stormwater Management Handbook can also be found here:

https://www.deq.virginia.gov/our-programs/water/stormwater/stormwater-construction/handbooks

There are several significant improvements in the new “Site Assessment and Design Guideline for Stormwater Management in Karst (Appendix E)” over previous karst guidance documents used in Virginia. We encourage readers to have a look at the handbook, and to use from it and borrow from it wherever useful. In addition, any feedback on ways to improve the document are greatly appreciated.

To draw attention to compliance requirements under state law, we have included in Appendix E clear references to portions of the Virginia Administrative Code (quoted above) that explicitly address karst issues. In addition, although not regulated at the state level, we alert developers on the need to comply with federal Underground Injection Control (UIC) regulations when discharging stormwater runoff to sinkholes or other karst features. The simple fact of discharging water to a karst feature may constitute improvement and thus necessitate registration and, in some cases, permitting of the karst feature as an "improved sinkhole" stormwater injection well. This determination must be made by the regulatory agency (US-EPA) on a case by case basis.

We have included detailed descriptions of karst and karst features to help users understand karst systems and the importance of their protection for human health and the environment. We have provided clear guidelines for performance of karst-specific preliminary and detailed site investigations, as required by law, prior to development on karst. These guidelines are consistent with the new ASTM Standard Practice D8512-23 – Standard Practice for Preliminary Karst Terrain Assessment for Site Development (https://www.astm.org/d8512-23.html), which grew out of the Virginia Cave Board's Karst Assessment Standard Practice (https://www.dcr.virginia.gov/natural-heritage/document/karst-assessment-guidelines.pdf). Bob Denton, current (2024) chairperson of the Virginia Cave Board was lead author of both of these documents.

Historically, developers have found a work-around to avoid addressing karst issues, even in cases where a site lies on carbonate bedrock, by simply failing to acknowledge that the pro-

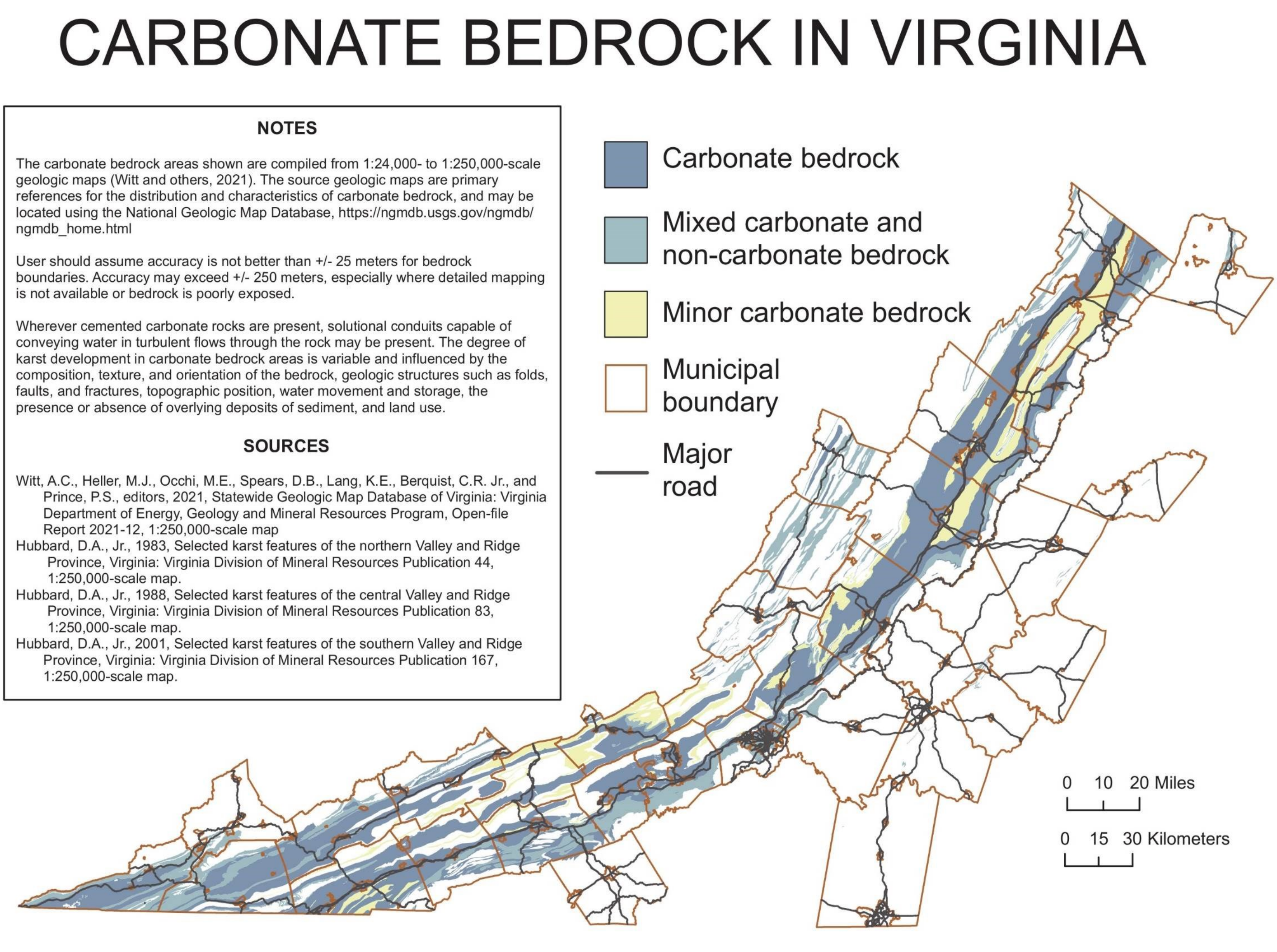


Figure 2. VDOE-DGMR Open-file Report 2023-01, Carbonate Rock Map of Virginia

ject is on karst, which frequently went unnoticed during plan review. To help developers, plan reviewers, and regulators comply with the law, at VDCR's request the Virginia Department of Energy's Division of Geology and Mineral developed a new map (Figure 2), with associated geospatial dataset, entitled "Carbonate Formations in Virginia" as an Open file report (Heller, 2023). The 2024 Virginia Stormwater Handbook uses this map as the authority to be used when screening projects for the presence of karst. The map and associated data are available at https://energy.virginia.gov/geology/Sinkholes.shtml, where users can download other useful karst-related data including a state-wide geodatabase of sinkholes based on work by Dave Hubbard (1983, 1988, 2001).

Finally, we emphasize using design approaches that work with and incorporate pre-existing hydrologic and topographic features of the site, while discouraging major changes in surface hydrology that are likely to have negative repercussions for the underlying karst aquifer. We provide information on the applicability of best management practices (BMPs) in karst areas, identifying some as generally favored for use in karst and others as discouraged or needing modification. Unlike previous guidance documents used in Virginia, we include references to BMPs for mitigating sinkhole collapses and for the modification, when necessary, of sinkholes and karst features to receive stormwater runoff.

Conclusion

Appendix E of the 2024 Virginia Stormwater Management Handbook is unlikely to be the last word regarding karst considerations for stormwater management in the Commonwealth, but it marks a major advance over previous guidance documents. In addition, the handbook addresses karst considerations as appropriate throughout the main body of the document. VDEQ's choice to make the handbook a living document should facilitate maintenance of up-to-date guidance that accommodates regulatory changes, technological and scientific advances, new data, and most importantly the needs of developers, regulators, and citizen stakeholders.

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Assessing Trail Use Impacts to Groundwater Quality in Mammoth Cave National Park

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Abstract

The Crawford Hydrology Lab conducted a study from June 2021—July 2022 to quantitatively assess potential impacts of trail use to groundwater quality within Mammoth Cave National Park using a non-conditional, synoptic sampling regime (13 sampling rounds over one year) to test for a suite of water quality and hydrologic parameters. Four groundwater basins with different types of trail use (hiking, biking, and horses) were selected; the Great Onyx basin, with no established visitor trails, was selected as the control site and the other three basins, Running Branch, Ganter Bluehole, and Buffalo Creek for their combination of trail use and surface activities with the potential to impact water quality through surface erosion and/or fecal bacteria contamination.

Groundwater impacts from trail use were identified as contamination by human and/or animal fecal waste. Fecal Indicator Bacteria (FIB) as total coliform (TC) and *E. coli* were ubiquitous and alone were not discernable according to trail use impacts between basins—all samples exceeded federal and state drinking water standards. However, Microbial Source Tracking (MST) results were consistent with land use in all cases, indicating that FIB concentrations at the springs accurately represent human and animal activity within each basin and that these activities do degrade groundwater quality through fecal bacteria contamination, though the relative contributions of FIB contamination among different sources could not be assessed. No impacts related to trail use were identified among the other water quality parameters evaluated (pH, temperature, Specific Conductance (SpC), turbidity, orthophosphate, nitrate) at the drainage basin scale.

The Influence of Geology on Groundwater Recharge at the Cave Lakes of Jewel Cave

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Abstract

Cave lakes were first discovered in Jewel Cave in 2015 where cave passages intercept the Madison aquifer. Hourglass Lake is the nearest to the shallow edge of the aquifer and was expected to show more variability from seasonal recharge than New Year's Lake, which is 2,000 feet (600 m) down-gradient. However, Hourglass Lake levels are observed to respond more slowly and with less variability than Near Year's Lake. This raises a fundamental question about the recharge mechanism for the Madison aquifer and cave lakes.

To resolve the question, well data was used to identify the recharge area as being south of the Jewel Cave Fault. Geologic data and observations were used to identify a recharge zone comprised of exposures of the Pahasapa Limestone and the two lowest subunits of the overlying Minnelusa Formation.

A map showing the geology, cave passages, and lake locations indicates that recharge only reaches the cave lakes via a lateral path from the recharge zone. Hourglass Lake is 0.5 miles (0.8 km) from the recharge zone, whereas Near Year's Lake is only 0.2 miles (0.3 km) away. Using geological constraints, we conclude that the hydrologic behavior of the two lakes is path dependent: The shorter the path to the recharge zone, the more pronounced the response to precipitation events. This hypothesis will be tested as more monitoring is established at additional lakes.

For now, the map provides a framework for understanding the relationship between precipitation and behavior of the cave lakes. This will ultimately inform managers about normal responses to external influences, so they can take action when abnormal circumstances arise.

Introduction

Jewel Cave is located in the southern Black Hills, approximately 13 miles (21 km) west of Custer, SD (Figure 1). The Black Hills are a roughly north-trending asymmetrical dome that formed during the Laramide orogeny. The dome is approximately 100 miles (160 km) long and 60 miles (100 km) wide. Erosion has exposed a core of Precambrian metamorphic rock surrounded by radially outward-dipping, younger sedimentary units. Uplift and erosion led to dissolution events that allowed karst features to form in some of the carbonate units. The Pahasapa Limestone contains most of the Black Hills' karst features, including Jewel Cave and Wind Cave, as well as many smaller caves, sinkholes, sinking streams, and resurgent springs. At Jewel Cave, over 215 miles (350 km) of cave passages have been mapped beneath 4 square miles (10 km^2) of surface area and exploration is ongoing.

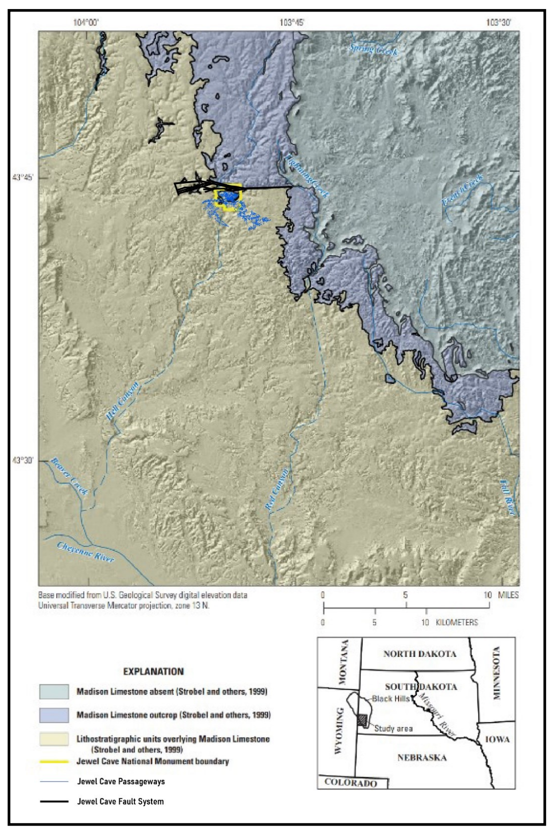


Figure 1. Location of Jewel Cave National Monument and project area. After Anderson et al. (2019).

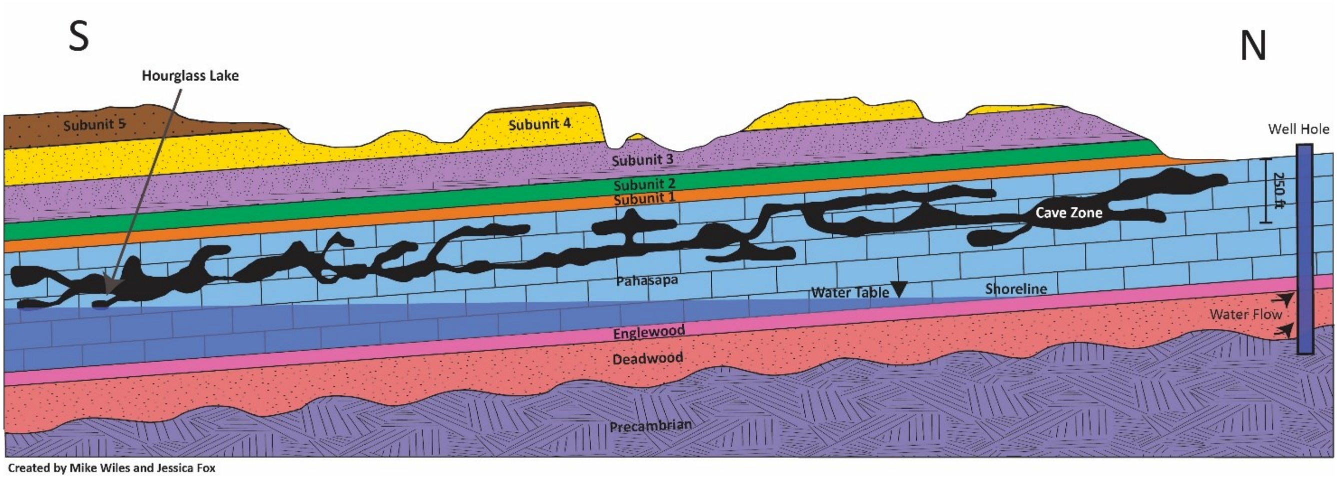


Figure 2. An idealized cross-section of the local geologic units, cave passages, cave lakes, and Madison aquifer near the 'shoreline.'

Background

Explorers discovered Jewel Cave's first cave lake in 2015. Twelve additional cave lakes have been found since then, varying greatly in size. These lakes form where cave passages intercept the Madison aquifer. The water levels of two lakes have been monitored since 2017 and the USGS has produced two Special Investigation Reports by Anderson et al. (2019) and Medler (2022). These reports produced an updated potentiometric surface map of the Madison aquifer and an analysis of the elevation changes of groundwater at Hourglass Lake and New Year's Lake.

The data collected for New Year's Lake and Hourglass Lake includes discrete water levels measured by NPS staff and volunteers and continuous data measured by pressure transducers. The discrete measurements were made by surveying to the water level from a known reference point. Beginning in 2017, eleven measurements were collected at Hourglass Lake and four were collected at New Year's Lake. Pressure transducers were installed in March of 2018 for Hourglass Lake and October of 2018 for New Year's Lake. The data collected between March 2018 and April of 2021 is used in this analysis.

Hourglass Lake is nearest to the shallow edge of the Madison aquifer, a conceptual "shoreline" (Figure 2). Because it is located 2,000 feet (600 km) up-gradient from New Year's Lake, it was expected to experience greater lake level variability from seasonal recharge. However, measured data trends reveal much higher variability at New Year's Lake than that at Hourglass Lake (Figure 3). Therefore, an analysis of the local geology and recharge mechanisms was needed to identify potential causes for the unexpected data trends.

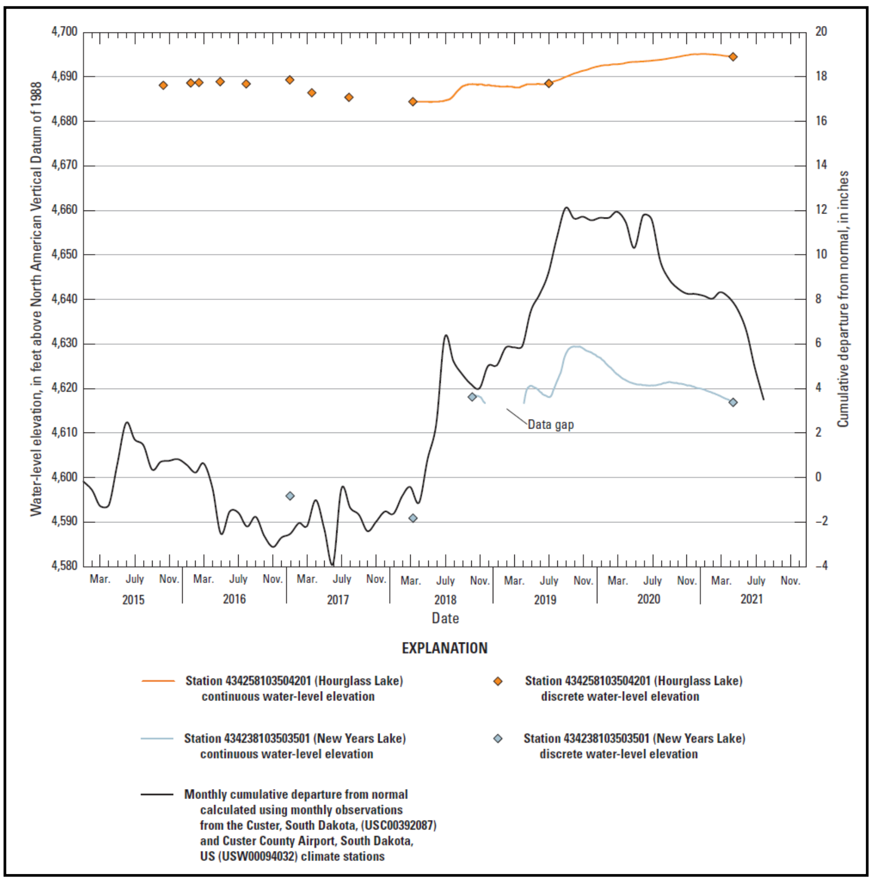
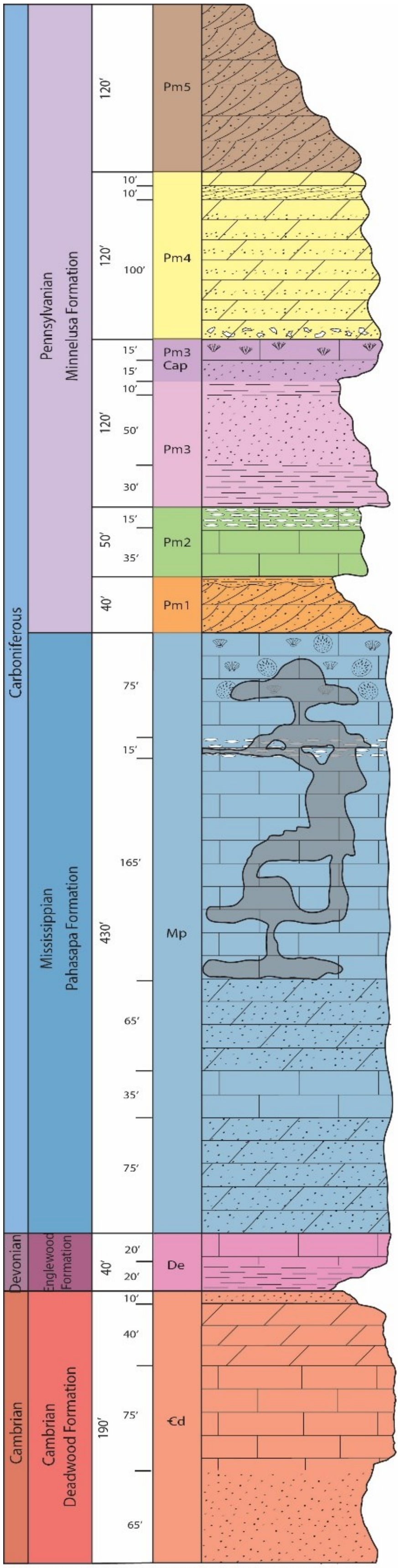


Figure 3. A plot showing the continuous and discrete water level data collected for Hourglass Lake and New Years Lake, as well as the cumulative departure from normal precipitation amounts. Figure from Medler (2022).



Created by Erin Dundass, Updated by Jessica Fox

Figure 4. A stratigraphic column depicting the four major geologic units and Minnelusa subunits in the Jewel Cave area. After Dyer (1961) and Davis (2003).

Geology of the Study Area

The Jewel Cave area has prominent outcrop exposures of the Pennsylvanian Minnelusa Formation and the Mississippian Pahasapa Limestone. In the subsurface, the Pahasapa is commonly called the Madison Formation. The underlying Devonian Englewood Limestone and the Cambrian Deadwood Formation are not exposed at the surface, but both are significant to the hydrogeology in the study area. Below are descriptions of each unit and a stratigraphic column for the study area based on work by Dyer (1961) and Davis (2003) (Figure 4).

The Minnelusa Formation varies regionally, but typically contains layers of interbedded limestone, dolomite, sandstone, and shale that can be mapped as six subunits. In this study area, a maximum thickness of 450' (140 m) of Minnelusa is seen, accounting for five of the six of its subunits. The lowest two subunits were first recognized by Wiles (1992). Four additional subunits were identified by Davis (2003) who also integrated all six subunits into a stratigraphic column that is now widely used for geological mapping in the southern Black Hills. Henceforth, the subunits of the Minnelusa will simply be referred to as Subunit 1, Subunit 2, etc.

Subunit 5 is 120' (35 m) of varicolored, medium to coarse grained sandstones that are often cross bedded. The base of the subunit is distinct due to the presence of blue-gray chert nodules and a thin limestone layer, often with thin layers of banded chert.

Subunit 4 is 120' (35 m) thick and consists of alternating beds of dolomite and yellow to red sandstone. The sandstones are fine to medium grained, often cross-bedded, and usually non-calcareous,

Subunit 3 is 120' (35 m) thick with a distinct limestone cap 10-15' (3-5 m) thick that often bears *Chaetetes milliporaceous* fossils near the upper contact. Beneath the limestone cap approximately 15' (5 m) of sandstone rests on a 10' (3 m) thick layer of gray shale, followed by 50' (15 m) of various sandstones that are often quartzitic. The lowest 15-30' (5-9 m) of the unit is a red shale.

Subunit 2 is 50' (15 m) of 1-3' (0.3-1m) thick limestone beds, interbedded by sandstones and shales up to 6" (15 cm) thick. The upper 15' (5 m) of this unit is often characterized by abundant angular chert.

Subunit 1 is 40' (12 m) thick and composed of upper red siltstone/shale that is thickness compensatory with the lower varicolored, fine to medium grained cross-bedded sandstone.

The Pahasapa Limestone is 430' (130 m) thick and forms prominent outcrops in the study area. The upper 255' (80m) of the unit consists of massive tan to gray limestone that commonly includes brachiopod fossils. There is also a 15' (5 m) thick zone of interbedded chert located 75' (23 m) below the top of the unit. The lower portion of the unit has 65' (20m) of cross-bedded dolomitic sandstone, then 35 more feet (11 m) of limestone, and a base of 75' (23 m) of cross-bedded dolomitic sandstone. It's important to note that the passages at Jewel Cave and Wind Cave, totaling 385 miles (620 km), are found exclusively within the upper 250' (75 m) of the unit.

The Englewood Formation is a 40’ (12 m) thick unit composed of fossiliferous, finely crystalline, pink and buff limestone in the upper half. The lower half is composed of shale.

The Deadwood Formation is 190’ (60 m) thick and composed of limestone and sandstone. There is an upper 10’ (3 m) layer of medium to coarse grained sandstone. Below are 40’ (12 m) of fine to medium crystalline dolomite, followed by 75’ (23 m) of coarsely crystalline limestone with sandy and silty zones. The base of the unit is composed of 65’ (20 m) of fine to medium grained sandstone. There is often a few feet of a basal conglomerate layer with pebble to cobble sized clasts.

Structures

The Jewel Cave Fault is located north of Jewel Cave and runs east-west for approximately six miles (Figure 1). The east end has 600’ (180 m) of vertical displacement near Lightning Creek, with the north block displaced upward. Near the known cave passages, it splinters into a zone of several lower-displacement faults, with a diminished total displacement of 300’ (90 m). These faults cross Hell Canyon and diminish to zero displacement near the west end of Tepee Canyon (Figure 1). Jewel Cave itself is located within blocks bounded by subsidiary faults (not shown), in which cave passages have formed along joints and minor faults with less than 20’ (6 m) of displacement.

Infiltration

Annual precipitation in the southern Black Hills is 18.8 inches (48 cm), based on WCRR (2016) records for the Custer area. According to the USFS Research Station over 95 percent of that is returned to the atmosphere via evapotranspiration (Orr, 1959). Consequently, less than 1 inch (2.5cm) of precipitation is available to recharge the Madison aquifer annually.

There are two possible ways for meteoric water to enter the subsurface and recharge an aquifer: 1) as diffuse infiltration directly through permeable bedrock (mainly sandstones) and fractured bedrock (sandstones and limestone/dolomite[1]), or 2) as runoff that feeds streams which may be lost to permeable and fractured rocks farther downstream. The second recharge path plays a minor role in the area because no perennial streams flow through the area except for a one-mile segment north of the cave (West Hell Canyon Spring to US Highway 16) and a one-mile segment in Bear Spring Creek, several miles north of Jewel Cave. Both are north of the Jewel Cave Fault zone (Figure 7).

[1]The primary permeability of limestone and dolomite is too low to support any meaningful contribution to the infiltration process. For practical purposes, all water movement and storage is dependent on secondary permeability provided by fractures, especially where the fractures have been dissolutionally enlarged.

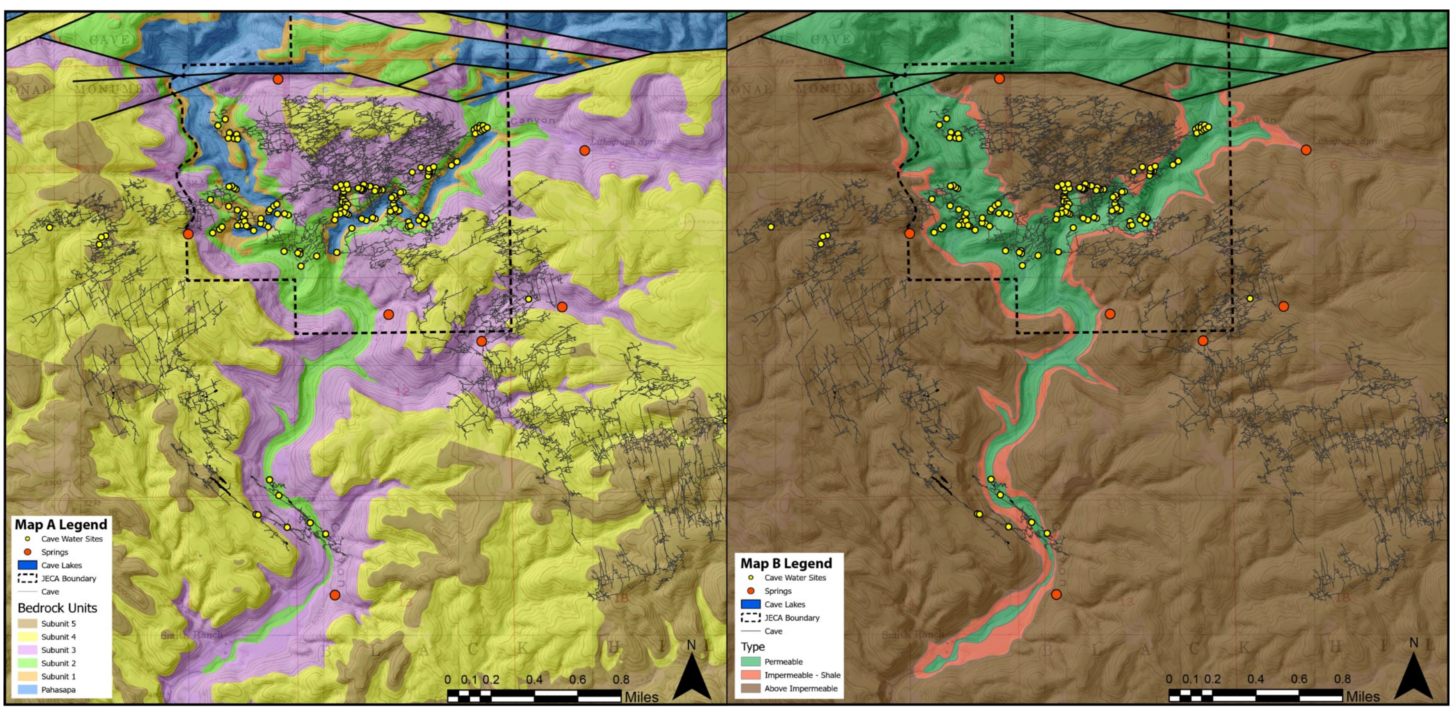


Figure 5. Two map panels depicting the major faults (>100’or 30 m displacement), cave passages, cave drip sites, and spring locations in the Jewel Cave Area. Panel A (left) shows a map of the geologic units, while panel B (right) shows the infiltration zones.

Well Name	Location	Water Source	Depth (ft)
Old Jewel Cave Well	103.8403587°W, 43.7330720°N	Deadwood	810
New Jewel Cave Well	103.8415542°W, 43.7344341°N	Deadwood	700
Warne Well	103.7708677°W, 43.7341401°N	Deadwood	675
Litzen Well	103.7658611°W, 43.7164597°N	Deadwood	480
Trusty Well	103.7616780°W, 43.7017026°N	No water source	>600 [3]
Hell Canyon Well	103.8751624°W, 43.6464570°N	Minnelusa	160
Huer Well 1	103.7931241°W, 43.7034084°N	Deadwood	1100
Huer Well 2	103.7897000°W, 43.7031540°N	Minnelusa	320
Urroz Well	103.7666416°W, 43.7216681°N	Deadwood	525

Table 1. A record of the wells in the study area used to approximate the extents of the Minnelusa, Madison, and Deadwoods aquifers.

The impermeable shale of Subunit 3 introduces an alternative pathway because it prevents the downward movement of diffuse infiltration. Water infiltrates through the rock units overlying the shale and once it reaches the shale, moves laterally to springs where it is discharged into surface drainages. From here, it can flow downhill to permeable units where it infiltrates down to the Madison aquifer. The impermeability of the shale is nearly complete, as evidenced by the strong correlation between wet areas of the cave and the areas where Subunit 3 has been removed by erosion (Wiles, 1992). Approximately 85% of the known drip sites in the cave are located beneath where the shale has been eroded. (Figure 5). As a result, over 99% of the known cave passages are devoid of dripping, or any evidence of past dripping. The exceptions are near the elevator shaft, which was excavated through the shale, and in a few intensely fractured zones, where the overlying shale was presumably disrupted by faulting. The evidence for the impermeability of the shale is further supported by the fact that all springs in the area originate at this layer, while no springs are found in other bedrock units.

On the other hand, cave passages are subject to infiltration where units below the shale are directly exposed at the surface. The moderate permeability of Subunit 2 is primarily fracture based. Since the subunit is composed of interbedded limestone and clastics it has reduced structural strength, so fractures form due to folding, faulting, or slumping. Subunit 1 has substantial primary permeability and storage capacity, due to its interconnected pore space. While the primary permeability of the Pahasapa limestone is negligible, there is significant secondary permeability due to the fractures and conduits present in the limestone. Based on statistics provided by COMPASS[2] the known passage-sized openings account for approximately one percent of the volume of the unit. Once water has passed the shales of Subunit 3, it can freely move through Subunits 1 and 2, and the Pahasapa to recharge the Madison aquifer.

Well Data

Although there are few wells in this area, their drilling logs can be used to make a rough approximation of the extents of the Minnelusa aquifer, Madison aquifer, and Deadwood aquifer.

- Two Jewel Cave wells were drilled from the top of the Madison into the Precambrian, with no significant water found in the Madison. All water is pumped from the Deadwood aquifer.
- The Warne Well was drilled through the lower 40' (12m) of the Minnelusa and all of the Madison with no significant water found. All water is pumped from the Deadwood aquifer.
- The Litzen Well was drilled from the top of the Madison and showed no significant water within the formation. All water is pumped from the Deadwood aquifer.
- The Trusty Well was drilled from 60' (18m) below the top of the Madison into the Precambrian. This well yielded no water, showing that neither the Madison aquifer nor the Deadwood aquifer extends that far east.
- Huer Well 1 was drilled from Subunit 5 to near the bottom of the Deadwood. No water was reported in Subunit 3 or in the Madison. Water in the Deadwood rose to a static head of approximately 45' (14m) above the top of the formation.
- Huer Well 2 was drilled from Subunit 5 and encountered water near the base of Subunit 3.

[2]A widely used computer program for processing and plotting cave survey data.

[3]Personal communication (Wiles, 2000)

- The Hell Canyon Well was drilled 160’ (50m) from near the top of Subunit 5, so must reach the upper third of Subunit 4. Water was present, but the elevation was not recorded. This could be part of a Minnelusa aquifer, supported by the basal shale of Subunit 3, located 150’ (45m) farther down.
- The Urroz well was drilled from near the top of the Madison, all the way to the basal conglomerate of the Deadwood. It appears that water was encountered in the lower sandstone. Perhaps confined by the dolomite and limestone beds, it rose 55’ (17m) but not above the top of the formation.

Local Extent of Aquifers

Minnelusa Aquifer

The Minnelusa aquifer is present throughout much of the Black Hills and is often intimately interconnected with the underlying Madison aquifer. However, the Minnelusa aquifer does not exist in the Jewel Cave area because Hell Canyon and Lithograph Canyon dissect the Minnelusa Formation, so water can’t accumulate to form a zone of saturation. Instead, it discharges into the canyons as small springs at the impermeable shale layer of Subunit 3. Water may also accumulate in low spots on the top of the basal shale and form perched water tables, as is the case with Huer Well 2. However, these perched water tables are small in extent, and do not represent an integrated saturation zone in the Minnelusa.

Madison Aquifer

The extent of the Pahasapa Limestone does not correspond to the extent of the Madison aquifer. Although precipitation can enter at any exposed outcrop, the aquifer will only form at a base level where all voids are filled, resulting in an integrated zone of saturation and corresponding piezometric surface. The Madison aquifer is not a continuous body of water, but rather a network of saturated fractures and conduits within the limestone (Figure 6).

An unconfined portion of the aquifer is present in the southwest part of the project area, where cave passages within the dipping limestone intersect the sloping gradient of the saturated zone and result in cave lakes. Due to the sloping gradient, water movement within the aquifer is to the south.

From Hourglass Lake, the Madison aquifer does not extend as far north as the Jewel Cave fault, nor as far east as Pass Creek (Figure 7). It is unlikely that the aquifer exists north of the Jewel Cave fault zone because Hell Canyon cuts almost entirely through the Pahasapa, to at least as far north as Bull Spring (Figure 7). The deep incision would drain the limestone and preclude the development of an aquifer. There is no clear evidence of what happens in the fault zone, which is about 3,700’ (1,130m) wide at Hell Canyon, from north to south.

Deadwood Aquifer

At Jewel Cave, the Deadwood aquifer is a confined aquifer, with a 100-foot pressure head (Dyer, 1961). It extends farther

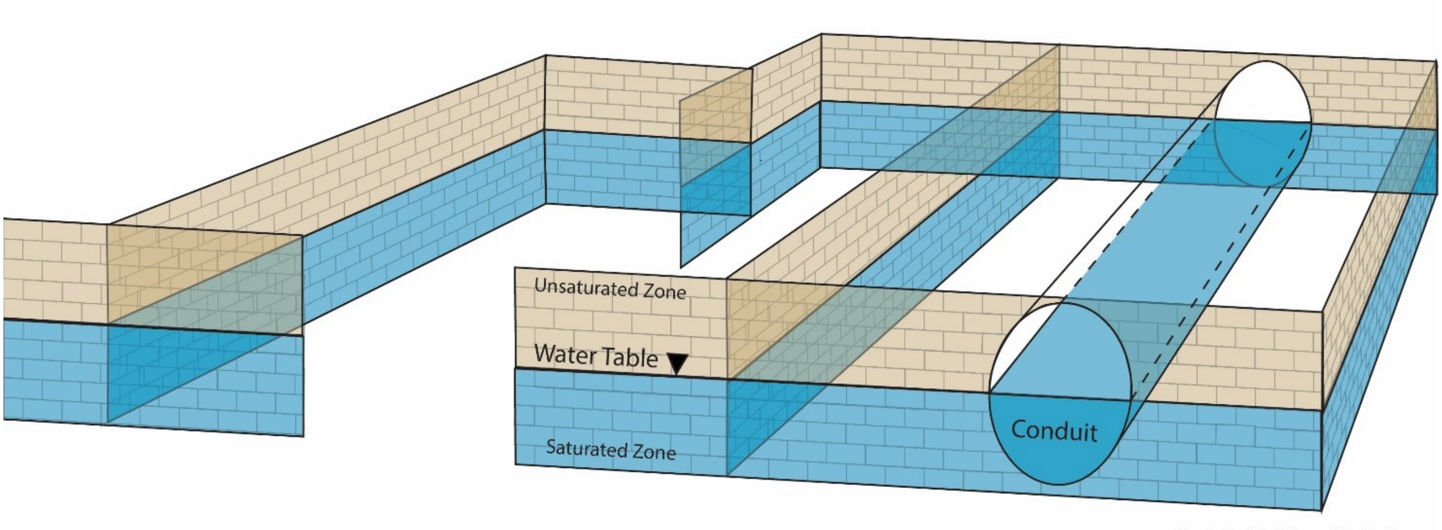


Figure 6. A conceptual diagram depicting the network of fractures and conduits that allow water movement through the Pahasapa Limestone.

east than the Madison aquifer, but not to the head of Leighton Canyon, as evidenced by the Trusty Well being dry (Wiles, 2000). It is hydrologically separated from the Madison aquifer by shale in the lower Englewood limestone and therefore does not contribute any water to the Madison. The presence of the impermeable shale in the Englewood also serves as evidence that Jewel Cave did not form hypogenically because water could not rise from below.

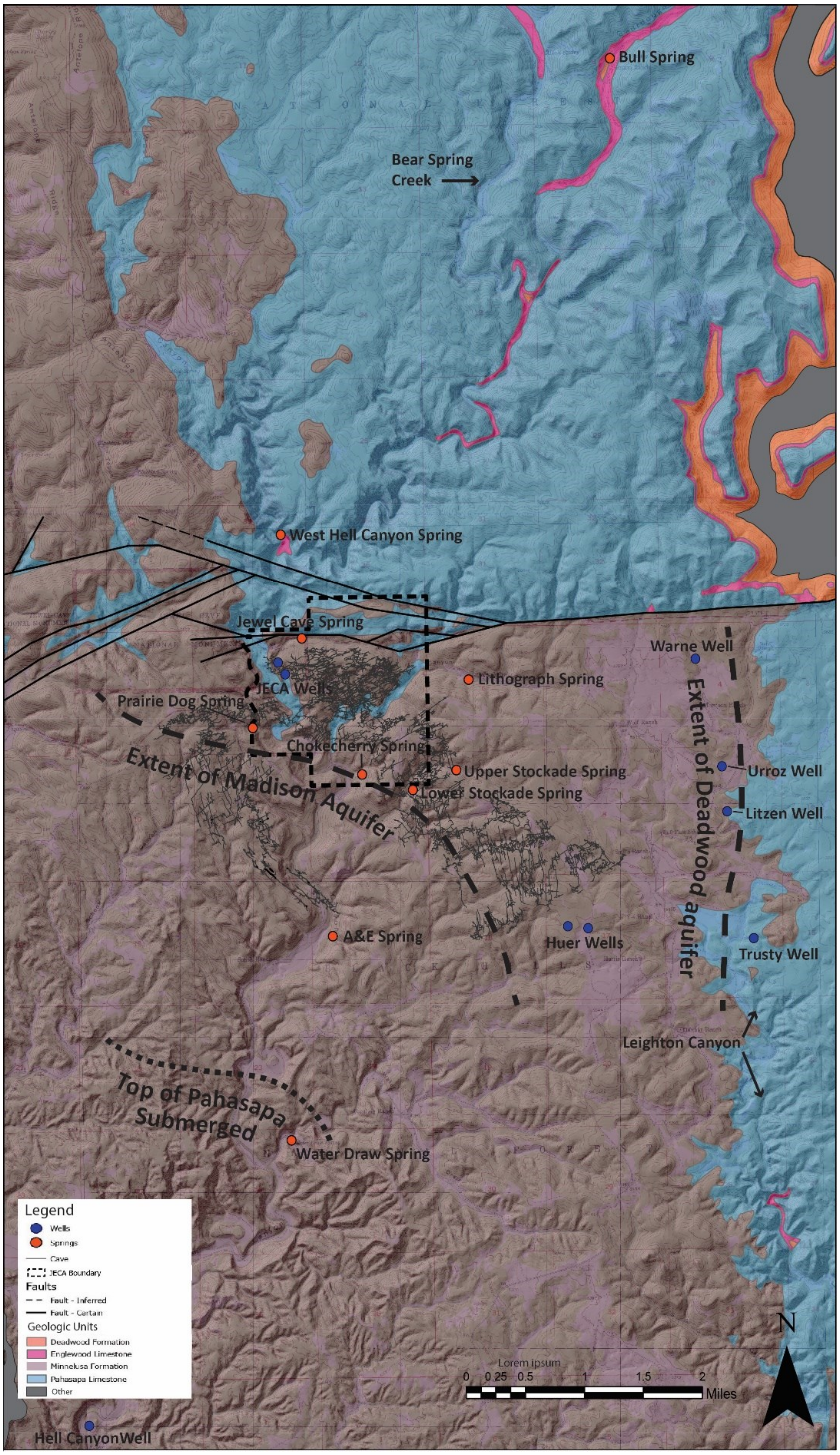


Figure 7. A map depicting the approximate extents of the Madison and Deadwood aquifer based on well logs. All well and spring locations are shown as well. Based on geology map by Redden and DeWitt (2008).

Proposed Recharge Mechanism

The recharge area can be defined as surface exposures of Subunit 2 (limestone), Subunit 1 (sandstone), and the Pahasapa Limestone. They are clearly visible on a geological map, with alluvium and colluvium removed for clarity (Figure 5A). Merging them together as a "recharge zone" helps to visualize how precipitation travels to the Madison aquifer and causes fluctuations in the water levels at the cave lakes (Figure 8).

Assuming virtually all precipitation enters the Madison aquifer via the recharge zone, the hydrologic behavior of each lake would be path dependent: the farther the lake from the recharge zone, the longer it would take to respond to the new recharge water, and the more muted the response would be. Because the Madison aquifer is comprised of fractures and conduits, dispersion time would not be negligible after precipitation events. This would cause the water table to be elevated where active recharge takes place. In summary, the recharge would not be a directly downward movement from the surface, but rather a lateral movement away from the elongate recharge zone – with an unmeasured southerly component due to the local gradient in the Madison aquifer.

This point is illustrated in Figure 8, which shows that the most direct route from the recharge area to Hourglass Lake is 0.5 miles (0.8m), and 0.2 miles (0.3m) for New Year's Lake. Each lake's response is inversely proportional to its distance from the recharge zone.

Further south, Snake Lake and Nevertheless Lake are directly beneath the recharge zone and would presumably be even more responsive to precipitation events than New Year's Lake. This can be verified by expanding water-level monitoring to additional cave lakes and creating longer term data sets.

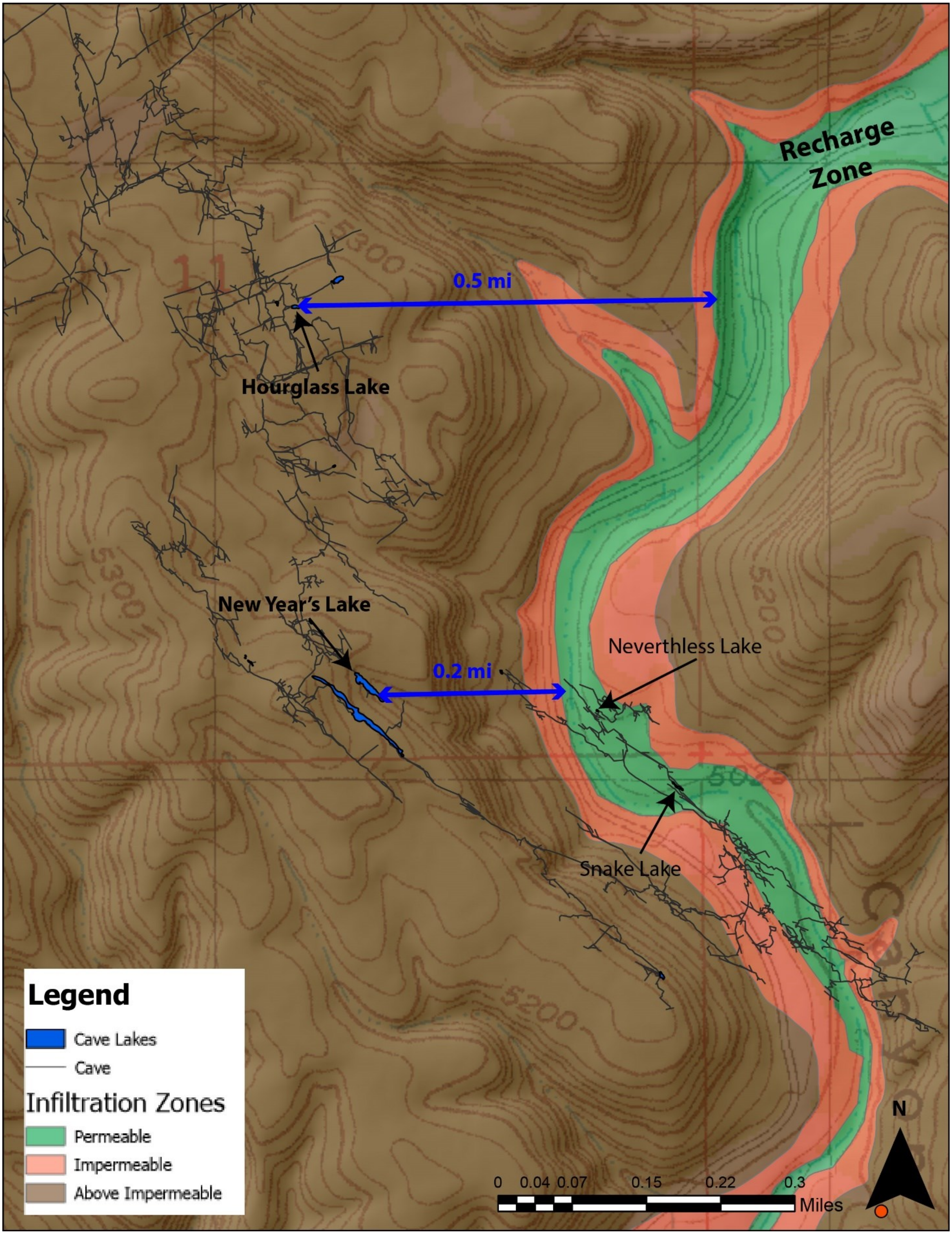


Figure 8. A map showing the locations of both Hourglass Lake and New Year's Lake in relation to the permeable recharge zone.

Conclusion

This paper consolidates fragmented and previously unpublished information to create a clearer hydrogeologic framework for the area. While the proposed recharge mechanism is hypothetical, it provides a reasonable explanation for the unexpected recharge behavior and a starting point for future research. Additional research and data are needed before any hard conclusions may be drawn. Particularly, collecting water-level measurements at more cave lakes and over longer periods of time will be critical to advancing this work.

It is essential for cave managers to make management decisions based on knowledge of the geology in their area because it is intimately interconnected to cave processes. Resource information should be of sufficient detail and quality to meet the specific needs that may arise. Having a solid hydrologic framework for the area can aid in management decisions, particularly those related to water quality protection and pollutants. Additionally, a framework depicting 'normal' conditions will help managers notice and respond to abnormalities when they arise.

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Using Dove Satellite Images to Update a Map of Sinkhole Flooding at Stones River National Battlefield, Tennessee

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Abstract

Dove satellite images show that at Stones River National Battlefield, Tennessee flooding happened at 10 locations during 2020-2021. These locations ranged in area from ~576 to 45,206 m^2, and totaled ~127,277 m^2 which is ~2.9% of the area of the Battlefield. Flooding was identified by visually inspecting 3 m cell size color-infrared (CIR) Dove satellite images acquired on 8 February 2020 and 29 March 2021. The flooded depressions were delineated by manually selecting the topographic contours conforming most closely to the flooded areas. Contours (0.25 m interval) were generated from a Quality Level 2 (best available) 3D Elevation Program LiDAR Digital Terrain Model (3DEP LiDAR DTM) having a 0.76 m cell size. Of these 10 locations, 8 are also on a published map of 2001-2002 flooding which was created by interpreting air photos. Of the other 2, one is a sinkhole which is ~40 m from the nearest road, and the other is a constructed ephemeral pond which is ~60 m from the nearest trail and ~230 m from the nearest road. There is little impact on visitors from flooding at these two locations because of the distance to the nearest trails and roads. These two features comprise only 3.2% of the total flooded area and 0.095% of the area of the Battlefield, showing that Dove satellites can image relatively small water features. In addition, the flooded sinkhole and surrounding forest are a good place to look for past and ongoing forest change.

Introduction

Sinkhole flooding at Stones River National Battlefield, Tennessee

Stones River National Battlefield is located ~45 km southeast of downtown Nashville, Tennessee on the north side of the City of Murfreesboro in Rutherford County (Fig. 1). The Battlefield consists primarily of a single large contiguous area and nearby geographically separate satellite locations. The focus of this report is on the single large contiguous area which we refer to as the "main area" throughout this paper. The Battlefield is entirely underlain by Late Ordovician carbonate, and much is underlain by aquifer units within the Ridley Limestone (Thornberry-Ehrlich, 2012). Therefore, sinkholes and karren are found at several locations. Bradley and Hileman (2006) showed that some sinkholes remained flooded for at least 11 days after 2001-2002 rainstorms.

The main area of the Battlefield is ~0.8 km W of the West Fork of the Stones River, and the sinkholes are within FEMA-designated 100- and 500-year floodplains. Note, however, that the sinkholes flood at roughly the same time that the West Fork of the Stones River reaches flood stage (Bradley and Hileman, 2006), and this happened on average once every 417 days between October 1, 2007 and August 8, 2022 (Abolins and Og-

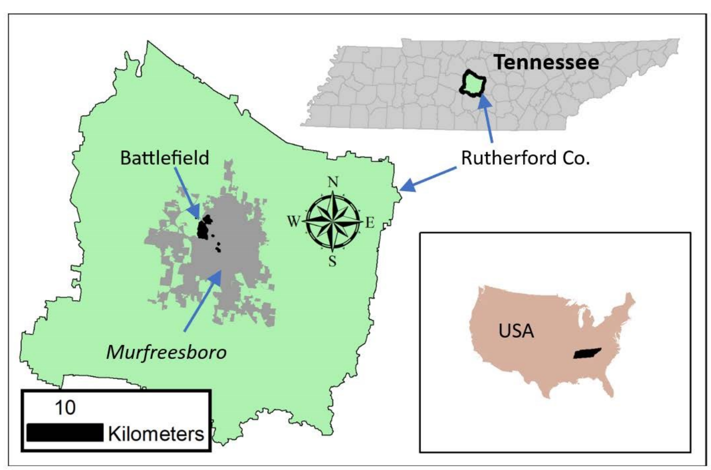


Fig. 1. Location of Stones River National Battlefield in relation to the City of Murfreesboro in Rutherford County, Tennessee.

den, 2023). Therefore, the sinkholes flood with a frequency more typical of a floodway than a 100- or 500-year floodplain.

Dove Satellite Imagery

Since 2016 it has been possible to use Dove multispectral satellite images to update maps depicting floods (e.g., Abolins and Ogden, 2023). Dove images are acquired daily and are made available to academics at no cost by Planet.com. The satellite cannot see through clouds. However, clouds generally dissipate within a day or two of major Tennessee rainstorms, and water lingers in many sinkholes for days. Therefore, it is possible to use the satellite images to create 3 m cell size maps of sinkhole flooding.

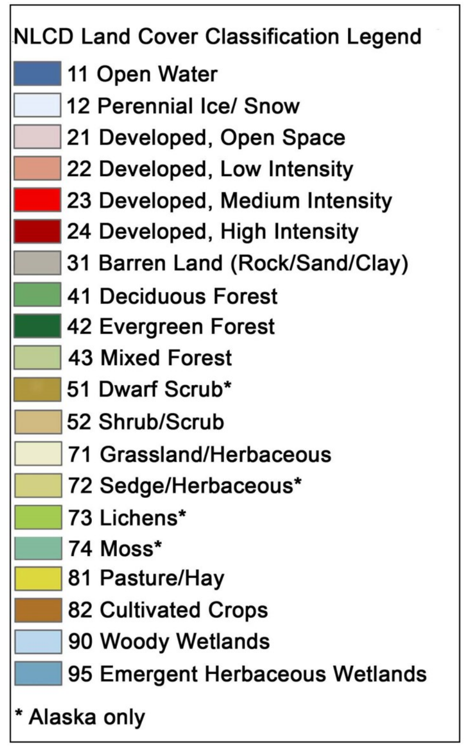
Changing Precipitation and Land Cover/Land Use, 2001-2021

The motivation for updating the map of sinkhole flooding is that precipitation and developed land increased in the vicinity of the Battlefield during 2001-2021. For example, National Weather Service precipitation normals increased from 133.9 cm for 1981-2010 to 139.9 cm for 1991-2020. In addition, the National Land Cover Dataset (NLCD) shows that there was extensive conversion of pasture to developed land south of the main Battlefield area between 2001 and 2021 (Fig. 2). Land cover/land use change south of the main Battlefield area is relevant because groundwater dye traces show that water flows underground from that area into the subsurface below the main Battlefield area. The increase in precipitation and developed land both increase the potential for flooding within the main Battlefield area.

Methods

Color-infrared (CIR) Dove images were examined for two cloud-free dates: February 8, 2020 (Fig. 3A) and March 29, 2021 (Fig. 3B). These dates follow flood events on the West Fork and are ~2 days and ~1 day post-peak stage, respectively. Precipitation (21.34 cm during March 26-28, 2021) and peak stage (5.88 m) on the West Fork of the Stones River were larger in March, 2021 than during the 2001-2002 and 2020 events. Precipitation during February 4-6, 2020 was 9.91 cm, exceeding that of 1 of the 3 events during 2001-2002. The stage on the West Fork of the Stones River peaked at 5.88 m on February 6, 2020, exceeding the stage associated with 2 of the 3 events during 2001-2002.

On the images, green vegetation is red and flooded sinkholes are dark blue-gray. To delineate the flooded sinkholes, the Tennessee 3DEP LiDAR DTM (0.76 m cell size, vertical quality level 2) was contoured with a 0.25 m interval. Then the contours best-approximating the flooding were selected manually. Topographic depressions that flooded in 2020-2021 but not in 2001-2002 were identified. With permission from the Battlefield, we visited these depressions on October 14, 2023 to



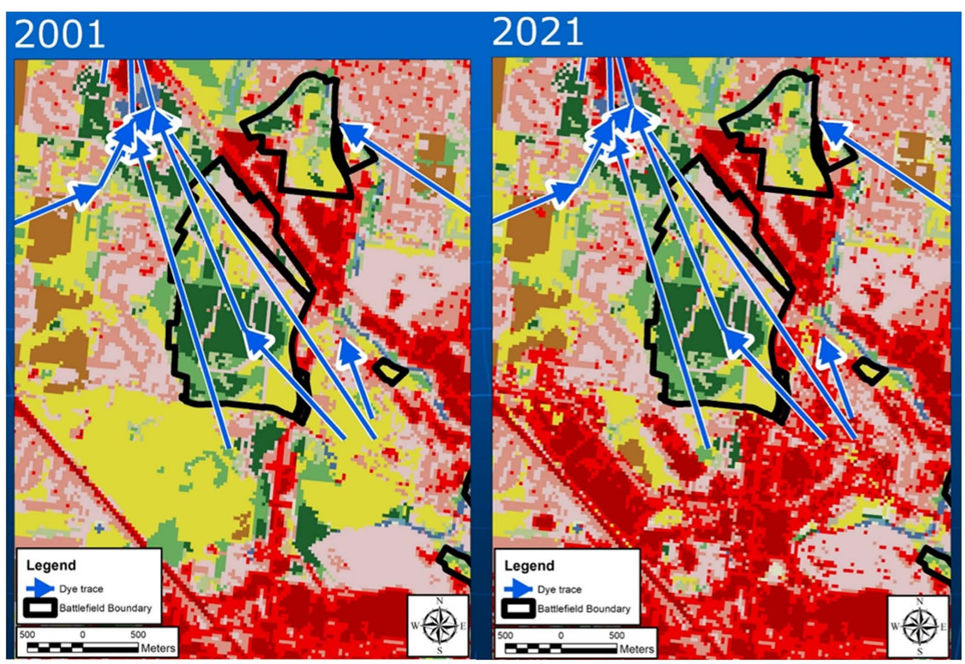


Fig. 2. Land cover/land use (LCLU) change in the vicinity of the main Battlefield area, 2001-2021. Blue arrows are groundwater dye traces. LCLU sources: NLCD 2001 (U.S. Geological Survey, 2003) & NCLD 2021 (Dewitz, 2023). Dye trace sources: Ogden et al. (1998, 1999, 2002) and Abolins and Ogden (2021).

observe the geomorphology and land cover/land use at close range. We also examined (a) a Park Service Battlefield map, (b) the NLCD (2001 & 2021), and (c) the May, 2023 FEMA waterbodies update to better-understand the nature and history of these depressions.

Results

Dove satellite images show that flooding happened at 10 locations during 2020-2021 (Fig. 4). These locations ranged in area from ~576 to 45,206 m^2, and totaled ~127,277 m^2 which is ~2.9% of the surface area of the Battlefield. They had water surface elevations ranging from ~165.75 m to 172 m which means the flooding happened primarily at elevations below ~61% of the Battlefield. Of these 10 locations, 2 are not on the map of 2001-2002 flooding (Bradley and Hileman, 2006). These two (A and B on Fig. 4) have a combined area of 4,153 m^2 which is 3.2% of the total flooded area and 0.095% of the area of the Battlefield. We obtained a research permit from Stones River National Battlefield and examined these locations on the ground on October 14, 2023.

Sinkhole (A on Fig. 4)

The northern location is a water-filled sinkhole within a forest, and the water is visible from above through a break in the canopy (Fig. 5). Of the 10 flooded depressions, the sinkhole is the 5th smallest in area at 3,577 m^2.

Ephemeral pond (B on Fig. 4)

The southern location is an anthropogenic ephemeral pond within a natural drainage along the Battlefield boundary. Soil was excavated and piled up, creating 3 berms (Fig. 6). The berms were constructed some time ago because vegetation is growing on top of them (Fig. 6B). For example, one tree has an ~1 m diameter. An animal path (Fig. 6C) leads from an open gate in the boundary fence (Fig. 6D) into the depression. Of the 10 flooded depressions, the ephemeral pond is the smallest at 576 m^2.

Discussion

Sinkhole (A on Fig. 4)

The sinkhole has probably been a wet area since 2001 because it is woody wetland on NLCD 2001 and 2021. In addition, this location has appeared as a waterbody on park maps in the past (Fig. 7), and it is visible on Google Earth historical imagery going back to 1997. This location is within the FEMA 100-year

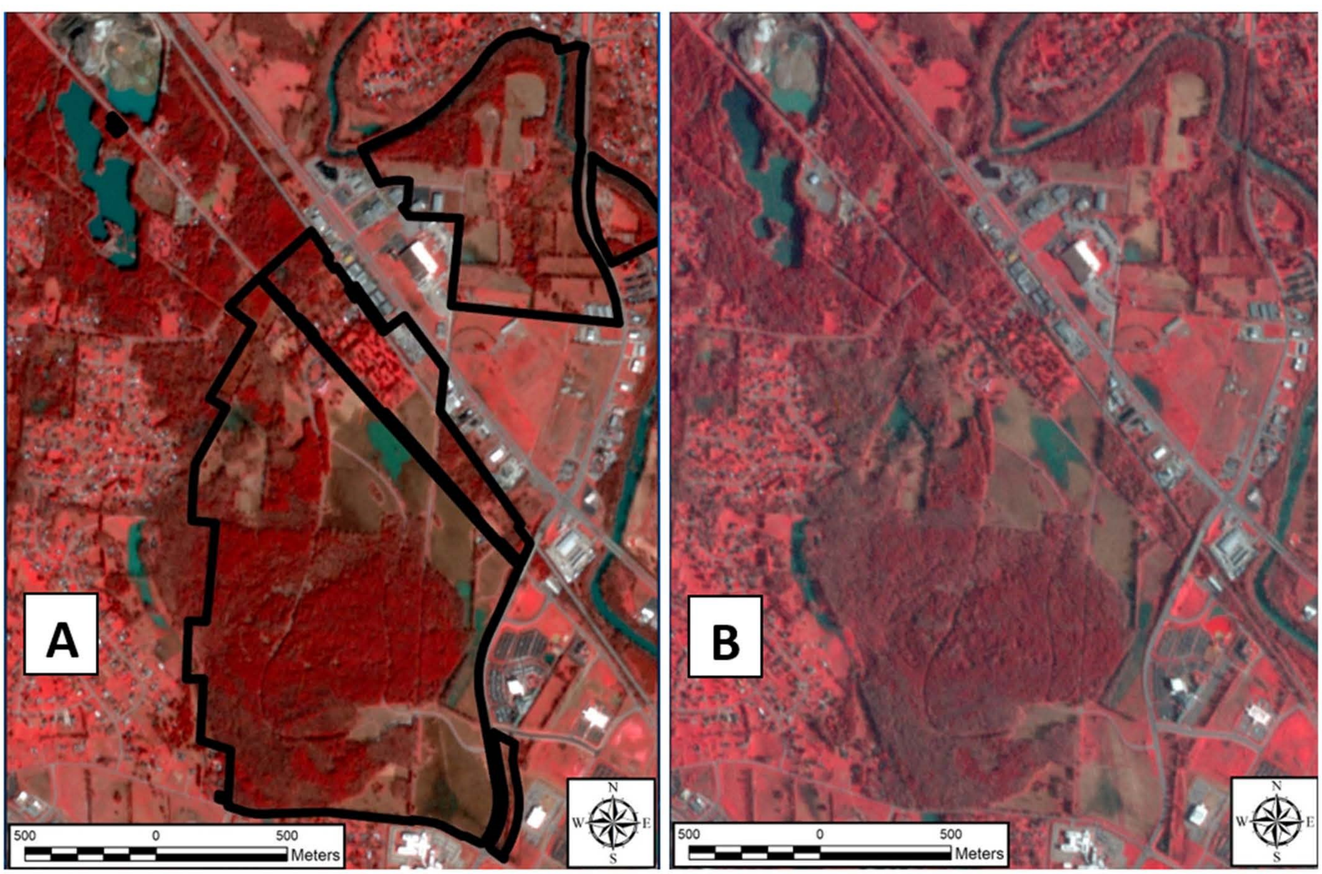


Fig. 3. Sinkhole flooding on (A) February 8, 2020 and (B) March 29, 2021. Dove satellite color-infrared (CIR) images.

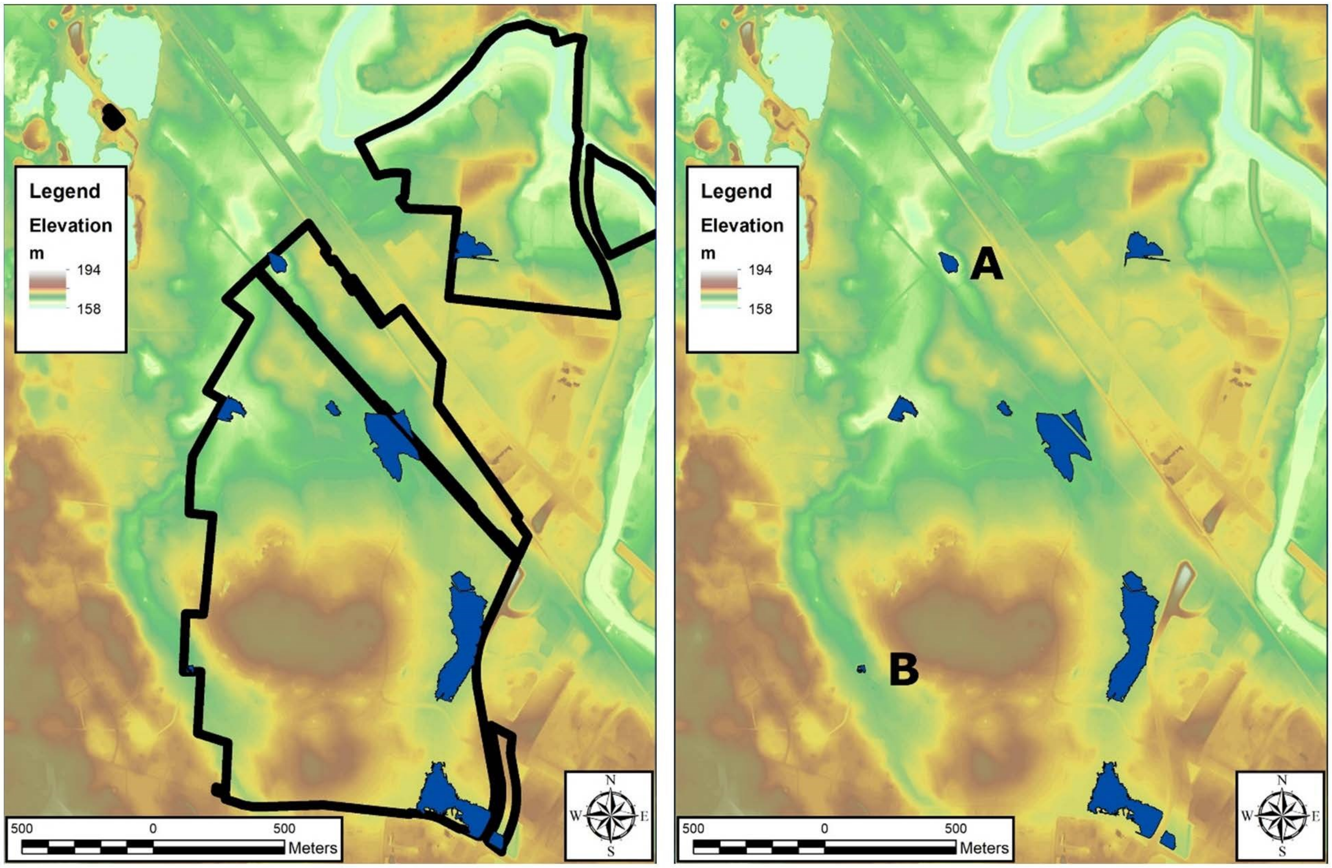


Fig. 4 (above). Sinkhole flooding during 2020-2021. The flooded features are the same on both maps, but the Battlefield boundary has been omitted on the map on the right, so that the flooded features can be seen clearly. ***A*** *(sinkhole) and* ***B*** *(ephemeral pond) are not on the map of 2001-2002 flooding.*

floodplain (Fig. 8A). However, it is outside the Law (2002) “flood-prone areas” (Fig. 8B), and it is not included on the May, 2023 FEMA waterbodies map (Fig. 8A).

The sinkhole is probably fed by groundwater at times when there has not been much rainfall. For example, it contained water on October 14, 2023 even though the West Fork of the Stones River had not been at flood stage since February, 2022. Also, there had been no precipitation since a 0.8 cm event on October 6, 2023, and there were no 72-hour precipitation events during 2023 that compared with events associated with sinkhole flooding in 2001-2002 (Bradley and Hileman, 2006), 2020 (Abolins and Ogden, 2023), and 2021. In addition, this location is at the lowest elevation of the 10 flooded areas which is consistent with groundwater entering the depression.

Ephemeral pond (B on Fig. 4)

Google Earth historical imagery shows that the vegetated berms surrounding the ephemeral pond have existed since at least 2007, and the pond contained water on May 4, 2010 (Fig. 9) after a major rainfall event associated with both riverine and sinkhole flooding in surrounding areas. The ephemeral pond is a FEMA May, 2023 waterbody (Fig. 8A), and it is located within the 100-year FEMA floodplain (Fig. 8A) and the Law (2002) flood-prone areas (Fig. 8B).

Impact on visitors

Neither flooding of the sinkhole nor of the ephemeral pond have much impact on visitors because both locations are distant from trails and roads. The sinkhole is ~40 m from the nearest road, and the ephemeral pond is ~60 m from the nearest trail and ~230 m from the nearest road.

Climate and development impacts

The two features that are not on the 2001-2002 map comprise only 3.2% of the total flooded area and 0.095% of the area of

*Fig. 5 (right). Flooded sinkhole in a forest at **A** on Fig. 4. Photo taken at north end looking southeast.*

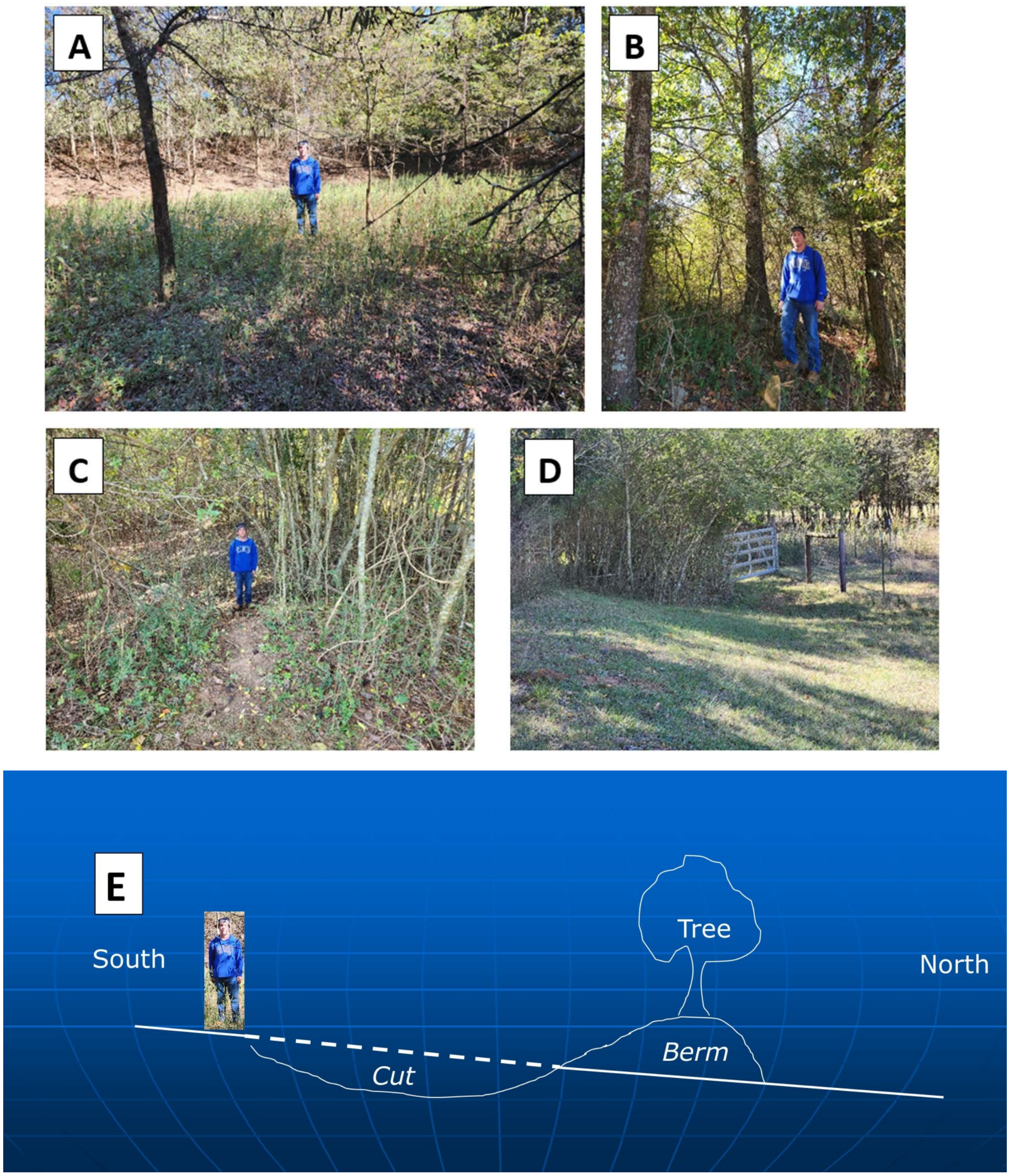


Fig. 6. (A) Inside the dry ephemeral pond with the north berm in the background. (B) An ~1 m circumference tree growing on the berm. (C) Animal path leading from open gate into ephemeral pond. (D) Open gate in Battlefield boundary. (E) Schematic cross section through ephemeral pond. (Not to scale.)

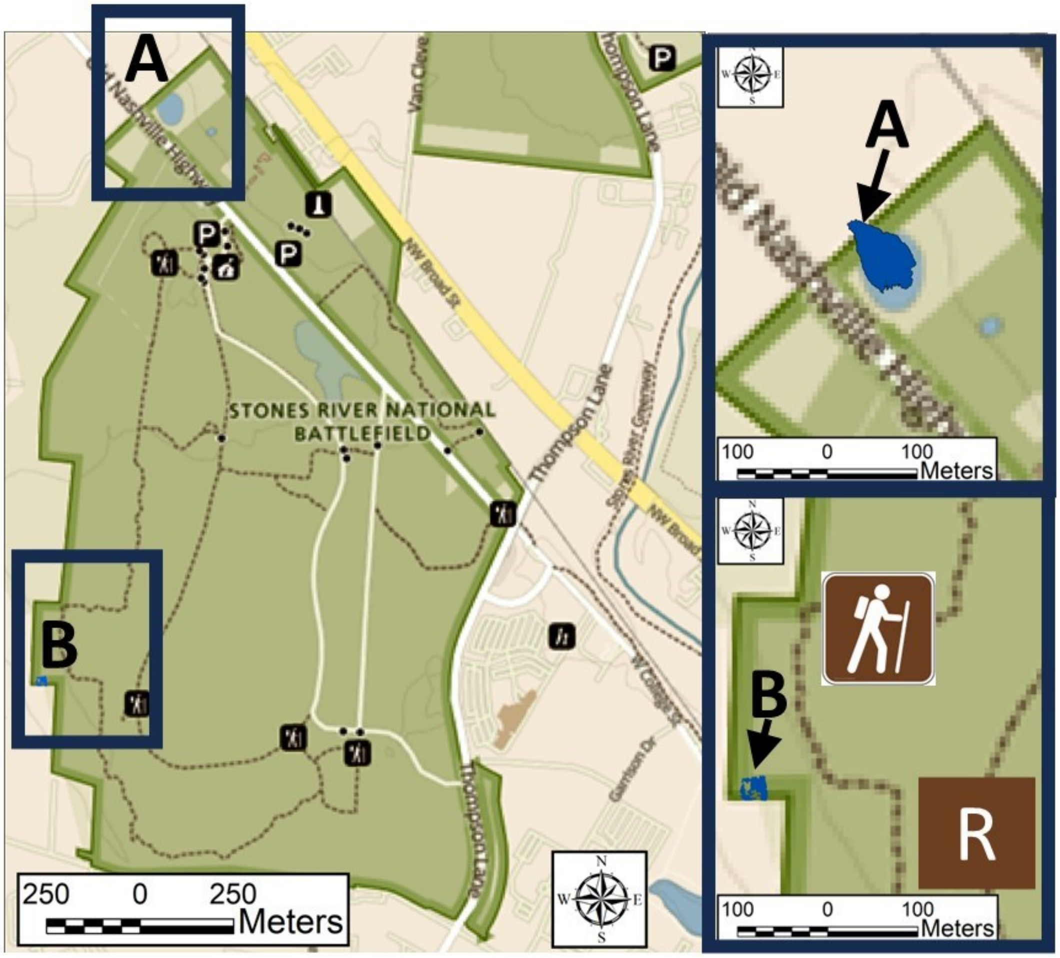


Fig. 7. The sinkhole (A on Fig. 4) appeared on park maps available online as recently as August, 2023. "R" is a road now generally used by the public as a trail.

the Battlefield. Furthermore, the sinkhole has existed as a wet area since at least 2001, and the ephemeral pond is anthropogenic. Nonetheless, the sinkhole and surrounding forest are a good place to look for past and ongoing change because a 17-year decline in tree recruitment has been documented in a similar karst depression near Tullahoma, TN (Evans et al., 2022). This is especially relevant because the Tennessee climate is predicted to continue to become wetter (e.g., Fitzpatrick and Dunn, 2019).

Conclusions

Comparison of Dove satellite images with a previously-published map of sinkhole flooding (Bradley and Hileman, 2006) shows that 8 sinkholes that flooded in 2020-2021 also flooded in 2001-2002. Examination of 2020-2021 Dove satellite images and field observations revealed flooding in 2 topographic depressions that are not on the 2001-2002 map. One of these is a flooded sinkhole which has been a woody wetland since at least 2001, and the other is a constructed ephemeral pond. These two comprise only 3.2% of the total flooded area and 0.095% of the area of the Battlefield, showing that the Dove satellite can image relatively small features. Note that the flooded sinkhole is not on the May, 2023 FEMA waterbodies map and is not within a previously-published map of flood-prone areas (Law, 2002). Flooding in the sinkhole and

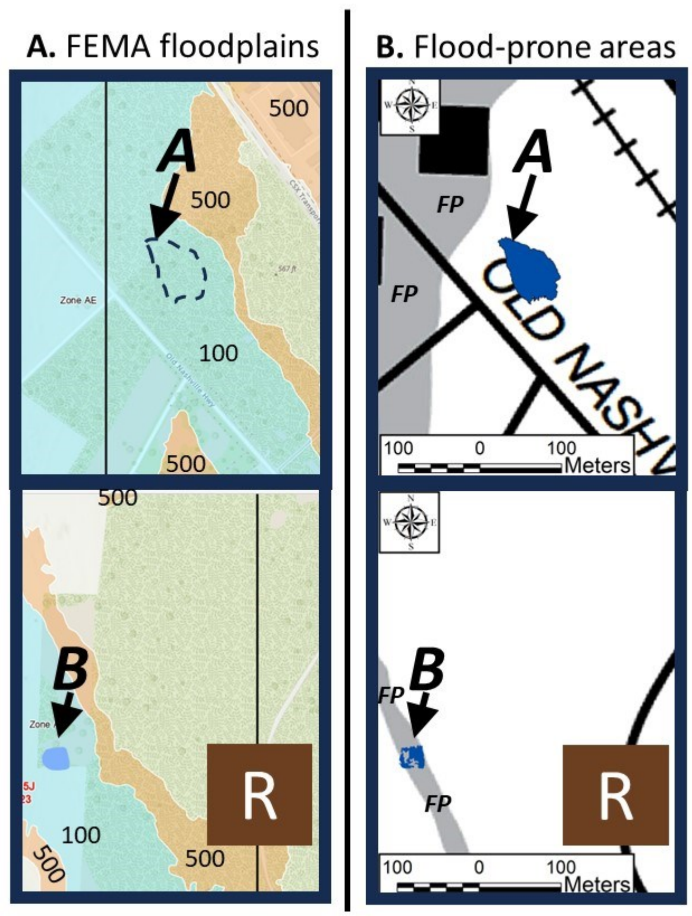


Fig. 8. (A) The flooded sinkhole (A:A) and ephemeral pond (A:B) in relation to 100-year and 500-year floodplains and May, 2023 FEMA waterbodies (blue). (B) The flooded sinkhole (B:A) and ephemeral pond (B:B) in relation to Law (2002) flood-prone areas.

Fig. 9. May 4, 2010 Google Earth historical image of flooded ephemeral pond.

ephemeral pond has little impact on visitors because they are >40 m from trails and roads. However, the sinkhole and surrounding forest are a good place to look for past and ongoing forest change, and the potential for change is especially relevant because the Tennessee climate is likely to continue to become wetter (e.g., Fitzpatrick and Dunn, 2019).

Acknowledgements

The authors are thankful for the assistance of Ranger Jim Lewis and Biology Technician Daniel Knorp who helped them obtain a research permit.

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Oral Presentations

Bats and WNS Panel Discussion: Answering Your Questions

Chair Steve Samoray

Bat Artificial Roosting Structures

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Abstract

For decades, bats have faced a large number of stressors including habitat degradation, critical levels of disturbance, and disease. In the late 1960s, the Indiana bat (*Myotis sodalis*) was listed as federally endangered due to extremely high levels of disturbance within their cave roosts during the winter hibernation period, resulting in energetic loss. Within the implementation of cave gates and seasonal restrictions, karst managers have been able to sustain populations of this endangered bat species. When White Nose Syndrome was introduced to the United States in 2006, these already imperiled bats faced further declines. Due to this added stressor during the winter hibernation period, the energetic opportunities on the landscape and in the seasons surrounding this critical time are even more important. We investigate the use of specifically designed artificial roosts and the potential to deploy these structures for immediate, longer lasting habitat during the migration maternity seasons for Indiana bats. We discuss the use of these tools as a management strategy for private and public land managers.

Gray Bat Movements and Use of Caves in Tennessee: The More We Know, The More We Don't

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Abstract

Gray bats (*Myotis grisescens*) have been on the endangered species list since 1976 and have come a long way in recovery. Commercial wind energy development is an emerging threat throughout their range that requires new approaches to conservation compared to the site-based protection that has led the way for gray bat conservation for decades. A better understanding of the full breadth of landscape use by gray bats is needed to inform future conservation efforts.

In 2018 we began developing models of gray bat movements and possible migration pathways. Simultaneously, we collected movement data on individual gray bats during summer foraging and spring migration using aerial telemetry and the Motus Wildlife Tracking System (Motus). The telemetry data suggested we have a lot to learn about landscape and cave use by gray bats in Tennessee. Summer foraging tracking revealed gray bats can travel 48 miles in a night and may roost shift for several nights. Our gray bat migration data show that gray bats often move between caves and other roosts throughout the migration season making it challenging to determine when a migration is complete. This, coupled with the large nightly movements during the summer, suggests that gray bats are using large areas of Tennessee throughout the spring, summer, and fall. Continued protection and conservation of roost sites is critical to gray bat recovery efforts, but we have much to learn about how this species uses other habitats in Tennessee and where conservation focus would be most beneficial.

Summer Cave Use by Tricolored Bats Declined in Response to White-Nose Syndrome Despite Persistence in Winter Hibernacula in the Southeastern United States

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Abstract

Several bat species experienced rapid population declines in the northern United States and Canada in response to the white-nose syndrome (WNS) epizootic. The pathogen has since spread across the United States, including the southeast, where relatively warm temperatures may change host–pathogen interactions. In the cave-rich Tennessee-Alabama-Georgia (TAG) region, we examined the impacts of WNS and forest cover on the Tricolored Bat metapopulation using a long-term dataset of 832 summer and winter cave bat counts conducted in 2004–2022. In all periods, bats were more likely to be present and abundant in caves surrounded by high percent forest cover, reiterating the importance of forest management for bat conservation. When comparing the years before and after the pathogen arrived in 2010–2012, bat presence and abundance during winter hibernation did not change. This stability contrasts significant declines in other studies, suggesting that Tricolored Bat populations are responding differently to WNS in small hibernacula in the TAG region. Though fewer Tricolored Bats used caves in the summer than during hibernation, hundreds of Tricolored Bats were found across 108 caves pre-WNS. Unlike stable winter trends, bat presence and abundance declined in the post-WNS period in summer, when cave use is optional. This first broad geographical analysis of summer cave use highlights a potentially important change in bat behavior. Disease surveillance and conservation efforts that target caves with relatively small Tricolored Bat colonies in winter and/or summer may be important for regional population persistence of this threatened species.

Status Updates for Federally Listed Bats Occurring in Eastern U.S.: Implications for Cave and Land Management

Inebnit, Tommy

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ABSTRACT

There are five bats (Gray bat, Indiana bat, Northern Long-eared bat, Ozark Big-eared bat, and Virginia Big-eared bat) federally listed in the eastern U.S. that are associated with caves. Additionally, the Tricolored bat is proposed for listing and the Little Brown bat is being reviewed to determine if listing is warranted. While some of these bats have been listed for over 4 decades for reasons including in-cave disturbance and loss of habitat, others have recently become endangered primarily due to WNS. The U.S Fish and Wildlife Service has statutory obligations to review petitioned species for listing as well as to conduct a "5-Year Review" of every listed species to assess its status. Newly listed species, such as the Northern Long-eared and Tricolored bat, can cause concern for cave and land managers in part due to the species' broad use of habitat types/caves and in the case of the tricolored bat, its continued prevalence in cave systems throughout its range. This presentation will provide an overview of these species, an update on their listing status, and potential implications to land managers.

An Update on White-Nose Syndrome and the Coordinated Response in the United States

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[4] *United States Fish and Wildlife Service, Bloomington, Indiana*

[5] *United States Fish and Wildlife Service, Sacramento, California*

[6] *United States Fish and Wildlife Service, Helena, Montana*

[7] *United States Fish and Wildlife Service, Athens, Georgia*

[8] *United States Fish and Wildlife Service, Houston, Texas*

Abstract

Almost 17 years have passed since white-nose syndrome was discovered in North America. The causative fungus, *Pseudogymnoascus destructans*, has been confirmed in 42 U.S. states and 10 Canadian provinces. Twelve North American bat species have been confirmed with the disease, with impacts ranging from negligible to severe. The U.S. national response plan for white-nose syndrome, formally enacted in 2011, provides the framework for the community of managers, scientists, and stakeholders to investigate, monitor, and manage the pathogen and bats affected by it. The U.S. Fish and Wildlife Service (Service) is the lead federal agency coordinating the collaborative response to the disease. Since 2008 the Service has awarded over $50M to support research and management through which partners have made a surge in scientific knowledge and capacity and build expertise, and advanced bat monitoring and conservation initiatives across the continent. These accomplishments are bolstered by partners in cave and karst conservation who have provided critical expertise, groundbreaking research, invaluable protection of habitats, and commitment to precautionary measures like white-nose syndrome decontamination in support of bat conservation. As we adapt the national response to address changing needs for coordinating research and management of bats and their habitats, we are testing a variety of tools to lessen impacts of white-nose syndrome, updating relevant guidance and recommendations, and taking action to protect populations from other stressors that threaten their survival and recovery.

Oral Presentations

Cave Management Session

Chair: Andy Armstrong

Southeastern Cave Conservancy: 30 years of Saving Caves

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Abstract

Southeastern Cave Conservancy, Inc. (SCCi) is the largest land conservancy in the world solely dedicated to cave and karst landscape conservation. The southeastern United States is home to thousands of significant caves; many are under threat from development or misuse. SCCi protects caves and surrounding limestone landscapes, known as karst, through conservation, education, and recreational opportunities. SCCi protects more than 170 caves and approximately 5,000 acres across 37 preserves in 7 southern states. SCCi protects these resources for future generations and the species that call them home. More caves and karst lands need protection and SCCi continues to work towards that end. This is done through a variety of acquisition and management strategies, including fee simple ownership, leases, and access agreements. SCCi also works with local and regional partners to provide cave and karst management strategies on their lands. SCCi's proprietary "Online Permitting System" (OPS) has been an integral tool for resource management and tracking recreational visitation. It also significantly mitigates liability concerns by having all visitors sign an online liability release before permits are approved. SCCi is now working with other cave and karst management organizations to rollout OPS on their properties, such as the National Speleological Society (NSS) and the state of Georgia (GA DNR).

This presentation will describe the evolution of SCCi from its humble beginnings in 1991 to the present day, and discuss the successes and challenges associated with our management strategies and OPS.

Coordinating the Dream Team to Inventory Caves in White Pine County, Nevada

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Abstract

In 2020, Great Basin National Park and the Humboldt-Toiyabe National Forest, Ely Ranger District, wrote a multimillion-dollar grant proposal to protect wild caves in White Pine County, Nevada. A major component of the project consisted of hiring a multidisciplinary team consisting of an archaeologist, geologist, paleontologist, two biologists and a tribal member. They were tasked with inventorying up to 30 Park caves and up to 15 Forest caves, and to prepare detailed reports on each of their disciplines, as well as maps and photos of each cave. The project was approved, and the crew started in June 2022, with their first stop at the NSS Convention to make connections and round out their cave knowledge. Over the past year the crew has visited 43 caves, with 1 to 28 visits per cave. The multidisciplinary approach has allowed for the crew to become well-rounded in many aspects of cave science and management. Some notable results include discovery of new cave passage, quantification of cave biota in select caves, a better understanding of the speleogenesis and geologic history of the area, identification of various Pleistocene bones to include wolverine, wolf, condor, pika, Harrington's mountain goat, and *Camelops*, time-lapse photography of developing cave ice formations, investigation of historic inscriptions, and more. Fieldwork ended in October 2023, followed by data analysis and final report writing. We hope this model of a multidisciplinary team will be useful to others looking for a comprehensive understanding of caves on lands they manage.

INTRODUCTION

In 2019, Great Basin National Park (GBNP) finalized its Wild Caves and Karst Management Plan. The plan included a list of data gaps and desired future work, which became the impetus for writing a grant proposal in the Conservation Initiatives program of the Southern Nevada Public Lands Management Act (SNPLMA). This grant source rewards multi-agency programs with cultural and educational components. Therefore, the Park contacted the Humboldt-Toiyabe National Forest (HTNF)-Ely Ranger District and the Bureau of Land Management (BLM) to see if they would like to be partners to learn more about caves in a county-wide effort. Although BLM did not have personnel available to work on the development and implementation of such a project, the HTNF did, and serious work began in crafting the proposal.

The proposal encompassed many components, including a detailed report for each agency with detailed information on selected caves; a rock art condition assessment and protection at two caves; an ethnographic study to learn how local tribes thought and felt about nearby caves; and development of educational opportunities such as a CaveSim trailer at the Park and developing a wild cave tour through Lehman Caves. The total price for this project? Over two million dollars. Local grottos and groups wrote letters of support, and the proposal ended up being the top-ranked one.

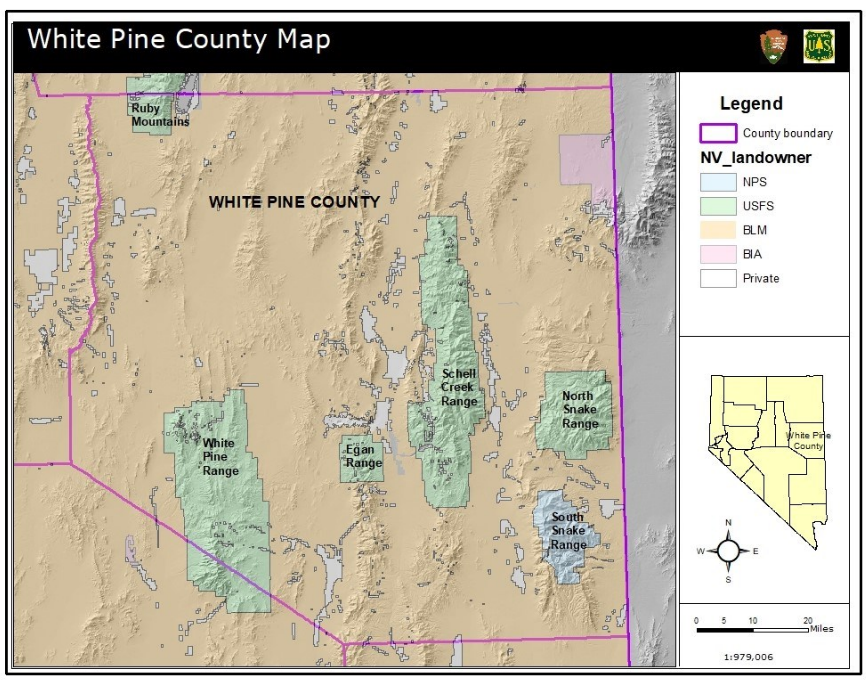

Figure 1. The Dream Team focused on caves in White Pine County on lands administered by Great Basin National Park and the Humboldt-Toiyabe National Forest-Ely District.

This paper focuses on the Dream Team, a multidisciplinary team of cave scientists hired to inventory and write up information on the caves for GBNP and HTNF in White Pine County, Nevada (Figure 1). The local cave managers wanted to greatly augment the information we currently knew. A previous study on the HTNF (Gilleland 2012) provided a snapshot and basic information on some of the caves. For caves in GBNP, biological inventories (Krejca and Taylor 2003, Taylor et al. 2008), water quality studies (Paul et al. 2014), and a cave condition report worked on by various cave specialists (NPS Staff 2019) gave a starting point.

HIRING THE DREAM TEAM

We wanted to hire a Dream Team that could work across two different US Departments, the Department of the Interior (on National Park Service [NPS]-managed land) and the Department of Agriculture (on US Forest Service [USFS]-managed land). This meant that we needed a go-between, and for that we reached out to the Great Basin Institute (GBI), a non-profit that advances applied research to support science-based adaptive management of public lands. GBI has a robust hiring process in place. Before any hiring could take place, though, agreements with GBI with both the NPS and USFS had to be written and signed. In addition, some challenges had to be overcome. Where would the Dream Team live? A severe housing shortage in both Baker, NV, and Ely, NV, left very few options. Renovations on an old bar, The Outlaw, in Baker were recently completed, which provided adequate housing. In addition, office space couldn't be guaranteed by either GBNP or HTNF, but there was potential space within The Outlaw.

Figure 2. The Dream Team: Geologist Louise Hose, Archaeologist Brianna Patterson, Paleontologist Peter Druschke, Biologist Jean Krejca and Biologist Shiloh McCollum.

With those details finalized, interviews commenced. Instead of the five full-time members we anticipated hiring, we decided to hire two as part-time as that was their preference and we wanted their expertise on the team. No tribal members applied. Fortunately, we had the flexibility to make adjustments, and hired: Archaeologist-Brianna Patterson, Biologists-Shiloh McCollum and Jean Krejca, Geologist-Louise Hose, and Paleontologist-Peter Druschke (Figure 2). We augmented the group as geologist (Doug Powell) and ecologist (Gretchen Baker).

THE DREAM TEAM STARTS

The Dream Team started June 6, 2022, with a brief introduction to the project, each other, and some park caves. The team started figuring out their strategy to visit up to 30 NPS caves and up to 15 USFS caves during the approximately year and a half of the project. The biologists recommended approximately 17 visits per cave to find all the biota. That clearly wouldn't happen in the timeframe available, so we settled on a goal of 4 visits per cave, realizing that those caves that turned out to be more interesting would get more visits and some would get less.

The team didn't have much time to get settled into Nevada as at the end of the first week it was time to head to the NSS Convention in South Dakota, where they could round out their cave knowledge, meet other specialists in their respective fields, and attend a variety of talks and workshops.

Upon returning, the Dream Team continued to inventory caves in their specialties as well as noting cave climate, taking photos, improving rigging, installing wildlife cameras at cave entrances, and more. Experts were invited to provide their input, volunteers from local and distant grottos assisted with various aspects. As the team reviewed current cave maps and realized that some time and effort would be needed to do additional cave maps, we arranged for Peter Sprouse to do a cave cartography workshop in August 2022.

Interspersed with the daily routine of going out to a cave and searching it thoroughly were some special events. The NSS Western Regional was hosted at GBNP in October 2022, with Dream Team members leading multiple trips to wild caves in the Park and on HTNF. In December 2022, GBNP hosted an Orientation to Cave Rescue class through the National Cave

Rescue Commission, where team members enhanced and reviewed their cave rescue knowledge. In January 2023, the team assisted with the annual Lehman Caves Lint Camp, which involved a speleothem repair workshop, restoring the cave, and wild cave trips.

RESULTS

Over the course of the field season portion of the project, the Dream Team visited a total of 43 caves on 265 cave trips. This was split between 28 NPS caves with 176 trips and 15 USFS caves with 89 trips. The number of trips per cave varied from 1 to 28, with an average of 6.5 visits per cave.

Archaeology highlights included finding and documenting pictographs in the entrance of Old Man's Cave that had previously been overlooked, documenting 200 historic inscriptions that go back to 1885 in Snake Creek Cave, and expanding the context for cave use by prehistoric and historic people in the area (Figure 3).

Biology highlights included finding a new cave spider and probable new beetle species located in several caves, expanding the range for several taxa, and getting better photos for some of the taxa. Many caves were sampled for the first time, and within these vials that are being carefully curated, certainly other new discoveries await. A study within the project (see McCollum et al. in this volume) quantified information on two extremely important endemic species (Figure 4). Another significant find was the discovery of an order of Arachnids that had not previously been found in Nevada, or for that matter, in most of the U.S. Additional research and a forthcoming paper are in the works.

Figure 3. Archaeologist Brianna Patterson documents cultural resources in a cave.

Geology highlights included a much better understanding of the genesis of the caves in the area (Figure 5), very detailed geologic descriptions for each cave, and reviews from experienced speleologists. One of the most exciting finds is that two mammillaries dated with uranium-lead tests revealed dates of 12.5 and 11.4 million years old. This is on the older end of what was expected and may help to develop a better idea of the Basin and Range geologic processes and timing. More detail on geologic findings is found in the Hose et al. paper in this volume.

Paleontology highlights include bighorn sheep, wolverine, *Camelops*, extinct horse, wolf, and other bones from a variety of caves. Marmot and packrat bones are some of the most encountered in the caves. The Dream Team assisted with paleontology excavations at Ladder Cave in HTNF with permit-holders Dr. Steve Emslie and Larry Coats, which included condor remains as well as well-preserved coprolites of the extinct Harrington's goat, packrats, and possibly pika, which are now extirpated from the area.

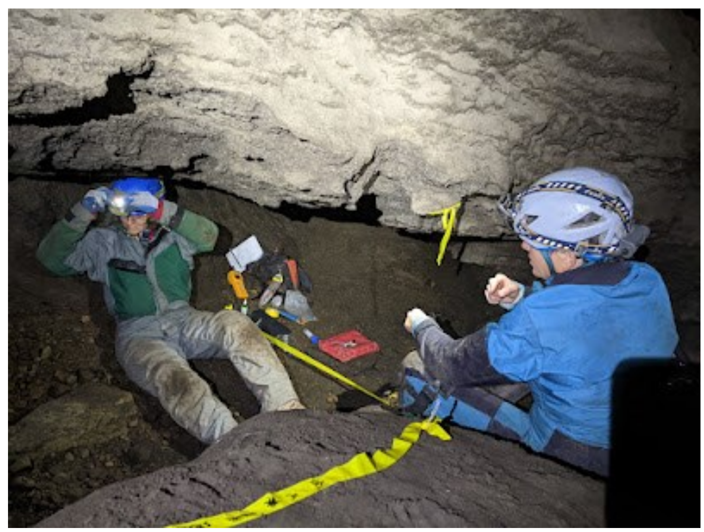

Figure 4. Biologists Shiloh McCollum and Jean Krejca get ready to count endemics on a transect in Model Cave.

Much progress was made in several other areas. Cave climate data was collected with hand-held meters as well as dataloggers. Analysis of this data will be ongoing. Cave maps for several caves, including Long Cold Cave, one of the deepest caves in the state of Nevada, have been finished, and are ongoing for other caves. Thousands of photos are being reviewed and select ones will be shared in the final agency reports.

Figure 5. Geologists Doug Powell, volunteer Harvey DuChene, and Louise Hose discuss cave geology in a small but spectacular cave.

DISCUSSION

The Dream Team added a new chapter to the information known about caves in White Pine County, Nevada. Having the team's focus, as well as experts they invited, helped bring awareness to these understudied resources. This occurred despite some substantial challenges in the project. One was cave access. Many of the caves included extensive hikes at high elevation, making for very long days and very heavy packs. One such cave, when entered, had a big boulder that started moving towards the hole we would rappel through to get to the next level. We decided against continuing, not wanted to be pinned in the bottom of a distant, frigid cave. Fortunately, the next year when we returned the conditions had improved and we were able to get down to the bottom of the cave. Nearly every cave in the Great Basin requires crawling and, in some cases, belly crawling with extremely tight squeezes. Some of these tight squeezes precluded members of the Dream Team from entering, and the ones that could fit through the tightest squeezes often didn't want to return for a second visit. Thus, some areas of caves had quite limited visitation. The high snow pack in winter 2022-2023 made the second summer season more challenging, as we often had to hike through deep snow to access the caves early in the season. However, this big snow pack allowed for a glimpse into how the caves react to big water, something that only happens every 20 years or so.

Other challenges included limitations on paleontology collecting in NPS caves due to other circumstances beyond the project's control and trying to find the right balance of field and office time. Trip reports were written after each cave trip, but with so many caves visited and over 250 trip reports, distilling this into a final report for each agency is extremely time consuming. Nevertheless, we are delighted to have this much data. It certainly beats a lack of data.

NEXT STEPS

Field work concluded on October 26, 2023, with the Dream Team converting to remote working to finish the report in 2024. The final outline includes detailed reports for each cave with technical language, as well as a manager's summary for each cave that gives an overview. In addition, appendices with species lists, geological descriptions, and more will be included in the report, as well as an extensive references section. Excerpts are expected to be shared in a future issue of the *Journal of Speleology,* other refereed journals, and *The NSS News*.

The report will also recommend what future actions should be taken. Some of these include further studies, such as additional mammillary dating using uranium-lead dating, cave microbiology inventories, taxonomy follow up for potential new species, cave ice studies, and dye tracing. Realizing that there is still so much to be learned about the caves of White Pine County, a phase two of the Wild Caves study is being considered. The proposal would be submitted in 2025, and if funded, run from 2026-2030.

CONCLUSIONS

The term "Dream Team" was used to refer to the Wild Cave Crew with high hopes before the team was even selected to generate excitement for caves in a remote part of the U.S. The crew has certainly lived up to its moniker, making wonderful discoveries, documenting each cave in detail, and showing great camaraderie and professionalism. The multidisciplinary nature of the team has made each team member more well-rounded and able to be on the lookout for cave features that are outside their area of interest. This has strengthened the team and made for even better results. In addition, the interagency cooperation helped greatly to put the resources into a more regional context. It is also more efficient to have one multidisciplinary team working across jurisdictional boundaries than hiring two separate teams at separate times, as we are able to use the knowledge gained without having to re-train a new crew. This multidisciplinary approach is highly recommended for other areas that are looking to conduct cave inventories.

ACKNOWLEDGEMENTS

This project would not have happened without the generous funding from the Southern Nevada Public Lands Management Act (SNPLMA). Hiring the Dream Team was made possible through the Great Basin Institute, with special thanks to Director of Development Chris Warner, who was willing to take a risk on a project with so many unknowns at the beginning. The Dream Team crew made the magic happen; a huge thanks to Peter Druschke, Louise Hose, Jean Krejca, Shiloh McCollum, and Brianna Patterson. The support of the management team at Great Basin National Park, particularly Bryan Hamilton, Nichole Andler, James Woolsey, and Glen Dearden helped with the submittal of the project proposal. The support of Jose Noriega at the HTNF-Ely District was critical. Thanks to Bruce Eldridge for renting out the old Outlaw building to the Dream Team.

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From basins to ranges: teaming up with scientists to discover the extraordinary resources beneath your feet

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ABSTRACT

The Protecting Wild Caves in White Pine County Project is demonstrating amazing returns of value as resource management agencies, empowered with financial resources and supportive management, team up with outside scientists. The Project is set in east-central Nevada within the Basin and Range province where general geologic studies are spotty and mostly focused on mining and mineral resources. Knowledge about the area's cave geology was out-of-date and limited when Great Basin National Park and Humboldt-Toiyabe National Forest initiated the project. During the last 17 months, the Wild Caves Project has documented that most of the region's significant caves have hypogenic origins, and most of those caves have mammillaries that developed just below the regional water table. Radiometric (U-Pb) dates of mammillaries from two caves were 13.1Ma and 11.4 Ma. The mammillaries precipitated in established caves while the mountain ranges rose. The extensional environment facilitated their preservation. These caves are astoundingly old and deserve recognition and appropriate management for sites with outstanding universal value!

Since revealing some of our findings at the 2023 National Speleological Society Convention, there has been considerable interest in building on our work. Geoscientists from four universities have started or plan more in-depth investigations. Keys to the success of this project are working as a multi-disciplinary team, financial support that includes outside lab fees, supportive supervisors, and working on a regional scale across agency boundaries, which facilitates seeing regional patterns. This growing body of information adds to the toolbox that land managers have for making management decisions.

INTRODUCTION

What drives U.S. federal land managers to manage cave resources? Priority is almost always directed towards funded programs with requirements originating from acts of Congress that have priority concerns and require special attention and protection. Governmental agencies are charged with executing congressional acts through implementing regulations that are often overseen by citizen organizations ready and willing to sue if the requirements are not implemented. These laws include:

1. Antiquities Act of 1906
2. Migratory Bird Act of 1918
3. Clean Air Act of 1970
4. Clean Water Act 1972
5. Endangered Species Act of 1973 (ESA)
6. Archaeological Resources Protection Act of 1979
7. Federal Cave Resources Protection Act of 1988
8. Paleontological Resources Preservation Act of 2009

Thus, air, archaeological, biological, paleontological, and water resources command the majority of most land manager's attention, budget, and effort. So, the question must be asked, what protects geologic resources? What protects the physical *cave*, in addition to the air, water, organisms (living and dead), and cultural resources within it?

Primarily, geo-resources rely on the indirect protection provided by the above listed laws. Conflicts with other multiple land uses such as mining can lead to habitat loss and destruction of living organisms. Archaeological or paleontological resources can also be destroyed or severely compromised. Thus, geologic protections often ride on the coattails of the ESA or other laws protecting other resources.

If a cave on federal land lies within a formal Wilderness Area, significant protections are extended to all geologic resources including caves, which is another form of indirect protection. The Federal Cave Resource Protection Act also provides significant protection to the set of caves that it covers. However, it is limited to most, and certainly not all, federal lands. (Massive areas of Department of Defense land are not included.) Also, the managing agency must formally designate the cave "significant". (The National Park Service designates all features deemed to be caves as "significant", thus avoiding the need for individual cave designations.)

Another potential rationale for protecting geologic resources in caves is an agency's mission or the enabling legislation for a park/forest/reserve etc. If a unit has been set aside to protect a cave or group of caves, then the need to shield the geologic resources is an easy case to make.

However, what if the geology of a cave is extraordinary but it doesn't merit special consideration for any of the above reasons? Why would a land manager divert financial, staff, or time resources to actively study and protect the geologic resources? Perhaps to protect their and their agency's reputation and legacy? To do the "right" thing?

Figure 1. The beauty of Lechuguilla Cave beauty in Carlsbad Caverns National Park makes it clear that it is a very special cave deserving protection. Photo by Dave Bunnell.

CASE STUDY #1: PROMETHEUS, THE BRISTLECONE PINE – A CAUTIONARY TALE

Prometheus was a living Great Basin bristlecone pine tree in east-central Nevada, USA. The tree was named after the mythological figure.

In 1964, a graduate student studying the climate history of the region decided to core the tree for its growth ring record. This method usually does not harm the tree, but the student's coring tool broke inside the tree. He received permission from the governing agency to cut it down for further study. Based on the tree ring record, the student estimated the age of Prometheus to have been around 4900 years, establishing it as having been the oldest known living tree on Earth.

While horrifying for everyone involved, the Prometheus incident did lead to the need to protect and preserve ancient trees, and to balance scientific research with conservation efforts to protect these extraordinarily long-living organisms. This case demonstrates the need for governing agencies to know about, understand, appreciate, and value their resources. After all, no one wants to be part of the next Prometheus debacle.

CASE STUDY #2: DISCOVERY CAVE

When does a geologic resource deserve special protection? How can a land manager know that a speleothem or an outcrop within a cave is extraordinary? There is no guidance from anything equivalent to the ESA or Antiquities Act. In many cases, managers rely on aesthetics. Lechuguilla Cave in New Mexico has speleothems of spectacular beauty and size (Figure 1). Therefore, it is easy to make the case that this cave exhibits extraordinary geologic resources. Lehman Caves in Great Basin National Park, Nevada, displays hundreds of distinctive and attractive shields (Figure 2). It is easy to make the case that it is a special geologic resource. Aesthetics are probably the easiest criteria for non-cave specialists to recognize and appreciate, and without a specialist evaluating a cave's geology, it is often the only geo-resources acknowledged. However, appearance should not be the only criteria for determining a cave's geologic value. The Endangered Species Act values the tiny and the ugly in the biological world. A dingy, 12,000-year-old jawbone of a Camelops (Pleistocene camel) is valued and protected even if not attractive. Likewise, some extremely important geologic resources may not stand out to the non-specialist but still deserve protection.

Figure 2. The Parachute speleothem with draperies hanging off the shields are the flagship feature of Lehman Caves in Great Basin National Park.

Discovery Cave is a relatively small cave in a canyon on the east flank of the Northern Snake Range of the Humboldt-Toiyabe National Forest in east-central Nevada (Figure 3). Less than 100 meters long, it is extensively decorated with stalactites, stalagmites, columns, popcorn, and other calcite speleothems (Figure 4). The floor is covered with deep deposits of "dirt" and organic debris, much of it derived from resident wood rats. To the casual visitor, the cave probably would not impress them as a special cave, other than its aesthetic attributes of abundant secondary mineral deposits, some rarely seen elsewhere (Figure 5). Cave geologists, on the other hand, quickly recognized a valuable geologic resource, cave folia, which is well-displayed on the walls of Discovery Cave. The folia have a measured dip of 6^{o} to the west (Figure 6), which are direct indicators of the tilting of the cave and bedrock since the origin of the folia. Therefore, the age of the folia indicates that amount of tilt during that period of time, potentially providing important information about the geologic history for this region.

Calcite folia form at and just below a water table (Hill and Forte 1997). Their bottom edges are sub-parallel to the water table at the time of deposition. These folia grew before the completion of mountain building in the region, which ended about eight million years ago (Evans et al. 2015; Rowley et al. 2017). Since the folia are older than eight million years, the cave must be even older. Based on what surface geologists had already determined, the cave could be as old as 16 million years old.

Under the folia in Discovery Cave are mammillary deposits. They must be older than the folia but younger than the cave. When we started the White Pine County Wild Caves Project in 2022, dating the Discovery Cave mammillaries was prioritized. A sample was collected (Figure 7), sent to the University of New Mexico and dated using U-Pb techniques. The well-behaved isochron determined an age of 11.4 $\pm$0.41 million years old (Figure 8).

Figure 3. Google Earth image showing the approximate locations of Discovery, Burial, and Smith Creek caves.

Figure 4. Abundant but common calcite speleothem and a dirt floor in Discovery Cave. Photo by Dave Bunnell.

Figure 5. Unique "quills" in Discovery Cave. Photo by Dave Bunnell.

Figure 6. Tilted folia in Discovery Cave strongly suggests that this cave is very old…older than the most recent mountain-building event about eight million years ago. Photo by Dave Bunnell.

Figure 7. This corroded mammillary deposit in Discovery Cave was sampled and proved about 11 million years old.

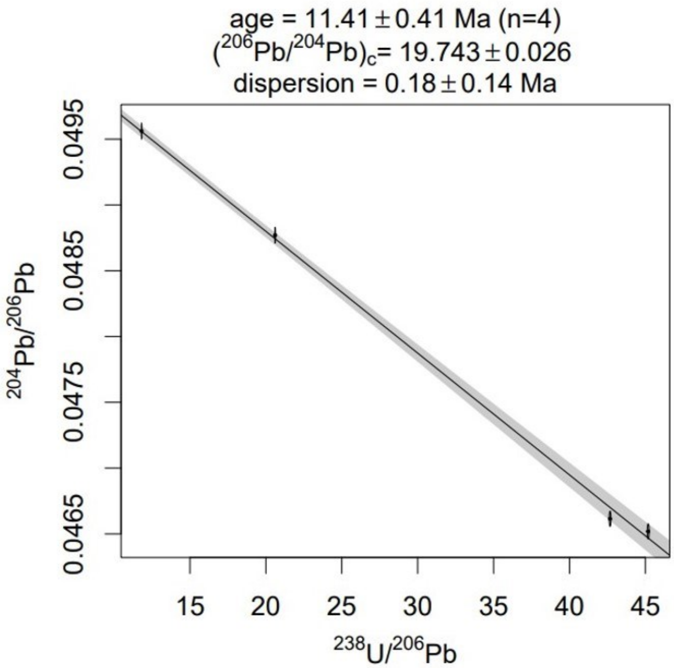

Figure 8. This isochron shows the age of the mammillary sample in Discovery Cave.

CASE STUDY #3: INDIAN BURIAL CAVE

Indian Burial Cave, a hypogenic cave on Bureau of Land Management land at the eastern base of the Southern Snake Range (Figure 3), also contains tilted folia that grew over mammillaries (Figure 9). We dated a sample from there and it records an age of 13.08 +0.84million years (Figure 10).

Figure 9. Tilted folia in Indian Burial Cave. Photo by Dave Bunnell.

INFORMING OUR UNDERSTANDING OF BASIN AND RANGE TECTONISM

The Northern and Southern Snake Ranges and the adjacent Snake Valley to the east are part of the central Basin and Range province. Simplifying the geologic history that is relevant to the caves, this area was comprised of a thick sequence of sedimentary rocks in the Oligocene, estimated to have been about 6- to 10-km thick (Miller et al. 1983; Wrobel et al. 2022) and up to 30-km thick where Mesozoic structures had repeated layers by thrust faulting and folding (Wernicke 1981). About 17 million years ago, the upper plate of a low angle fault (now called the Snake Range Décollement) slid eastward an estimated 10- and 60- km (Miller et al. 1999). Removing all this heavy load caused the remaining rocks to rebound, much as a down comforter rises and fluffs once a heavy suitcase is removed from on top of the bed. Then about 10 million years ago, the crust started to stretch and block faulting began (Figure 11). During this time period, the Snake Range rose and Snake Valley dropped.

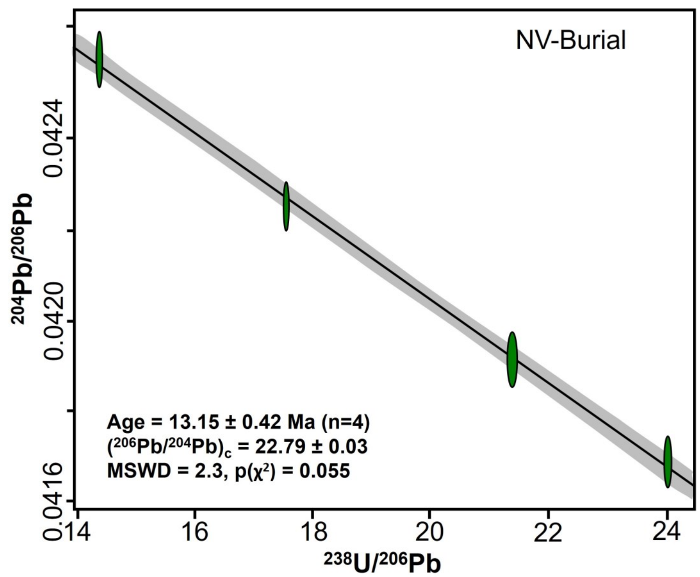

Figure 10. This well-behaved isochron shows the age of the mammillary sample in Indian Burial Cave.

Discovery and Indian Burial Caves' mammillaries grew 11- to 13-million years ago in established caves before and/or while the basins dropped and ranges rose, perhaps as early as 16 mil-

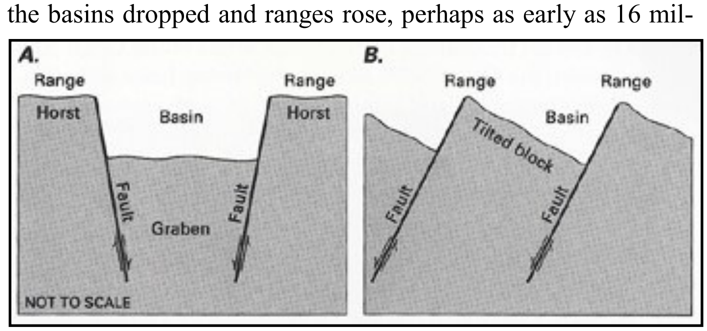

Figure 11. Cartoon showing Basin and Range extension faulting. Image by the National Park Service at: https://www.nps.gov/media/photo/view.htm?id=7FCAB69D-955D-4B19-8FCB-222547C128A4

lion years ago. These findings have implications well beyond what they tell us about the caves. These dates will help geologists refine our understanding of the timing of the events that formed the mountains and valleys in this part of the Basin and Range. The geology of these caves will contribute to better understanding the geologic history of this area and provide all geologists with more information about how and when mountain building occurred. We expect that the mammillary samples will, as work continues, also help reveal information on the environment (e.g., water temperature, water chemistry) approximately 11-13 million years ago.

Clearly, it is important to protect these two caves that host outstanding geologic resources. We expect Discovery Cave to continue as a fascinating and valuable natural laboratory. The cave is on U.S. Forest Service land and has been designated "significant". It has also been mapped, gated, and basic archaeological/historical, biological, geologic, and paleontological inventories completed. On the other hand and after many decades of recreational use, Indian Burial Cave was permanently closed by the Bureau of Land Management in 2017 to all visitations, including research, without completion of a geologic inventory. The mammillary sample from Indian Burial that was recently dated had been collected for a mineralogical study of the folia and mammillaries in the 1970s. The rest of the cave's geology has only been superficially documented.

INFORMING OUR UNDERSTANDING OF REGIONAL GEOMORPHOLOGY AND SPELEOGENETIC HISTORY

Caves serve as immense troves of preserved prehistoric and historic information. These ancient Snake Range hypogenic caves, over 10 million years old, store information about the paleo-aquifer levels and chemistry, paleoclimate, and canyon incision history. Dating allochthonous sediments (e.g., ash layers) and paleontological samples from within the caves informs our understanding of when the caves were exposed to the surface. (These hypogenic caves likely developed without entrances connecting them to the surface and were breached later.) Detailed geoinventories across a region can identify what valuable information may be derived from the caves.

GEOINVENTORY: THE CURRENT STATE OF THE ART

If a geoinventory is included in a cave mapping and inventory process, it is likely that those inventories are completed by volunteers who are not geo-speleologists. While they may do well in recording the location of the more common and expected speleothems and speleogens, many "non-standard" secondary deposits and unexpected outcrops in the bedrock may go unrecognized and, thus, isolated observations important to the big picture will not be included in the inventories. These challenges increase when working in hypogenic (artesian) caves or caves with mixed speleogenetic histories. Most cavers and most geologists are trained to understand epigenic caves (i.e., voids dissolved by water infiltrating from the surface). Just as biological surveys are typically best done by trained biologists and archaeological inventories by trained archaeologists, the best results for geoinventories come from workers well-versed in geology and, specifically, cave geology.

WILD CAVES OF WHITE PINE COUNTY PROJECT

The Wild Caves of White Pine County project, described by Baker and Powell (this volume), began in June 2022 when a team of scientist-cavers were hired to conduct an extensive, multi-disciplinary study of approximately 45 caves in Great Basin National Park and the Humboldt-Toiyabe National Forest. Prior to this project, speleo-biological inventories had been conducted by Taylor and Krejca (2003; Gilleland 2012) in both the Park and Forest as well as work done by Park staff in Lehman Caves within the Park. The U.S. Geological Survey and the state of Nevada had recently investigated the karst hydrology in the Park (Prudic and Gancy 2009; Paul et al. 2014), and Tom Aley (2012a,b) had conducted dye tracing in the Park. (The Forest has very limited karst hydrologic systems.) A team of professional paleontologists has recently been working under cooperative agreements with the Forest, where considerable work in paleontology had been done previously. A full-time paleontologist on the Park staff had made some investigations of the caves prior to his recent retirement.

Very little work had been done on the cave geology in either the Park or Forest. In the early 1960s, several U.S. Geological Survey geologist-cavers worked in Lehman Caves and occasionally park staff had contributed geologic observations to the Park files, mostly as trip reports. All other documentation of the cave geology came in the form of voluntary trip reports by cavers.

This project more-or-less put cave geology on equal footing with other disciplines. Three cavers comprised the geology team: one part-time geologist (Dr. Louise Hose), one full-time paleontologist with a doctorate in geology (Dr. Peter Druschke), and our Forest Service leader and geologist (Doug Powell). We have also been joined by several highly qualified, volunteer cave geologists. We were granted research and collecting permits from both agencies and funding for outside laboratory work was available, which has supported our mammillary dating project.

We have identified 12 more caves with mammillaries in the project and we are attempting to obtain dates for all of them. One site, Smith Creek Cave, has a mammillary deposit almost a meter thick (Figure 12). Based on proven mammillary growth rates at Devils Hole, Nevada, the Smith Creek Cave deposit may represent nearly one million years of geologic record (Li et al. 2021)! There are many other Basin and Range caves with mammillaries and dating all of them would, undoubtedly, prove useful in better defining and refining the timing of Basin and Range mountain building. But that will have to be another project.

Figure 12. This spar and mammillary deposit in Smith Creek Cave is more than 90-cm thick and likely represents hundreds of thousands of years of the region's groundwater and geologic history.

This project has resulted in many other exceptional geologic observations. In the off-trail passages of Lehman Caves in the Park, the project and associated volunteers have identified the unusual uranium-vanadium mineral metatyamunite, an acid pool, and pseudoscallops, as well as a rimmed floor vent, gypsum crusts, extensive bubble tracks, and coralloidal hollow stalagmites…all evidence pointing to sulfuric-acid hypogenic speleogenesis. In Old Mans Cave in the Forest, we have greatly extended observations about coral pipe speleothems and documented "cockscombs" (woodrat urine posts on the floor) as well as extensive paleokarst in the bedrock, which had not been documented by surface geology mapping efforts.

Our cave observations have led to identifying several glaring errors in the best available surface geology maps of the Park. Recognition that Lehman Caves dramatically changes in its northern passages led to the conclusion that there must be an overlying, mostly impermeable caprock over that part of the cave. A large, previously unrecognized quartzite block was then identified and mapped on the surface over the northern part of the cave. In the high elevation part of the Park, recognition that several caves formed in the head scarp of a major, rotated block led to identifying a very large mass wasting block that should be, but is not, on the currently available surface geology map (Whitebread 1969). In the same part of the Park, a small cave is formed completely within a large talus pile, which is also of mappable size but missing from the available maps.

KEYS TO PROJECT SUCCESS

1. Using a multidisciplinary team creates great collaboration. Everyone is a well-trained observer with scientific sensibilities, and that commonly leads to a team member alerting the appropriate specialist to something special. Several important geologic observations were first noted by one of the biologists. More observers resulted in more observations of interesting resources.

2. Financial support and use of outside laboratory analyses were a great help and rare in the world of U.S. speleology. While the tilted folia had been identified by Hose in 2016, the University of New Mexico Asmerom Lab's radiometric dating effort of the underlying mammillary deposit was key to proving the value of the site.

3. Supportive, knowledgeable supervisors were critical to our success. Both the Park and Forest supervisors worked to facilitate our achievements.

4. One of the most unique and valuable elements of this project was the ability to work across agency boundaries, allowing a regional scale perspective.

Many of the most unusual and intriguing features were seen in numerous caves, providing broad context for our observations.

WHAT DOES ALL THIS MEAN TO THE MANAGEMENT OF THESE CAVES?

While this paper limits our discussion to a few of the extraordinary geologic findings, our final report (currently in preparation) will recognize the remarkable and diverse scientific value of many of these caves. Their astonishing antiquity (three caves in this area are now documented as more than 10 million years old) demonstrates their survival through the basin-dropping and range-rising events that formed the Basin and Range Province, marking these caves as truly extraordinary on an international level. They contain geological and paleontological resources that inform us about climatic, hydrologic, and ecological conditions both underground and on the surface back into the Miocene Epoch.

The National Natural Landmarks designation looks at a site's "condition, illustrative character, rarity, diversity, and value to science and education". Many of the region's hypogenic caves are in excellent condition. They are also unique in illustrating the nature of hypogenic processes in the Miocene. They contain several rare speleothems (e.g., folia, quills, trays) as well as being unique in their documented antiquity. Their diverse arrays of speleothems and Pleistocene fossils are impressive. All of these features have and will provide internationally significant scientific and educational value. Surely these caves qualify for designation as National Natural Landmarks.

These caves and this area may meet the requirements for other prestigious designations, such as an International Union of Geological Sciences Geoheritage Site. We seem on our way to developing a strong argument that some of these caves qualify for inclusion on the World Heritage List, which required "outstanding universal value" and protective management.

Applying for designations like those mentioned above is a largely political decision that can bring positive and negative consequences. But, applying for such status isn't an option without the sort of data being documented by the Wild Cave Project.

CONCLUSIONS

Without multidisciplinary inventories and investigations like the Wild Cave Project, managers are not likely to know, understand, and fully appreciate the treasures beneath their feet. They probably don't recognize tools for more robust protection that might be available, such as special site recognitions. They risk inadvertently becoming entangled in the 21st century's next Prometheus Debacle.

In addition to basic documentation of the various caves' geologic resources, we made several findings that will revise the current geologic maps and geologic history of the area. We have added datapoints documenting when the regional water table was at various heights above the current valley and much more related data are likely to come with future laboratory results. We have added new contributions to the surface geology maps of three, previously unrecognized, "mappable" areas in the National Park resulting from observations first made in caves.

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Vital Signs: Long-Term Monitoring for Best Management of Long-Term Karst Resources

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Timpanogos Cave National Monument, 2038 West Alpine Loop Rd., American Fork, Utah 84003

Abstract

Timpanogos Cave National Monument conducts monthly cave water quality sampling and monitoring as part of an effort to observe the "vital signs" of the cave environment. In partnership with NPS Inventory and Monitoring, three cave pools are measured for physical and chemical parameters that could provide early warning signs for changes in the cave environment. Starting in 2008, park management allots budget, time, and effort for maintaining equipment, calibration, field sampling visits, and analysis of water quality data. Through the years, this effort has allowed quick identification and mitigation of impacts, insights into the hydrologic cycle, along with other less-expected results. Working with partners, the cave water quality program has led to more in-depth studies, including emerging contaminants analysis and insights into cave atmosphere. A ten-year trend report illuminated a surprising change in cave CO2 levels that has important implications for cave tour operations management worldwide. The discovery has led to a year-long in-depth study of cave CO2 levels in partnership with USGS.

Does Secrecy of Cave information Protect Caves, Karst and Public Interest

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Abstract

Most states with significant cave and karst resources have a cave survey that collects and disseminates data on the caves of their respective state. Many are incorporated as non-profit organizations and are operated by volunteer cavers. Few of those individuals have professional training or experience as resource managers which sometimes makes timely access to cave information difficult for researchers, land use managers, planners, and environmental professionals.

Some surveys, such as Tennessee and West Virginia, are relatively open with their data and willingly share it with cavers and public resource managers. Other states hold the data much closer and provide it to cavers and others on a "need to know" basis.

Caves and karst terrains are threatened by industrial and agricultural development, urbanization, rail and transportation corridors, etc. Public safety and vandalism are often cited as justification to restrict access to cave locational data. However, these data are also important for response by land use planners, resource managers, hazardous materials spill response, researchers, etc.

Caves are important locations for recharge into the underlying karst aquifers but can also act as pathways for contamination from both point and non-point pollution sources. Caves and cave streams are important points to monitor for air and water contamination from hazardous waste spills. In addition, caves can be used to inject dyes for groundwater basin delineation and dyes can also be used as surrogates for active spills.

Introduction

Most states with significant cave and karst resources have a cave survey that collects and disseminates data on the caves of their respective state. Many are incorporated under the U.S. Internal Revenue Service's 501(c)(3) code as tax exempt organizations and are directed and staffed by volunteer cavers with varied backgrounds. The ability for state surveys to respond to time sensitive requests for data is very limited – especially in addressing requests for data to assist with hazardous materials spill response. In addition, researchers, land use managers, planners, and environmental professionals also have a need for cave and karst data.

Some surveys, such as Tennessee and West Virginia, are relatively open with their data and willingly share it with cavers and public resource managers through electronic databases, published county surveys with locational data, maps and narrative files. Other state surveys hold the data much closer and provide it to cavers and others on a "need to know" basis. Some state surveys charge a fee for data searches for commercial interests.

The Importance of Cave and Karst Data

Caves and sinkholes are important locations for groundwater recharge into the underlying karst aquifers but can also act as a pathway for contamination. Caves and karst terrains are threatened by industrial and agricultural development, urbanization, transportation corridors, retail stores, sewage and hazardous materials spills and releases, point and non-point pollution, feed lots, truck wrecks, pipeline breaks, and even water from firefighting activities are threats. Caves and cave streams are also important points to monitor for air and water contamination from hazardous material spills and water degradation.

Dye tracing can be an important tool in understanding the fate and transport of hazardous materials released in karst. Dyes can be used to determine the groundwater basin boundaries, relationship between inputs and receptors (caves to springs and wells), can predict travel times and even contaminant loading or concentrations. During a release, caves, sinkholes (and trenches) can be used to inject dyes for groundwater basin delineation and dyes can also be used as surrogates for active spills or spill response planning.

Case Studies

1. While working at the Kentucky Division of Water, the Groundwater Branch was asked to provide technical assistance related to a large release of gasoline from an underground storage tank. It was in a karst area that had not been well documented by researchers but there were cavers that were active in some of the karst systems in the area. The caving group working in the area was contacted about any known caves, springs, cave streams, etc. The group responded that they couldn't release that information to the government. We asked them if they came across any gasoline vapors, that they notify us.

   Field investigations were initiated and when walking across a field to look at a sinkhole approximately 50 meters away, the wind shifted and the explosimeter pegged the needle as "too rich to explode." The wind shifted, the instrument was reading in the safe zone, and the crew moved away from the sinkhole area. A nearby gasoline station was found to have leaking tanks.

2. During the planning of the sewage treatment system for the small community of Spencer, Tennessee, sewage effluent was proposed to be discharged into a small stream/ravine flowing off the Cumberland Plateau and onto the karst near Fall Creek Falls State Park. In the ensuing years, Rumbling Falls Cave was discovered and mapped in secret with more than 16 miles of mapped cave and one of the longest cave rappels in the state. The cave was finally revealed to the engineering firm and land use planners after a considerable amount of engineering for the sanitary system had been completed. The controversy regarding the cost of reengineering the system and potential contamination of the large underground stream reached all the way to the governor's office. The sanitary discharge system was ultimately redesigned at considerable time and cost to protect the cave system.

3. A pressurized sanitary sewer line pipe broke and approximately 400,000 gallons of raw sewage was discharged into a dry stream bed within the recharge zone of the Edwards Aquifer, the primary water source for the city of San Antonio, Texas. The state cave survey was contacted to inquire about potential caves near the site for injection of dye to act as a surrogate to the sewage. The request was denied as that material couldn't be released without full board approval. This was a time sensitive issue, and the data wasn't available until many days after the release and was no longer relevant.

Discussion

Cave and karst data are important in land use planning, habitat preservation, delineation of groundwater basins, constraining groundwater velocities and contaminant loading, protecting subsurface and surface water ecologies, etc. Regulators and resource managers are tasked with protecting vulnerable karst resources, but can't protect or properly evaluate what they don't know about.

Limiting the distribution of cave data is also a safety issue as caves can present a danger to the inexperienced and unprepared. Caves are visited by neighborhood youth and can become sites for parties, vandalism of formations, spray painting (tagging), killing of bats and other wildlife, and disposal of trash. However, few caves have been impacted from the distribution of cave location data to responsible groups including organized cavers, researchers, or city, county, and state agencies, etc.

The availability of cave and karst data can also have a "time critical" component. In the event of a hazardous materials spill, dyes can be used as a surrogate to track a spill, but the trace needs to be initiated within 24 hours of a spill. Dyes are quicker and cheaper to analyze than biologic and chemical parameters defined by the Clean Drinking Water Act and can be used to identify receptors and indicate the arrival of contamination. Estimates can also be used to help constrain expected concentrations of contaminants and predict the passing of peak pollutant concentrations.

Few cave surveys are responsive enough to be able to provide timely useful data to be utilized for spill tracking - therefore, preplanning is important to successfully use dyes as surrogates.

The availability of cave data is also important in tracking volatile chemicals. Cave atmospheres can and have been impacted from commonly used materials such as gasoline and diesel fuel, crude oil, volatile organic compounds, PCBs, and sewage. Cave streams can also contain pathogenic materials from septic waste, sewage spills, and wastewater treatment plants.

As an example, sewage spills in karst create difficulties in spill evaluation and response. Untreated sewage poses a great threat to public and private water supplies as well as subterranean and surface water ecologies. Analysis of bacterial samples requires a 24-hour incubation period and expedited analysis for common parameters listed in the Safe Drinking Water Act. Most laboratories charge a premium for 24-to-48-hour turnaround for analysis.

Groundwater velocities in karst are commonly measured at 1.5 kilometers or more per day and can result in rapid impacts to water supplies. In many cases, public water supplies can't be easily turned off or replaced as they also provide fire protection to their service area. The uncertainty regarding the transport and fate of spills in many karst areas makes spill management difficult.

Dyes can be used as a surrogate for contaminants and are cheap, quick, and easy to detect in relation to biologic or chemical analyses. Identifying cave resources for dye injection is difficult without rapid access to cave inventory information. Some state surveys provide cave data which can be used as a resource in the preplanning process to emergency responders. However, this is generally the exception rather than the rule. Few state cave surveys are set up to respond quickly to environmental emergencies.

Cavers are the primary group that cares for and helps conserve caves. As caver ownership and access changes over time, some cave location data may be lost to local cavers. State cave surveys can secure and protect cave data, but the data is of little value if it isn't available to responsible cavers, researchers, and government entities.

Conclusion

The free exchange of cave data including location, access, cave maps, geologic and biologic inventories among responsible users, is critical to protect cave and karst resources and protect public health.

Cave Conservation Management and Restoration - International Workshops

Hildreth-Werker, Val
Hillsboro, NM

Abstract

With the guiding principle of *primum non nocere* (do no harm), we present philosophies, methods, and current best practices in cave restoration via online resources and in-cave workshops. International and domestic courses introduce field-friendly techniques and tools for cave restoration, speleothem repair, and human impact mitigation. Training events encourage minimum-impact caving ethics and principles for avoiding cross-contamination. Projects focus on awareness of anthropogenic effects, protection of natural and cultural resources, and consultation with speleologists in relevant disciplines. Workshops and seminars are supported by the peer -reviewed NSS volume titled *Cave Conservation and Restoration* (Hildreth-Werker and Werker; text is online at https://caves.org/wp-content/uploads/2022/06/CCR-Book.pdf). Classroom discussions and practical in-cave activities emphasize informed decisioning and questions such as whether to mitigate or not to mitigate. Teams perform in-cave impact assessment exercises and gain hands-on experience in restoring selected cave surfaces, sediments, and speleothems that have been harmed by development, infrastructure, tourism, and untutored visitation in show caves as well as wild caves. Each workshop design is appropriate to the conditions of the particular cave system and cultural region. With opportunities for in-depth analysis, in-cave application of principles, and fine-tuning of skills, participants

The Northeastern Cave Conservancy and Thacher State Park: A Collaboration Fifty Years in the Making

Berger, Mitchell

Northeastern Cave Conservancy, PO Box 254, Schoharie, New York, 12157, United States

Abstract

When a new government agency in charge of a state park closes off access to caves that had always been open to the public, it can easily seem as if a private land trust has no role to play in restoring that access. State parks and cave preserves each provide great value to different but overlapping segments of the public in both the recreational opportunities they offer and the conservation message they seek to spread. What is less often realized is that the organizations that manage these natural resources can also be of great assistance to each other. Each can provide unique capabilities to assist with management challenges faced by the other. Together, they can also expand the reach of their conservation messages to each other's audience.

In the 1970s, the community lost access to many of the caves in John Boyd Thacher State Park. We will explore the story of how attempts to regain that access began as a longshot, and in recent years have developed into a flourishing collaboration between the Northeastern Cave Conservancy and the park. Not only have we worked together on educational displays and karst inventory efforts, but at long last, the caves in the park are once again open to recreational visitors.

Partnerships and Collaborations

Seiser, Patricia[1]; Holliday, Cory[2]; Jackson, Dave[3]

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[2] The Nature Conservancy, Tennessee Chapter, 750 Big Branch Road, Granville, Tennessee 38564

[3] Dave Jackson, 13 Kreg Lane, Manitou Springs, Colorado, 80829

Abstract

This presentations addresses bringing together three organizations, one private, one Federal government, and one conservancy, with the same belief that caves and karst need to be protected and enjoyed, but with different focuses. The National Park Service (NPS) mission is to “preserve unimpaired the natural and cultural resources…{for} this and future generations. The Nature Conservancy (TNC) mission is “is to conserve the lands and waters on which all life depends.” CaveSim’s mission is to “teach people… environmental conservation and the joy of exploration.” The NPS provides support to bring CaveSim to National Park units, TNC educational events, National Speleological Society (NSS) conventions, and other educational venues. The results of this collaboration will be presented, along with the methods used to collaborate.

Introduction

The US Forest Service, US National Park Service, and The Nature Conservancy have all been collaborating with CaveSim to bring cave and karst conservation education to the public at events around the country. When we think about collaborating as organizations, it’s helpful to think about our mission statements and consider how they align. Here are excerpts of the mission statements of our four organizations:

The National Park Service (NPS) mission is to “preserve unimpaired the natural and cultural resources…{for} this and future generations.”

The Nature Conservancy (TNC) mission is “is to conserve the lands and waters on which all life depends.”

Kids at Pactola Lake (USFS) in South Dakota stand by the multi-agency CaveSim event banner.

A boy is awestruck upon entering CaveSim at a USFS-sponsored program in Los Alamos, NM in 2017. Photo by Thomas Graves.

The US Forest Service (USFS) mission is “to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations.”

CaveSim’s mission is to “teach people… environmental conservation and the joy of exploration.”

We can see commonality among the mission statements of NPS, TNC, USFS, and CaveSim. We see that the concepts of preservation and conservation align our organizations. Because our missions are aligned, but not identical, it makes sense for us to collaborate to achieve more together than we can achieve by ourselves.

A father and daughter explore CaveSim at the first event in which NPS, USFS, and CaveSim collaborated in 2017.

For those who have not been to a CaveSim educational program, a brief explanation will be helpful. CaveSim is a Colorado-based organization that creates immersive cave conservation exhibits and brings mobile versions of these exhibits to educational events around the country. At a typical program, 100-200 children explore a mobile CaveSim system while trying not to touch the speleothems, cave biota, and artifacts in the cave. Sensors embedded in each of these objects give participants feedback about their careful-caving skills, and participants receive a computerized conservation score when they exit the cave. The children love this experience, and it puts them in what psychologists refer to as a peak state, which makes the children receptive to lessons that CaveSim staff teach about conservation of bats, groundwater, caves, karst, artifacts, and more. These lessons are aligned with state academic standards, which allows schools to justify bringing the CaveSim program onto their campuses. The educational programs have been conducted in 20 states, and CaveSim has conducted an average of 129 days of program per year over the last three years (2021-2023).

In 2017, collaboration began between USFS, NPS, and CaveSim with several events. The USFS provided funding to bring CaveSim to National Get Outdoors Day in Denver, and Forest Service and NPS set up tents and tables near CaveSim. As Lima Soto said later, “CaveSim is always a HUGE hit.” This popularity was really helpful for the federal agencies because CaveSim drew a crowd to the agency tables so that USFS and NPS staff could share more information with the public about conservation and encourage the public to visit park sites with caves.

The collaboration in 2017 continued when the USFS helped provide funding to bring CaveSim to New Mexico for the NSS Convention and to public events at the New Mexico Museum of Natural History and Science as well as the Pajarito Environmental Education Center. These public events were very well attended and received local media attention. Local members of the National Speleological Society also helped with these events to help provide the public with information about how to get involved in wild caving the proper way should they choose to do so.

In 2018, the USFS provided some of the funding to bring CaveSim to Helena, MT for the NSS Convention where I worked with local kids from a science summer camp as well as local families who came for free educational events. The USFS once again set up tables with displays and activities so that families from the Helena area could learn about Forest Service resources in the region.

At all of the CaveSim events mentioned herein, participants learned about how caves and speleothems form, about cave

USFS staff and volunteers enjoyed exploring CaveSim at Pactola Lake in 2019.

exploration and safety (in both horizontal and vertical caving), about bat biology and White Nose Syndrome (WNS), and about cave rescue and what it takes to be a safe explorer.

Later in 2018, NPS continued to collaborate with CaveSim by putting on educational programs for schools at Cumberland Gap National Historical Park, and at schools around Mammoth Cave. These programs allowed park rangers to teach alongside CaveSim staff, which is a really effective way for students to learn more about National Parks in their local area.

In 2019, a public celebration was held in Custer, SD after the discovery of the 200^{th} mile of Jewel Cave. The Black Hills Parks and Forests Association (a non-profit that supports both NPS and USFS) made it possible for CaveSim to put on public

Co-author Dave Jackson teaches students in Kentucky about fragile gypsum flowers and how they form in caves.

events in downtown Custer and at a Forest Service visitor center (Pactola Lake).

Collaboration did not stop during the COVID-19 pandemic. Co-author Dave Jackson worked with Chuck Bitting at Buffalo National River to put together an educational video about karst hydrogeology. Dave and his young son built a 9-layer karst cake and then poured milk on top to demonstrate the dangers of groundwater pollution. Dave's wife Tracy Jackson is a geologist and science educator, and she included numerous geology lessons in the video.

The Nature Conservancy (TNC) also began collaborating with CaveSim during the Covid19 pandemic. Co-author Cory Holliday had published an educational video showing how TNC, USFS, and other organizations were working together to study and combat WNS. The pandemic had caused CaveSim to switch from in-person to online educational programs for schools, and Cory was kind enough to allow CaveSim to use the Nature Conservancy WNS video to educate students about WNS. This was especially helpful because some students raised concerns about the potential role of bats as a COVID-19 intermediate host species. Sharing the Nature Conservancy video helped CaveSim staff explain the ways in which high human population densities create bat-human interactions that can be problematic for both bats and humans.

TNC and CaveSim began collaborating on in-person educational programs in early 2023. TNC funded CaveSim programs at Jackson County Middle School in Gainesboro, TN, and the students absolutely loved it. TNC staff ran educational games about bat conservation and WNS, while CaveSim staff used the mobile cave exhibit and the Single Rope Techniques (SRT) tower to teach the students about caves and karst. Co-author Cory Holliday knew conceptually that we need meaningful engagement with kids to help them understand the value of cave resources, and the program at Jackson County Middle School was a trial run to help Cory determine if CaveSim is a tool that can be effective in building a constituency for conservation. Having an eighth grader in the school and knowing some of the teachers allowed Cory to get an inside perspective about how CaveSim was received. The students loved the program, and the feedback was entirely positive. Cory observed that the students really connected with the experience and lessons from CaveSim. Because the CaveSim lesson plans can be adapted to each region of the country, the lessons enabled TNC and CaveSim staff to incorporate information about local cave and karst resources that the kids could identify and be proud of. It was obvious that CaveSim is indeed an effective tool for building conservation advocates among our youth.

In the summer of 2023, the USFS and NPS helped bring CaveSim to West Virginia for the NSS Convention, and TNC was able to provide additional funding for the mobile cave to attend the 4-H Pioneer Camp in McMinnville, TN. The camp attendees were from a wider geography, but still connected really well with the CaveSim program because each youth participant was able to connect the lessons with the resources in their area of the state. Plans are currently underway to bring the CaveSim program back to one of the 4H camps in the summer of 2024.

By bringing multiple organizations together, we are able to bring the highly-engaging CaveSim conservation and science program to thousands more students around the country. We encourage you to join us in future collaborations.

The Spectrum of Cave Management and Protection: How Legislation, Regulations, Policies, and Case Law Intertwine

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Abstract

Caves can be owned and managed by the government, commercial entities, private owners, and conservation organizations. All of these stakeholders are subject to laws, regulations, and policies. This presentation gives an overview of what laws, policies, and regulations exist and how they impact different owners and managers. These include NPS and BLM regulations, resource specific acts, cave specific acts, tribal acts, state laws, and organizational policies. Compare selected states' cave protection laws and see examples of how they have been tested in the legal system. Also examine how different organizations can create and implement policies in order to effectively protect themselves and their caves. Using this overview, consider how you and your organization can better incorporate and utilize applicable laws and regulations and build upon those to be a better and more successful cave steward.

Oral Presentations

Cave and Karst Biological Studies Session

Chair: Jerry Lewis

Phylogeography, Speciation, and Cryptic Diversity in Pseudosinella Cave Springtails (Entomobryomorpha: Entomobryidae) of the Interior Low Plateau and Appalachian Valley & Ridge Karst Regions

Cramphorn, Brendan[1]*; Katz, Aron*[2,3]*; Niemiller, Matthew L.*[1]

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Abstract

Caves offer a unique opportunity to study the ecology and evolution of life in extreme environments. Many different groups of invertebrates and vertebrates have evolved similar adaptations to living in habitats that lack light and generally have limited energy resources. However, the same processes that drive diversification in subterranean fauna can also obscure true levels of biodiversity. Traditional taxonomy of most subterranean organisms has relied heavily on morphology. However, several molecular studies in recent years have uncovered high levels of cryptic diversity in some subterranean organisms in which more widely distributed species that were delimited previously using morphology are comprised of multiple, genetically distinct lineages. Unfortunately, due to the lack of taxonomic expertise and the difficulty of specimen collection, many subterranean species remain to be genetically studied. One such group is cave-adapted springtails of the genus Pseudosinella. The ongoing study levies over 300 specimens of *P.christianseni*, *P. hirsuta*, and *P. spinosa* from over 50 caves broadly distributed

Cave-Dwelling Fauna of the Wheeler National Wildlife Refuge Complex in Northern Alabama, USA

Niemiller, Matthew L.[1]; Slay, Michael E.[2]; Inebnit, Thomas[3]; Miller, Benjamin[4]; Tobin, Benjamin[5]; Hinkle, Amata[1]; Cramphorn, Brendan[1]; Cline, Eric[1]; Dooley, Katherine E.[1]; Higgs, Jared[1]; Jordan, Emma[1]; Niemiller, K. Denise K.[1]; Hubbell, J.B.[6]; Jones, Bradley D.[6]; Mann, Nathaniel[7]; Pitts, Steve[8]

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[5] *Kentucky Geological Survey, University of Kentucky, Lexington, Kentucky 40506, USA*

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[8] *Southeastern Cave Conservancy, Inc., Signal Mountain, Tennessee 37377, USA*

ABSTRACT

The 35,000+ acre Wheeler National Wildlife Refuge (NWR) Complex in northern Alabama, USA was established in 1938 for migratory birds and other wildlife. Although designated as a waterfowl refuge, the Wheeler NWR Complex managed by USFWS protects several important cave systems and their respective faunas at the Sauta Cave NWR, Fern Cave NWR, and Key Cave NWR. We conducted the first comprehensive bioinventories of aquatic and terrestrial vertebrates and invertebrates in several caves on Wheeler NWR in 2018–2022, including multiple trips to different sections of Fern Cave, Alabama's largest cave system. In addition, we compiled additional biological records from the scientific literature, biodiversity databases, and museum accessions to provide USFWS with important data on cave biodiversity, particularly species of conservation concern, on their properties. We documented >200 taxa, including 40+ cave-limited species. The Fern Cave system is particularly diverse with 27 cave-obligate taxa and is now recognized as a global hotspot for subterranean biodiversity. Moreover, caves on the Wheeler NWR Complex are critically important habitats for several federally endangered species, including Gray Bats (*Myotis grisescens*), Indiana Bats (*M. sodalis*), Alabama Cavefish (*Speoplatyrhinus poulsoni*), and Alabama Cave Shrimp (*Palaemonias alabamae*)

Systematic Microbiological Sampling of Karst Groundwaters in Virginia

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Abstract

We conducted a systematic investigation of the microbial communities and environmental DNA (fauna detection) present in cave-accessible groundwaters across four different karst regions in Virginia-- the Shenandoah Valley, Highland, New River Valley, and Mountain Empire Region. Two caves per region were selected based on their relation to known endemic subterranean species, geology and groundwater connections to evaluate if these parameters influence the composition of microbiological communities present. Our systematic inventory of microorganisms combined with groundwater geochemistry provides a strong foundation for understanding the interconnectivity of subterranean fauna with microorganisms and groundwater. Little is known about the habitat requirements of subterranean fauna— specifically, the extent to which the composition of aquatic microbial communities or water chemistry creates a suitable habitat. Baseline measurements increased our understanding of existing biological resources and will enable future studies of how seasons, aquifer levels and surface disturbances affect the composition of cave-resident microbial communities. These data will be used by various VA stakeholders to inform their management strategies.

Introduction

We systematically investigated microbial communities and environmental DNA in cave-accessible karst groundwaters across Virginia. Precedent for these types of systematic surveys and comprehensive biological inventories in the Virginias exists; in recent years systematic surveys of known caves that had already been biologically surveyed were completed. These systematic surveys, which included collecting all macrobiotic species across different habitats in a cave, immensely increased our understanding of subterranean biology and resulted in the discovery of several new species that inhabit Virginian karst areas. Because systematic surveys of previously biologically inventoried caves resulted in so many discoveries, we predicted that our systematic inventory of the unseen aspects of these caves-- specifically microorganisms, environmental DNA, and water chemistry-- would help establish a strong foundation for understanding the interconnectedness of subterranean fauna with microorganisms and groundwater. This is particularly important because little is known about the habitat requirements of subterranean fauna. Specifically, the extent to which the presence of certain aquatic microbes or specific water chemistry is required to create a suitable habitat for subterranean fauna remains unclear.

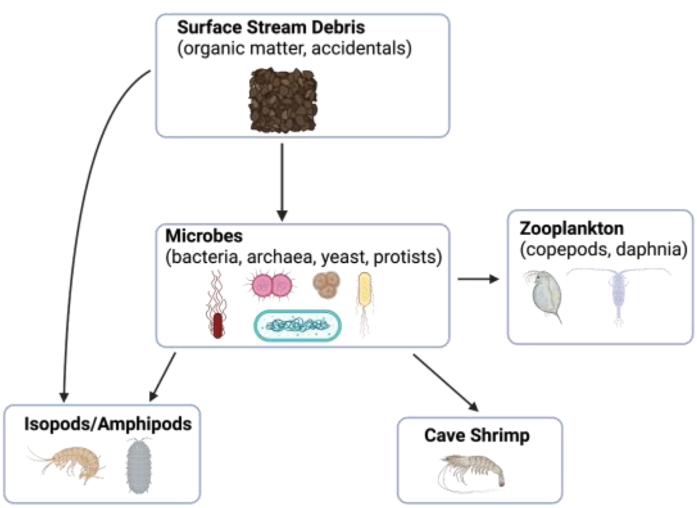

Figure 1: *Hypothesized food web diagram for aquatic cave habitats. Created with Biorender. Adapted from Helf, K.L., Olson, R.A., 2017. Subsurface Aquatic Ecology of Mammoth Cave. In: Hobbs, H.H., Olsen, R.A., Winkler, E.G., Culver, D.C. (eds.) Mammoth Cave, Cave and Karst Ecosystems of the World. Springer International Publishing. 209-226. Original figure modified from Barr and Kuehne (1971).*

Study Design

To be systematic in our survey of unseen karst groundwater biology, we worked with geologists familiar with the area to divide Virginia into four major karst regions. In consultation with members of the Virginia Department of Conservation and Recreation, Natural Heritage Program-- specifically Cave and Karst Field Scientist Katarina Kosič Ficco PhD, Karst Protection Coordinator Wil Orndorff, and Lead Cave and Karst Scientist Tom Malabad PhD-- we selected two caves in each of the karst regions of Virginia as sampling sites for our initial survey. Sites were selected for their relation to known endemic species, site diversity across karst regions, and for their relationship to different aquifers. At each site, we collected samples for microbiological sequence analysis, environmental DNA analysis (fauna detection), and water geochemistry (dissolved mineral matter). Sampling sites for Virginia are shown in Table 1. See Section 6, "Geologic Aspects of Study Design: Virginia," for further description of and justification for the selected karst regions.

Specific Aims

The goal of this project was to collect systematic baseline measurements of the aquatic microbial communities, water geochemistry, and environmental parameters in caves across different karst regions in Virginia. To enable comparisons, about half of the sample sites were cave areas where endemic species has previously been identified. The data generated by these experiments—specifically, a broad systematic survey of cave microbiomes across a particular region—is (to our knowledge) the first of its kind. These data will enable future study of how seasons, aquifer levels, and surface disturbances affect the composition of cave-resident microbial communities.

Motivating Questions

(1) Can baseline measurements of the microbial occupants of cave-accessible karst groundwater be used to monitor cave ecosystems?

(2) Are aquatic microbial communities shaped by local geology? Aquatic geochemistry?

(3) Can we identify a correlation between cave-resident aquatic microbial communities and the presence or absence of specific aquatic subterranean invertebrate species?

Geologic Aspects of Study Design: Virginia

We selected our sampling sites across four karst regions in Virginia, stretching from East to West (Figure 2). These areas feature a variety of karst phenomena-- sinking streams, discrete swallow holes, springs, open shafts, sinkholes, large open stream resurgences, losing streams, entranceless caves, and covered sinkhole plains. The stratified faulted and folded geology along the Shenandoah Valley and the Appalachian Mountains produced numerous compartmentalized (isolated) karst areas. These areas provide critical habitat for several rare subterranean species. Because species cannot migrate between the karst compartments, degradation of an isolated karst area may result in the extinction of endemic species.

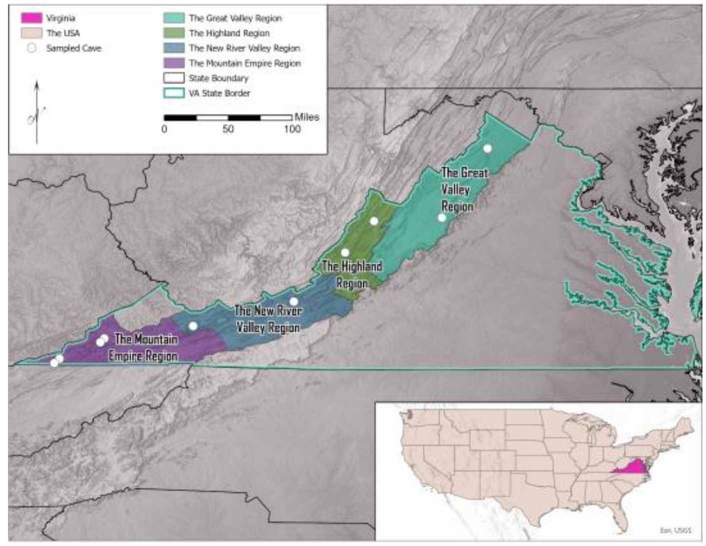

Figure 2: *The four karst regions of Virginia. Map generated by Katarina Kosič Ficco using internal databases created and maintained by the Virginia Department of Conservation and Recreation, Natural Heritage Program, Karst Program; basemap by ESRI.*

The four karst regions of Virginia (Figure 2) are differentiated based on their geological and physiographic characteristics. Carbonate rocks in Virginia range from the Cambrian to the Upper Triassic period. However, most documented caves are located in Paleozoic carbonate rocks, where predominant cave formers are Cambrian, Ordovician, Silurian, Devonian, and Mississippian limestones and dolostones (Palmer and Palmer, 2009) (Figure 2).

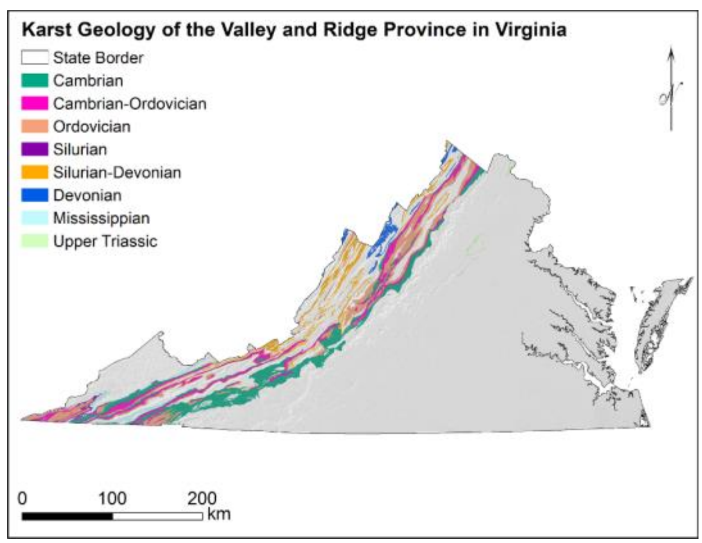

Figure 3: *Karst Geology of the Valley and Ridge Province in Virginia. Map generated by Katarina Kosič Ficco using internal databases created and maintained by the Virginia Department of Conservation and Recreation, Natural Heritage Program, Karst Program; basemap by ESRI.*

To date, there are approximately 2,900 caves recorded in Virginia. Most caves follow the fractured and joint-controlled strata and are often steeply dipping (Palmer and Palmer, 2009; Kosič Ficco, 2019). The stratified (Figure 3), faulted, and folded geology of the Appalachian thrust belt produced compartmentalized karst consisting of numerous isolated karst areas. This stratification provides for isolated self-confined aquifers, typical for the Valley and Ridge province (Palmer and Palmer, 2009; Kosič Ficco, 2019). Karst aquifers are recharged by the waters flowing from the sandstone-capped ridges that infiltrate through discrete swallow points and sinking streams or diffusely through the soil, regolith, and, most commonly, sandstone talus that covers the uplands of the mountains. Therefore, allogenic recharge is predominant in this area (Ginsberg and Palmer, 2002; Culver and White, 2005; Palmer and Palmer, 2009; Kosič Ficco, 2019). Isolated and compartmentalized karst provides a wide variety of cave life and several rare species known only from Virginia. Virginia has approximately 200 documented cave-limited invertebrate species, of which 150 are considered globally rare, the majority known only from Virginia. As the cave biology inventory continues, more and more new species are found.

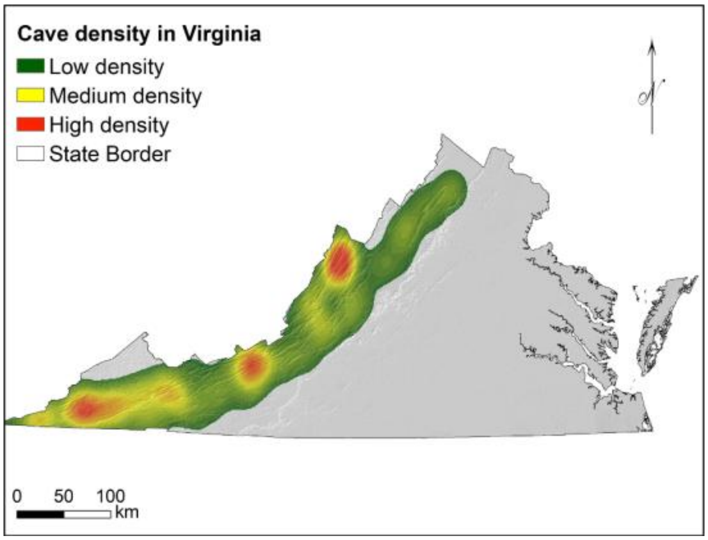

Figure 4A: Cave density in Virginia. Map generated by Katarina Kosič Ficco using internal databases created and maintained by the Virginia Department of Conservation and Recreation, Natural Heritage Program, Karst Program, in combination with data from the Virginia Speleological Survey; basemap by ESRI.

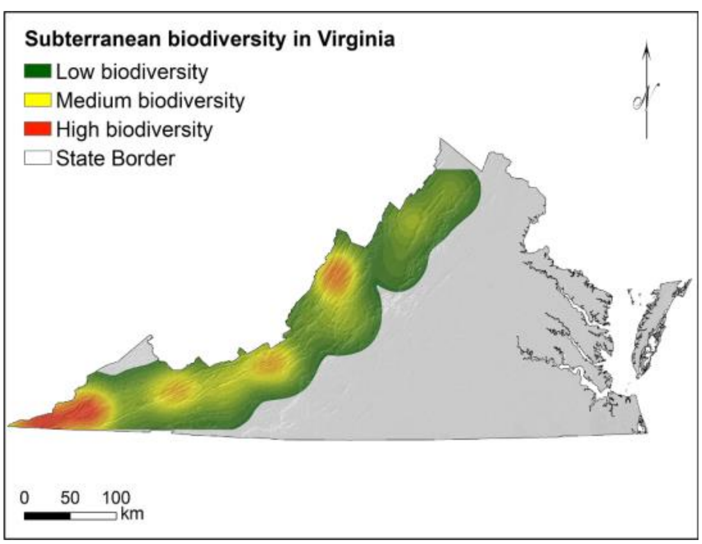

Figure 4B: Subterranean biodiversity in Virginia. Map generated by Katarina Kosič Ficco using internal databases created and maintained by the Virginia Department of Conservation and Recreation, Natural Heritage Program, Karst Program in combination with data from the Virginia Speleological Survey; basemap by ESRI.

The largest of Virginia's biodiversity hotspots are in the Highland and the Mountain Empire Regions (Figure 4B). The variety and quantity of species generally correlate to the number of identified and surveyed caves in a specific region (Figure 4A, 4B). An exception is in extreme Southwest Virginia, which is a national subterranean biodiversity hotspot (Culver et al., 2018), features a wide variety of subterranean species despite lower cave density. Particularly here, a species that live in only one karst spring or a single cave can be found. As such species remain limited to such a small habitat, the depletion of resources becomes a significant concern.

Entranceless caves that are completely sealed from the surface (Culver and White, 2005) and only uncovered by excavation are typical for the Highland Region, where Silurian and Devonian limestones are the predominant cave formers. Maze caves and large fossil passages characterize this region. Caves here exhibit helictites, aragonites, and highly preserved relics of coral reefs. The Highland Region is also the second-largest biodiversity hotspot in Virginia (Figure 4B).

The Great Valley Region in the Shenandoah Valley presents an entirely different character. Karst is deep-seated and generally developed in the Cambrian and Ordovician age bedrock. Shallow groundwater, autogenic recharge, and large karst springs are predominant (Palmer and Palmer, 2009). Here, caves are typically smaller and not particularly deep. Although limestone is occasionally exposed at the surface, and tourist caves are common in this region, cave entrances are often concealed. Access to the subterranean world is limited due to thick cover layers, which hampers our understanding of the Great Valley underground world and its biodiversity. Still, in this region, a wide variety of rare cave species can sometimes be found in a single, tiny cave. It is also home to a federally threatened species *An-*

trolana lira. This aquatic isopod lives in the deep phreatic zone and can only be found in the Great Valley of Virginia and West Virginia in the USA (Culver and White, 2005).

The New River Valley and Mountain Empire Regions share several similarities. Both regions are characterized by extensive cave systems and have the longest and deepest caves in the State. Ordovician and Cambrian limestones are the predominant cave formers in these regions. However, the largest cave systems in the Mountain Empire are formed in Mississippian limestone.

In extreme southwest Virginia, caves change character once again. Caves and karst in this area have little vertical relief. However, they provide a wide variety of karst phenomena, such as karst windows, big trunk passages, resurgences, unroofed cave passages, and perched springs (Culver and White, 2005; Palmer and Palmer, 2009; Culver et al., 2018). Caves in this area provide habitat to a wide variety of cave life, making them a biodiversity hotspot (Figure 4B).

Cave	Region
Madison Saltpeter	Great Valley
Ogsden	Great Valley
Helectite	Highland
Warm River	Highland
Unthanks	Mountain Empire
Rocky Hollow	Mountain Empire
Stompbottom	New River
Smokehole	New River

Table 1: *Primary sample sites for our initial systematic microbiological study of karst groundwaters in Virginia. Two caves were selected in each region. Sites were selected for their relation to known endemic species, site diversity across karst regions, and for their relationship to different aquifers.*

Methodology

Selecting Sample Sites in Cave

We sampled the water as it characteristically exists in the cave (e.g. a moving stream), and collected additional samples in places where the water changed character (e.g. a deep pool, or flowing over a different type of rock). To enable future resampling, each sample site was photographed, and survey equipment will be used to record the position of the sampling site relative to the nearest survey marker.

Sample Collection

Samples and preparation controls were collected outside of the path of human travel using aseptic technique and pre-sterilized cleanroom gloves (McMaster, 2815N11). Collected organisms were stored on ice prior to being processed. If it appeared that the sampled subterranean pool was being fed by the seepage of water through the epikarst, we additionally collected a soil sample on the surface above the subterranean pool.

Figure 5: *Measurements and samples collected at each sampling site. Figure created with Biorender.*

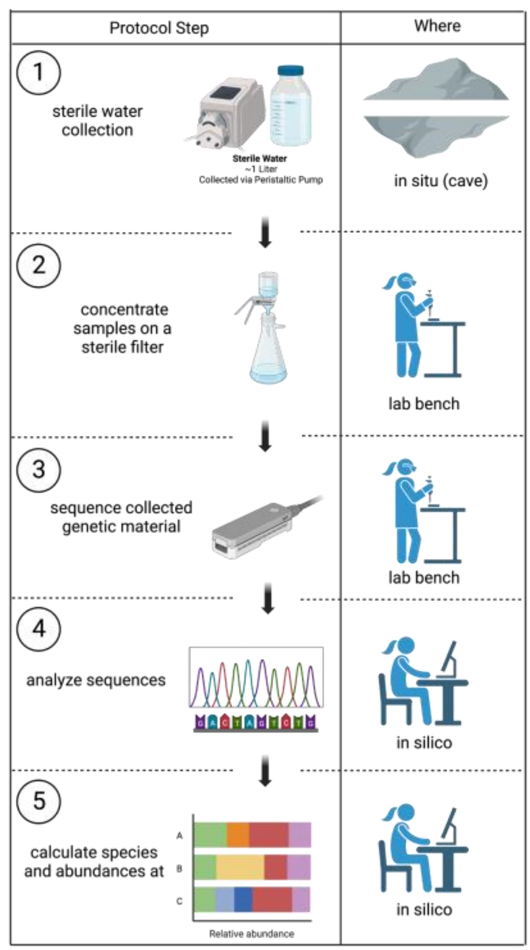

Figure 6: *Schematic overview of sample collection and analysis. Figure created with Biorender.*

Genomic Sample Processing

Genomic DNA was extracted using the DNeasy PowerSoil Pro Kit (Qiagen 47014). The extracted genomic DNA was split--one portion of the extracted gDNA was reserved for 16s stepout PCR, while the remaining gDNA was sequenced directly. For the 16s stepout samples, the V3/V4 variable region was amplified using the universal primers 515F (GTGCCAGC MGCCGCGGTAA) and 806R (GGACTACHVGGGTWTCTAAT) (Caporaso et al., 2011). Each PCR reaction contained 25 ul Long Amp Taq Master mix (New England Biolabs Inc, M0287S), 100 uM of the indexed primers, and 4 ng of template DNA, and was brought to a final volume of 50 ul using molecular grade water. The PCR was carried out as described in (Caporaso et al., 2011). Both the 16s stepout PCR products and the extracted gDNA were subjected to the following cleanup: Any potential upstream contaminants were removed from the extracted genomic DNA using 2.2 volumes of AMPure XP beads (Beckman Coulter A63881) which were subsequently washed 3x with 80% ethanol on a microcentrifuge tube magnet (Eppendorf 12321D). After drying, the genetic material was eluted off of the AMPure beads using ultrapure water (Gibco 15230001). Following quality control analysis by the Qubit 4.0 fluorometer (Q33238) and Agilent 4200 Tape Station System, these libraries were prepared with the manufacturer's library preparation kit (Oxford Nanopore SQK-NBD112.24) and sequenced on a nanopore MinION flongle flow cell (Oxford Nanopore FLO-FLG001), according to manufacturer's recommendations.

Figure 7: Sampling in Stompbottom Cave. Kosič Ficco unpacks the peristaltic pump while Drake takes notes. Photo by Mike Ficco.

Computational Methods

We performed basecalling locally using Guppy for Nanopore sequencing and then implemented Nanofilt for quality trimming and filtering (De Coster et al., 2019). We then used NanoR, "A user-friendly R package to analyze and compare nanopore sequencing data," for initial comparisons between sequencing runs and to determine whether resequencing was required (Bolognini et al., 2019). Once we were satisfied with the depth and quality of the sequencing runs, read data was demultiplexed and trimmed using bcl-convert 3.8.4 using Trimmomatic version 0.36 with the following parameters: LEADING:3 TRAILING:3 HEADCROP:5 SLIDINGWINDOW:4:15 MINLEN:36 (Bolger et al., 2014). Data was then analyzed using the QIIME 2 pipeline (as described in Kuczynski et al., 2011) and compared to results produced by EzBioCloud's 16S database (Yoon et al., 2017).

Discussion of Interim Findings

We first asked whether we could distinguish between samples from different karst regions based on their groundwater geochemistry. To visualize this, we used a Principal Component Analysis (PCA) to reduce the dimensionality of the 30-dimensional matrix containing the values for 15 measured cations and 15 measured anions in 2-dimensions. Interestingly, this dimensionality reduction (Figure 8) did not show a clear separation between the karst regions. After calculating the PCA, we ran k-means cluster analysis (run iteratively, testing n=2,3,4 or 5 clusters) and found that none of the major karst regions clustered together, suggesting that the geochemical composition of cave-accessible karst groundwater (across all cations and anions

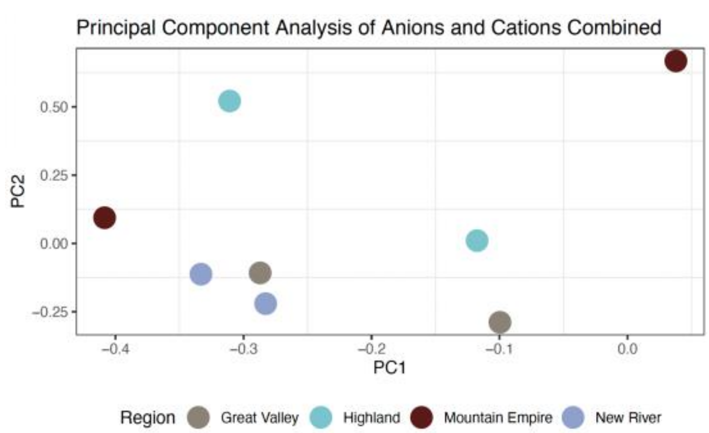

Figure 8: Principal Component Analysis of Cation and Anions measured in cave-accessible groundwater at primary sampling sites across 4 karst regions. In caves where multiple samples were taken, the median value was used for this analysis.

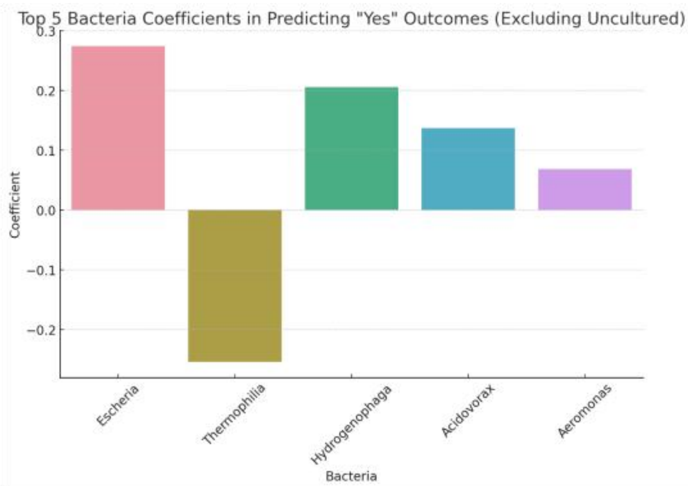

Figure 9: *Bar graph displaying correlation coefficients between the presence of aquatic isopods and certain bacterial genera. The data shown represents aquatic microbial communities measured across 16 sites in 12 caves. 9 of the sites in this analysis had the confirmed presence of aquatic isopods.*

measured) is not directly controlled by the karst region-- at least among the small number of caves (n=8) that we sampled.

One of the goals of this study was to describe the habitat requirements of subterranean fauna more precisely. Because we knew that some karst regions had a higher diversity of subterranean fauna and did not see a marked difference in groundwater geochemistry between regions, we next considered whether the presence of specific bacterial genera might be correlated with the presence of specific invertebrate fauna. We found a weak correlation between the presence of aquatic isopods and specific bacterial genera (Figure 9). These weak correlations suggest that further study is warranted to further untangle the possible relationship between aquatic microbial communities in caves and cave-resident aquatic invertebrates.

Conclusions and Future Directions

In this pilot study, we captured a snapshot of the microbiology and geochemistry of some aquatic communities in caves across the four karst regions of Virginia-- all primary samples were collected during the same week of May 2022. The patterns and properties of the aquatic communities we sampled provide a critical baseline for future studies. Future sampling across longer time scales and more caves will be required to test the hypotheses we developed in this pilot study. Our initial data (not shown) suggests that aquatic microbial communities vary between regions but do not directly correlate with the geochemical composition of the water. Further analysis of our data and future studies will consider a possible relationship between cave-resident aquatic microbial communities and the invertebrate species. Follow-up studies will include repeated sampling of the same areas in the same caves, as well as increased sampling density (geographic resolution) to better understand the impact of geologic units and the effect of microclimates on the microbial communities and invertebrate members of aquatic ecosystems in caves. Finally, further sampling will help us understand whether certain bacterial species are endemic to particular caves or karst areas in Virginia, as is the case with many cave-resident invertebrate species in Virginia.

Acknowledgments

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A Few Lessons Learned from Virginia Groundwater Isopods

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Abstract

The publication of the monograph of groundwater isopods of Virginia and the surrounding Appalachians (Lewis, et al., 2023) was the result of six years of work by a team from Virginia, Indiana and France. The completion of this work, which is the largest publication concerning the North American subterranean isopod fauna ever written, included 50 species of isopods, 24 of which were descriptions of species new to science.

The stage was set for the creation of this monographic treatment of groundwater isopods by the presence of the richest subterranean isopod fauna in North America, which was already known to occur in the caves and other groundwater habitats of Virginia (Lewis, 2009a). In addition, cave isopods were in the spotlight in Virginia, because two species are on the U.S. Fish and Wildlife Service list of threatened and endangered species. These are the Lee County cave isopod, *Lirceus usdagalun,* and the Madison cave isopod, *Antrolana lira*.

Publication of the Virginia groundwater isopod monograph was the result of intersecting circumstances that came together at the right time and place. In addition to the skillsets of this team of people combining to provide the raw material for providing all of the disparate pieces necessary to write the manuscript, the final piece of the puzzle was, ironically, the COVID-19 pandemic. The quarantine necessitated by the rampant spread of the virus facilitated the availability of the time to focus solely on writing and publishing the results of this large piece of research. The several years-long path to the completion of the book was paved with constant surprises and non sequiturs. We share a few of them here.

Common, widespread species are mostly neither common nor widespread—The diversity of isopods in the Appalachian Valley and Ridge karst of southwestern Virginia is the greatest known among asellid isopods in North America. As is being seen with other karst-related invertebrate groups, we found that species that had been viewed as widespread were usually complexes of cryptic species. The reason can be traced to the complex geology and geography, particularly in southwestern Virginia. The upper reaches of the Tennessee River form a complex dendritic pattern where the river's major tributaries – the Powell, Clinch and Holston rivers (figure 1) – bifurcate repeatedly around ridges, with their ultimate sources being springs emerging from one of the countless caves. The result of this

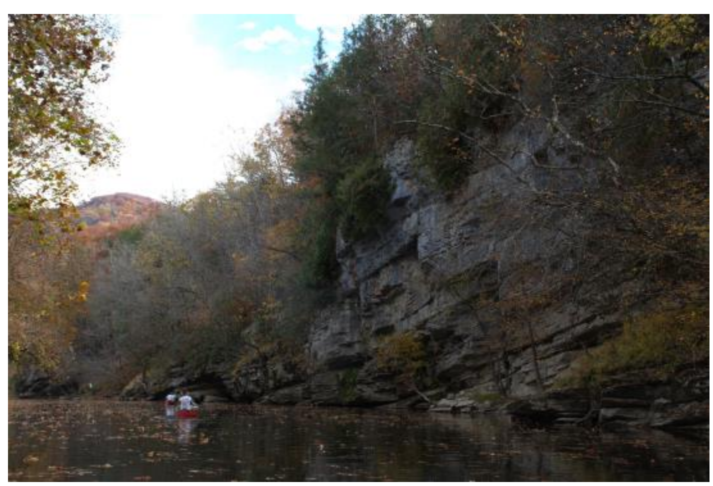

Figure 1. A scene on the Powell River, in southern Lee County, Virginia. The Powell, Clinch and Holston rivers in southwestern Virginia are each isolated by high mountains, and further subdivided by numerous smaller ridges. Massive limestone cliffs along the Powell River make some sections simplest to access for collecting trips by canoe (photo by J. Lewis).

abundance of geographic dispersal barriers is a wealth of opportunities for vicariance, and endemism is extreme. For example, when our work commenced in 2016, within the genus *Lirceus* there were only three species known in southwestern Virginia, all with essentially identical genital morphology that classical taxonomy would identify as the same species. These were the two stygobiont species, *Lirceus usdagalun* and *Lirceus culveri*, and one spring-dwelling species, *Lirceus hargeri*. The diversity discovered in Virginia was so great as to merit the creation of a new subgenus, *Hargerellus*, to receive the array of newly described cryptic species formerly identified as *Lirceus hargeri* and the related stygobiontic species. We described 13 new species of *Lirceus* (*Hargerellus*) in southwestern Virginia and adjacent Tennessee. There are now a total of seven described troglomorphic obligate cavernicolous species of *Lirceus* (*Hargerellus*) (figures 2, 3).

Figure 2. Collecting the type specimens of a new species of troglomorphic isopod, Lirceus bisetus, from Lane Cave, in Scott County, Virginia. From left to right, Salisa Lewis, Zenah Orndorff and Wil Orndorff (photo by J. Lewis).

Not all "cave" isopods live in caves—Many troglomorphic isopods do not live in caves. The unconsolidated deposits of the Coastal Plain of eastern Virginia are replete with populations of isopods (*Conasellus*) that have eyes that are reduced or absent, and little or no pigmentation. In an area where caves and karst

Figure 4. Chris Hobson at a seep in the Crow's Nest Natural Area Preserve in the Virginia coastal plain, where a population of the stygobiont isopod Conasellus hobsoni occurs. The water emerges from soil (photo by J. Lewis).

are absent, these species inhabit shallow soil interstices (figure 4). Within these saturated soil habitats the isopods are invisible to humans, but their presence becomes evident when they emerge in seeps, or the streams and ditches fed by the seeps. Sometimes these isopods can also be found in artificial windows into the groundwater, like agricultural drain tiles and wells. One of the Coastal Plain species are among the most en-

Figure 3. Examples of a range of morphological adaptations to subterranean existence among Virginia isopods of the subgenus Lirceus (Hargerellus), all described as new species by Lewis, et al. (2023). From left, Lirceus fonticulus, Cave Spring Cave, Lee County, a typical spring dweller; Lirceus bisetus, Lane Cave, Scott County, a stygobiont species with reduced eyes and pigmentation; Lirceus orndorffi, Hugh Young Cave, Tazewell County, another stygobiont species with reduced eyes and pigmentation; Lirceus littonensis, Litton Cave, Lee County, a completely eyeless and unpigmented stygobiont (photo by J. Lewis).

dangered subterranean isopods in Virginia, because the region along Chesapeake Bay and the Atlantic coast are among the most heavily populated and disturbed by humans in the state. *Conasellus meriwetheri* is a newly described species that inhabits the south side of Chesapeake Bay near its mouth, in the re-

Figure 5. The stygobiont Conasellus hobsoni exhibits variation in pigmentation, ranging from individuals with light brownish pigmentation and vestigial eyes (left), to completely unpigmented and eyeless (right) (photo by J. Lewis).

gion known as the Tidewater where streams flow from the Great Dismal Swamp into coastal estuaries. It appears from the large size of historic collections by Leslie Hubricht and others that this species was probably once abundant in this area. Today, the areas where these populations once existed are covered by the cities of Suffolk, Chesapeake, Norfolk, and Virginia Beach. The only sites not covered by roads, buildings or other infrastructure are mostly within the Great Dismal Swamp National Wildlife Refuge. To the best of our knowledge, the Tidewater groundwater isopod has not been seen in the 21st century – the status of this critically imperiled species is unknown.

<u>Appearances can be deceiving</u>—Troglomorphism is a slippery slope when it comes to speciation. We found that in some populations, the isopod *Conasellus hobsoni* has pigmented and unpigmented morphs inhabiting the same habitat and living side-by-side (figure 5). Of the four genera of asellid isopods inhabiting groundwaters in Virginia, we found that the greatest phenotypic plasticity was manifested in the genus *Conasellus*. That is to say, the outward appearance of some of the species was variable within species, with the presence of eyes and pigmentation not necessarily being indicative of speciation. The DNA sequencing of mitochondrial genes 16S and CO1, typically sensitive to changes indicative of speciation, indicated no differences indicative of speciation between pigmented/unpigmented and eyed/eyeless individuals in *Conasellus hobsoni* populations. In contrast, in isopods of the genus *Lirceus* we found that pigmentation patterns, or lack thereof in the case of the depigmented isopods, was well-correlated with speciation. Thus, in each case where a troglomorphic population was discovered, the molecular sequencing of *Lirceus* always showed significant differences consistent with speciation.

<u>Ignorance isn't bliss for groundwater isopods</u>—The only isopod known to inhabit a thermal spring in eastern North America is *Lirceus thermae*, which is known only from Berkeley Springs State Park, in West Virginia. The water emerges from orifices in adjacent concrete-lined basins, which are open to the public and managed as wading pools (figure 6). The isopods receive no protection at this time, although in all fairness, the species was unknown prior to the description of the monograph (Lewis, et al., 2023). In comparison, the thermal spring Socorro isopod, *Thermosphaeroma thermophilum,* was also known from a single spring in New Mexico, where it was protected as a federal endangered species (Lewis, 2009b). This species is now known

Figure 6. Berkeley Springs State Park, in West Virginia, is the only known locality in eastern North America where a freshwater isopod occurs in a thermal spring. The isopod Lirceus thermae is known only from two adjacent basins, which are managed as wading pools (photo by J. Lewis).

almost entirely from populations maintained in captive breeding facilities.

Cave biologists spend too much time in caves—Many years ago during a conversation with a friend of the senior authors, the cave biologist Dr. Thomas C. Barr, quipped that cave biologists would do well to quit going in caves, and go back into the sunlight and spend more time in springs or sinkholes. This was a surprising statement coming from a well-known cave biologist, but it turns out that in some respects he was absolutely right. Biodiversity has been demonstrated to be greater in at least some of these ecotones between surface and subterranean realms. As a case in point, we have discovered as much, if not more, diversity in springs than the caves that feed them, or the surface streams into which the water flows (Lewis, et al., 2023). The same can be said of the terrestrial communities found in sinkholes (Lewis, et al., 2020).

To conclude, in the midst of all this diversity, the federal endangered species Lee County Cave Isopod *Lirceus usdagalun,* has become our yardstick for measuring rarity. Ironically, even though it is an endangered species, *Lirceus usdagalun* has become one of the more common groundwater isopod species occurring in the karst of southwestern Virginia. In looking at managing the fauna, this is not to suggest providing less protection to the currently endangered species, but to the contrary, considering ways of managing this newly discovered wealth of rare species. How do we practice conservation management with an animal that lives in groundwater under the largest metropolitan area in Virginia? And how about a species known only from concrete basins used for wading pools? Can the entire subgenus *Hargerellus* be listed as endangered? There are many possibilities to consider, and the clock is ticking loudly for some of these species.

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Invertebrate Mark and Recapture, and Application for Managing Endemic Species

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Abstract

The majority of troglobitic invertebrates in the world are known from only a single scientific paper, the species description. Nevada's taxa are no different, with little known about the life histories or population sizes, making data-based management decisions difficult. Thus, we conducted a one-year long mark and recapture study in Great Basin National Park for *Sclerobunus ungulatus* Briggs (Model Cave harvestman) and *Microcreagris grandis* Muchmore (Great Basin cave pseudoscorpion) at three caves. Using fluorescent paint, micro-rulers, and extensive underground monthly searches, this investigation estimated population sizes, potential reproduction rates and timing, microhabitat use, and prey species availability. Based on datasets from three caves, we conclude that sites and species with higher numbers are best suited for these techniques. However, other trends, like seasonal abundance and microhabitat use, are still useful data for managing sites with lower numbers of troglobites. Comparing the dataset for two different species and among three different caves gives an excellent picture of this method's utility for understanding invertebrate troglobites on a larger scale. Using quantitative and qualitative data provides better insight into how to effectively manage cave and karst resources.

Introduction

There is limited information about cavernicolous endemic species due to the challenges researching cave and karst habitats. However, due to the environmental stability and simplicity, these settings can provide great opportunities to study biological concepts (Northup and Crawford 1992). Since many of the troglobitic invertebrates in the world are known from only a single scientific paper, the species description, it is important to learn more about the life history of these organisms. Since many troglobitic organisms are endemic to limited ranges and habitats, often from only one cave, it is even more important to understand their biology. Human impacts, intentional or unintentional, could lead to extinction more easily for these invertebrates due to this limited range (Elliott 2005). Gaps in our understanding lead to management mistakes. Although there are several studies of cave fauna, many of them are located in the eastern states where there are larger human populations (Culver 2001). In places like Nevada, there is very little known, which can lead to important management mistakes. Most literature related to Nevada cave invertebrates are species descriptions or paleontological records. To manage these caves effectively, understanding the biology of the inhabiting invertebrates is crucial, so that natural resources can be adequately protected while still providing human access.

Mark and recapture studies for cavernicolous insects are unusual compared to other more dynamic species like blind fish, crawfish, and bats. However, these studies are still very informative and frequently provide life history information in addition to population sizes (Gnaspini 1996, Lavoie 2007, Northup and Crawford 1992). Most mark and recapture studies last a very short period of time, with a marking period and then a recapture (Briggs et. al. 2022, Crinan et. al. 2022, Delaval et. al. 2023, Maestre and Pinto-da-Rocha 2004, Riecke et. al. 2021). In Briggs, there were 5 studies that lasted days, 3 studies that lasted weeks, 5 studies that were 3 months or less, 6 studies that were between 4-9 months, and only 1 study that lasted a year (2020). Rather than following more common timelines, this mark and recapture study was conducted for an entire year in order to have 1) a better assessment of populations, and 2) to gain knowledge about the life histories of the four endemic species in these caves.

At Great Basin National Park, there are four charismatic endemic species of concern to manage, Great Basin cave millipedes *Idagona lehmanensis* Shear, Lehman Caves millipedes *Nevadesmus ophimontis* Shear, Model Cave harvestmen *Sclerobunus ungulatus* Briggs, and Great Basin cave pseudoscorpions *Microcreagris grandis* Muchmore. Little is known about their population sizes, vagilities, behaviors, or life cycles. In order to make informed management decisions, a population study was conducted from September 2022 – October 2023 in selected Park caves for these endemic invertebrates. The study was conducted within three caves: Model Cave, Little Muddy Cave, and Root Cave. All three caves were observed to have abundant numbers of at least one endemic species, with Model Cave having larger numbers of all four species than other caves within the National Park.

Methods

Methodologies were loosely modelled after the mark and recapture survey work of harvestman *Ilhaia cuspidata* in Brazil (Mestre & Pinto-da-Rocha 2004). Several different water-based fluorescent paints were ordered and tested before we chose one brand for easy and safe use on invertebrates. Harvestmen and pseudoscorpions were gently collected using a soft paintbrush and a test tube, with a paper towel. Each one was deposited in a petri dish with a microscale ruler and gently painted with water-based fluorescent paint. They were photographed and then placed back in the same test tube. Once all specimens were documented, they were released back in the same or close to the same location they were found, starting in the furthest transect and moving forward so they would not be accidentally stepped on. Field days typically lasted 4 – 12 hours dependent on the abundance of target organisms. Often, Root Cave and Little Muddy Cave would be combined on the same field day since they shared the same watershed. Model Cave would be sampled on a separate day in order to conduct appropriate WNS decontamination procedures since it is in a different drainage (www.WhiteNoseSyndrome.org 2020).

<u>Study Sites</u> – Three caves were selected based on observations of large numbers of endemic species in the summer months of 2022. Root Cave and Little Muddy are in the Lehman Creek drainage, while Model Cave is in the Baker Creek drainage. Root Cave is a small cave (length 55.7 meters) at an elevation of 2,089 meters near Lehman Caves in Great Basin National Park (Taylor et. al. 2008). It is possible Root Cave attaches to Lehman Caves through subsurface conduits that are too small for humans to navigate, possibly to the Lost River Passage, although this has not been confirmed. Little Muddy is a slightly longer cave (309-meters long) at an elevation of 2,045 meters and from 1981 – 1992 was used for spelunking tours (Schmitz 1986, Taylor et. al. 2008). Both caves are an important habitat for *M. grandis*. Model Cave, the type locality for *N. ophimontis* and *S. ungulatus*, is longer (600 meters) at an elevation of 2,080 meters (Taylor et. al. 2008) and is an important habitat for *I. lehmanensis, M. grandis*, *S. ungulatus*, and *N. ophimontis*.

Figure 1.

<u>Transects</u> – Within each cave, four 3-m long transects were outlined (Figure 1). The total surface area varied with the width and height of the cave, but the length always remained the same for each transect. Transects were delineated with flagging on floors and ceilings (as needed to prevent problems with poten-

Figure 2.

tial flooding). Each transect was searched by two people to reduce searcher bias. In each transect, the first search lasted 15 minutes. If there were target organisms in the transect, the second searcher would look for 15 minutes, however if there were not any target organisms and few prey items found, the second search would only last 10 minutes. All times were recorded. Floors, walls, and ceilings that could be reached were meticulously searched for any invertebrates. Target organisms were collected in test tubes using soft-tipped paintbrushes (Figure 2). All other organisms were recorded to monitor prey availability and possible predator abundance. To reduce possible injury to the target organisms, each test tube also contained a strip of dry paper towel for the organism to grasp onto. Typically, there were two searchers and one transcriber for data for each month of data collection. Transect flagging was removed at the end of study to reduce microplastic contamination in these caves.

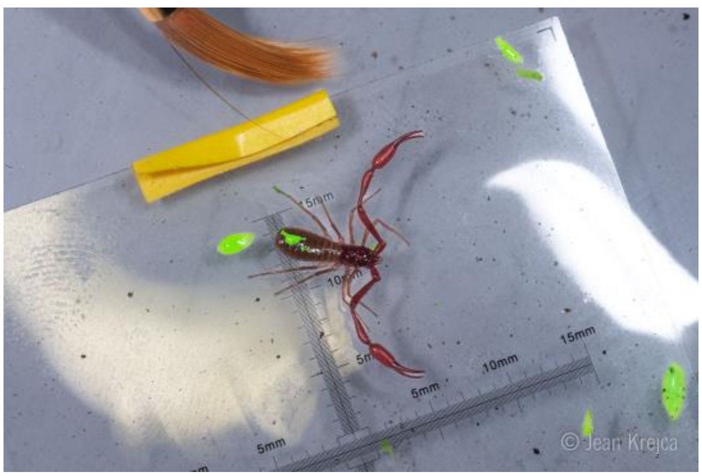


Figure 3.

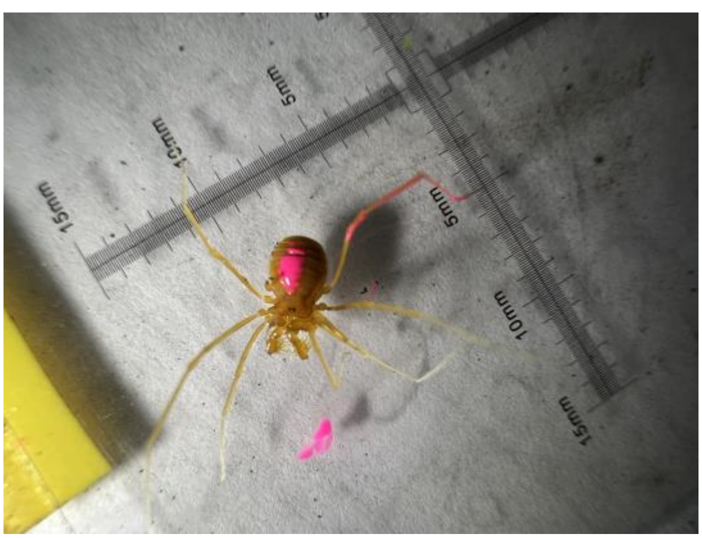


Figure 4.

Marking – All adults and last nymphal stage specimens captured were marked on the dorsal side of the abdomen and one of the back four legs with Golden High Flow Acrylics water-based fluorescent paint (Figure 3-4). Immature specimens were captured and photographed but were not marked in order to prevent potential problems with molting. The paint on the leg corresponded to the transect the invertebrate was collected (e.g. transect A was the 3rd leg on the left, transect B the 4th leg on the left, etc.). Once marked, specimens were photographed with a micro-scale ruler (Figure 3-4). Organisms were not sexed in the field due to difficulties observing the appropriate structures without a microscope. When the front four legs or appendages with the chela attached were accidentally painted, all the organisms demonstrated agitation. Paint was removed as best as possible to limit potential negative impacts, such as impeding feeding or reproductive behaviors. Paint did not seem to cause mortality, but there was some mortality outside of the transects due to human impacts. While it is possible that the paint came off of some of the specimens, most had a minimum of trace amounts in the joints of their legs or where sclerites articulate on the abdomen.

Statistical methods –The population sizes were estimated using the Lincoln-Peterson formula N = (M*C)/R where N is the population, M are previously marked specimens, C are the total number of organisms observed, and R are recaptures. This is commonly used as an estimation for simple mark and recapture studies (Cordoba-Aguilar 2008, Mercer 2012). All calculations were rounded down to the nearest whole number.

Results and Discussion

Modifications — Several problems were encountered that changed the nature of the study. During the first sampling interval, all four endemic species were collected: *N. ophimontis, I. lehmanensis, M. grandis,* and *S. ungulatus*. At this time the test tubes did not have paper towels in them. This, and possibly other unknown factors, contributed to 100% mortality in *N. ophimontis* and high mortality in *I. lehmanensis.* As a result, for the remainder of the study, these endemic species were observed and recorded, but not collected or marked. The only endemics consistently collected and marked were *M. grandis*, and *S. ungulatus*.

Great Basin National Park had an unusually wet year during the study's field work, which caused unusual flooding in Model Cave. The average precipitation in 2022 at Great Basin National

Figure 5.

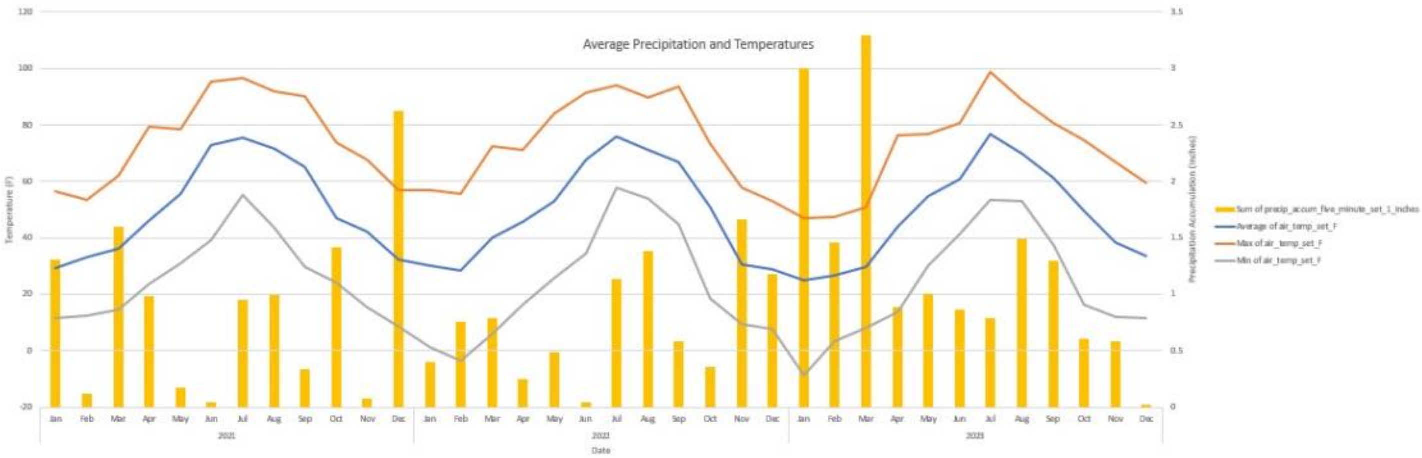
Park headquarters area was 25.3 cm, which is a relatively typical year. In 2023 there was 43.9 cm in annual precipitation, which is a significant increase (Graph 1). In Model Cave from April 2023 through September 2023, the transects' floor passages were flooded so all searching was focused on the walls and ceiling (

5). Transects were initially marked only the floor, but due to the abundant moisture additional flagging was added to the ceiling and walls to delineate transects (Figure 6). In June 2023, the flooding was too high to search at all. As a result of flooded stream passages organisms adjusted by moving to the walls and ceiling of the passages. More nutrients came into this section of the cave, and aquatic flies (Simuliidae) were observed in the passage. Pseudoscorpions were rarely observed after flooding. Prior to the flooding event, 16 *M. grandis* were marked, but after the flooding event, only 2 pseudoscorpions were observed. Harvestmen numbers dwindled after the floor was flooded. Prior to flooding, average collected individuals in one month was 18 with a high of 32 individuals and a low of 13 individuals. After the flooding the average collected individuals in one month were 13 individuals with a high of 20 organisms and a low of 7 individuals. Flooding seemed to impact the organisms, although a similar survey during a comparatively drier year would be needed to better ascertain the impact of flooding.

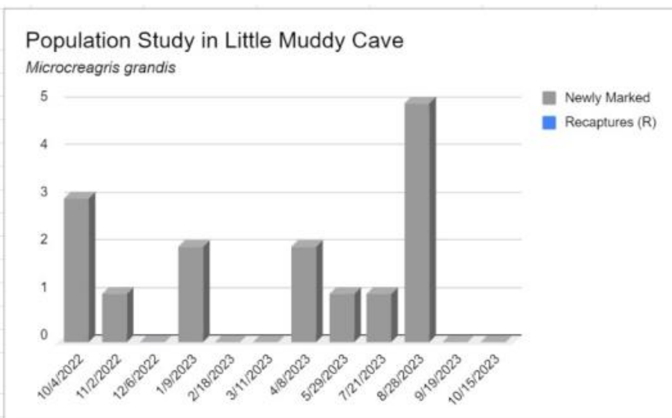
Figure 6.

<u>Total Numbers</u> – Model Cave provided enough recaptures to analyze the data for population size. Little Muddy did not have any recaptures during this study (Graph 2). It is thought that marked specimens emigrated from the human-used cave passages since no observations were made of dead marked organisms. The other possibility is that the paint wore off on these organisms, however, paint was usually persistent in joints on marked organisms. Root Cave only had 2 recaptures (Graph 3), which can be evaluated, but is not very helpful for an accurate population estimate. Given that Root and Lehman Caves are likely connected, emigration is a likely scenario. We still found 35 individuals of markable size, in a relatively smaller space, implying that it is an important habitat for pseudoscorpions. In Model Cave, the population of *S. ungulatus* was calculated to be approximately 230 individuals (Graph 5). In Model Cave, the population of *M. grandis* was calculated at approximately 28 individuals (Graph 4). This may not be an accurate representation of the population within Model Cave. After the flooding event, only two pseudoscorpions were observed, which were recaptures, found in exactly the same location. It may be that due to this unusual event, the data is inaccurately portraying population estimates.

Total numbers of all target species and organisms fluctuated throughout the year and throughout the study. In late spring of 2023, there were the fewest number of organisms found throughout all the caves. This level of seasonality is unusual in troglobitic organisms. In Little Muddy Cave, M. grandis was



Graph 1.



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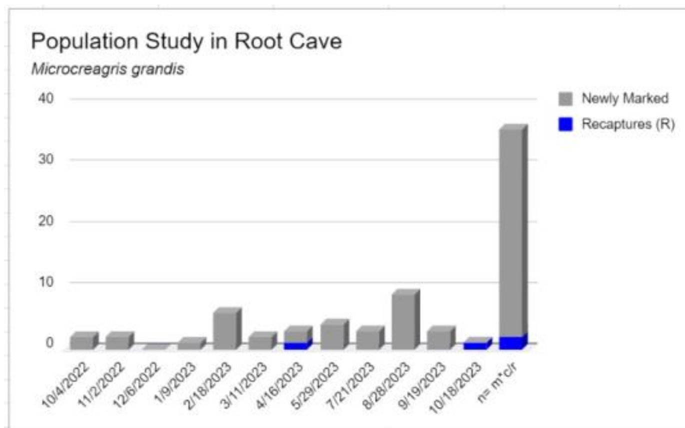
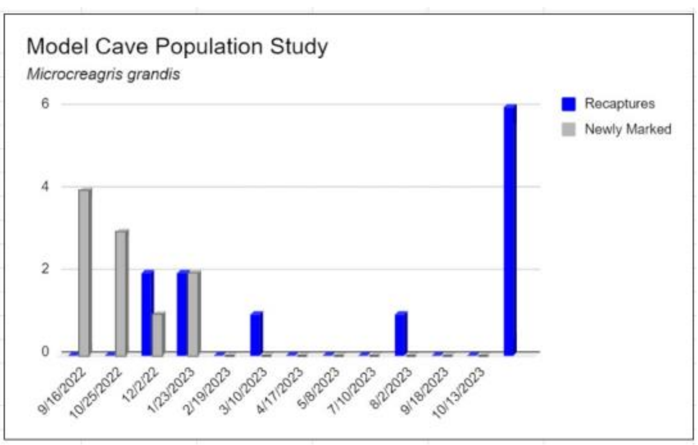


Graph 3.



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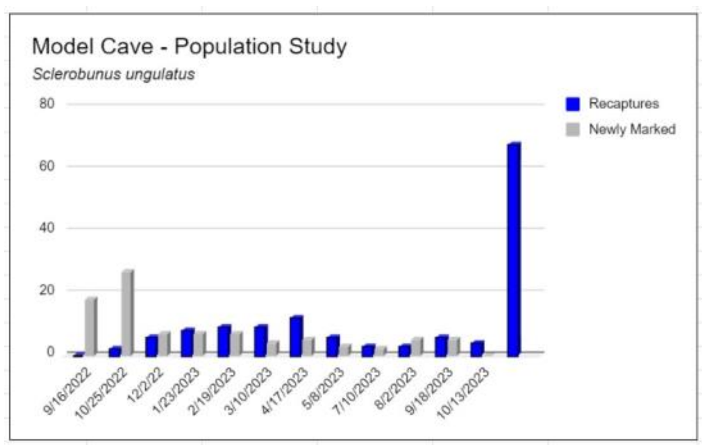

Graph 5.

almost bimodal with how few organisms were found in early spring (two between December 2022 and March 2023) and the greatest number in the fall (five in August 2023) (Graph 2). Root Cave slowly peaked in the fall, with lowest points in December 2022 - January 2023 (Graph 3). It may be related to reduced food availability or potentially just an artifact of the surveying methods, trap wariness, or an unusually wet and cold year. Model Cave had a different trend of fluctuations, likely from the unusual flooding event from April -September of 2023. *Microcreagris grandis* was only found twice after flooding (Graph 3), both times in a small crack on the ceiling. *Sclerobunus ungulatus* had large initial numbers but remained relatively constant after the first two months of surveying (Graph 5). Biomonitoring several times a year in the future may demonstrate whether this is an actual trend or a randomized event.

<u>Juvenile abundance and seasonality</u> –Most cave species lay smaller numbers of relatively larger eggs. This is expected in a nutrient poor environment (Northup and Crawford 1992). They may also reproduce continuously instead of seasonally, due to consistent climate (Gnaspini 1996, Mestre and Pinto-da-Rocha 2004, Pinto-da-Rocha 1996b). Neither eggs nor brood care were observed in Great Basin National Park Caves. Some species of pseudoscorpions will carry silken sacs filled with eggs or broods, but we did not see any eggs or broods during our time observing *M. grandis*. It is possible that adults find appropriate brood chambers to lay their eggs and then protect them, but this behavior was not observed, either. Root Cave exhibited the most immature *M. grandis* juveniles, noted in July, August, and September, 2023. In Model Cave only one immature *M. grandis* was observed in September. Correspondingly only one immature pseudoscorpion was observed in Little Muddy, recorded in August. Our sample size of observations is small, but supports the hypothesis that this species only reproduces once a year and offspring are observed in the late summer through early fall. There may be important habitat linked to reproduction near or in Root Cave, or it could be an artifact of searching a larger percentage of area within a smaller cave, or simply higher detectability due to passage morphology. It is more difficult to estimate the life stage of millipedes so there are no observations about frequency or abundance of juvenile offspring. *Sclerobunus ungulatus* appears to reproduce in small numbers all year long, with a peak in the fall months. December through April had the fewest immature specimens observed. A slow increase in juveniles was observed in spring and summer, but numbers greatly increased starting slowly in August (5 individuals) into September (7 total individuals) and peaking in October (15 individuals) of 2023. When juveniles were observed in October, they were the smallest instars. The differences we observed underground in abundance of juveniles is consistent with what we would expect for surface species, but other researchers find cavernicolous species reproducing year-round (Mestre and Pinto-da-Rocha 2004). It is possible these Nevada species are impacted by an exchange of nutrients with the surface due to the stream passage or they are still evolving to more cavernicolous traits. Without following these organisms for a longer duration or raising them in a terrarium, life expectancy will remain unknown, but other researchers found several different species to survive from 1-4 years by rearing organisms in a terrarium or multiple visits over several years (Pinto-da-Rocha 1996b).

<u>Movement within Systems</u> – *Sclerobunus ungulatus* often stayed close to the original point of capture as the majority of recaptures (where the original point of capture could be read from the leg code) were found near the same 4m transect as they were marked. From general observations, harvestmen did move around, but showed some fidelity in an area. Areas outside the transects were searched for marked individuals, but it was rare to see harvestmen. Even when observed outside of the transects, they were never more than a few meters away. Following the movements of individuals over time would yield additional data.

Microcreagris grandis appears to show less fidelity, although they occasionally demonstrate territoriality. For instance, one area in Root Cave was frequently occupied by a pseudoscorpion (30% of the time, for 3 of those 4 months in a row), but several marked pseudoscorpions were found outside of transects on different occasions. In places like Root Cave, which is probably connected to Lehman Caves, it may be that the pseudoscorpions are moving through subsurface conduits that are not observable. In Little Muddy, it was observed to have a varying population of pseudoscorpions. Often there was an abrupt increase one month, surrounded with low numbers before and after that month. For instance, in July 2023 there were two pseudoscorpions observed, then in August, there were five, followed by none in September. This variation in population seemed to correlate with summer through autumn having the greatest numbers, with fewer in winter and spring; where from November 2022 -

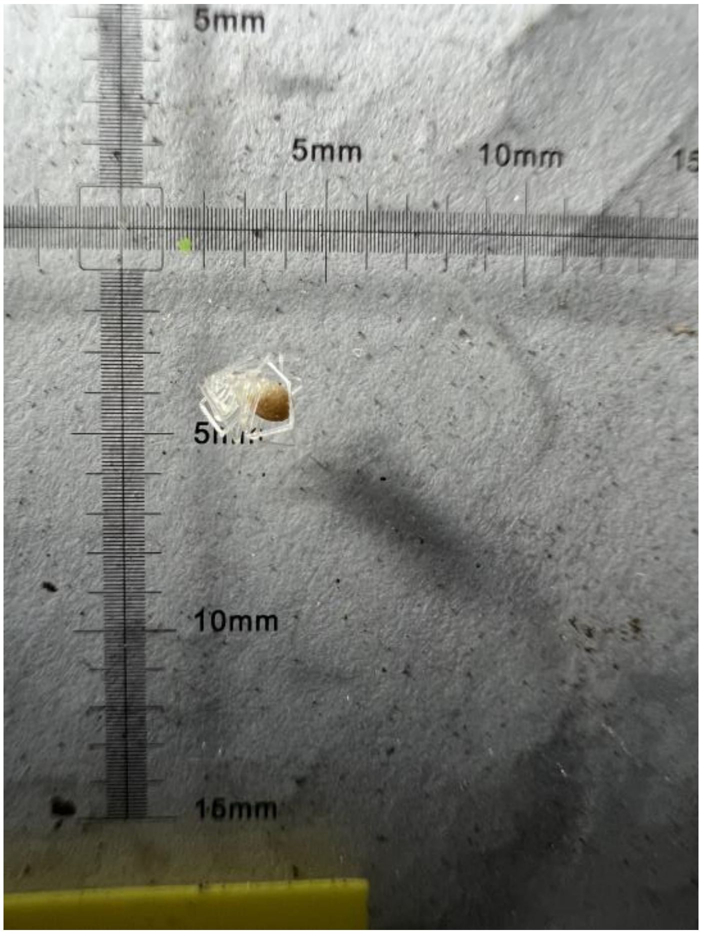

Figure 7.

Figure 8.

March 2023, only two pseudoscorpions were observed in total. It is possible this was a result of increased prey availability from the surface.

Feeding and behavior – *Sclerobunus ungulatus* was never observed actively feeding. Most harvestmen species are omnivorous, opportunistically feeding on small organisms, detritus, decaying organisms, vegetation, fungi, and feces (Pinto-da-Rocha 1996). As the stream flooding dissipated, the harvestmen did appear to have midguts full of dark material, the same color as the nutrient-rich floor sediments. They also had a relatively high degree of philopatry until the end of the flooding, where three marked organisms were found outside of the transects that none were observed before. Often in stable environments, Opiliones have stable mating territories (McLean et al. 2008), but that may not be the case with *S. ungulatus* since they do not have obvious sexual dimorphism commonly seen in competing males. These harvestmen often played "dead", frequently at early instars, which caused them to be temporarily lost in their habitat (Figure 7). If approached too aggressively with the paintbrush moving them to the microscale, larger instars would also defensively feign death.

Microcreagris grandis was observed feeding on very large diplurans without the dipluran trying to escape. Since the dipluran and the pseudoscorpion were nearly equal in size, but the dipluran was held by only one chela, and was barely moving (unusual in prey items), it is highly likely there are poisonous glands in the chela, similar to other pseudoscorpion species. When immature pseudoscorpions encountered each other they quickly backed away without aggressive or aggregation behaviors. However, when touched by paintbrushes, the pseudoscorpions defended themselves aggressively using their chelae (Figure 8).

Conclusion

This procedure is effective for larger populations, such as those found in Model Cave. These methods can be difficult for smaller and more vagile populations, as evidenced in Little Muddy where no recaptures were observed, and thus we could not estimate population sizes. Smaller populations would require some adjustments in experimental design for more increased efficacy. It may be more of an issue of density. In Root Cave the estimated population size of 46 in 55.7 meters provides the density of 1 organism in every 1.21 meters, with 21.5% of the length searched. In Little Muddy, we found a total of 10 organisms in less than 4% of the length of the cave, without any recaptures, for a density of 1 organism in every 30 meters. Thus, for smaller densities, like Little Muddy, perhaps a greater percentage of cave needs to be searched to find appropriate numbers to estimate population sizes. Most of the data collected, excluding seasonality and juvenile abundance, was evident after 3-4 months of mark and recapture, which makes it an accessible study for land managers that heavily rely on seasonal employees. This is also heavily evident in the literature (Culver 2001). The only problem with choosing a shorter period of time is if it is while the population is dwindling before a large increase, such as evident in Root Cave or Model Cave during the flooding event. Overall, initial population studies such as this provide important baseline data prior to wildfires, climate change, changing water levels, unforeseen natural impacts, and various human impacts.

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Environmental DNA (eDNA) as an Effective Approach for Monitoring and Studying Groundwater Biodiversity

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Abstract

The conservation and management of groundwater biodiversity is often limited by a lack of knowledge on the distributions of species (i.e., the Wallacean shortfall) due to the significant challenges biologists face accessing and sampling groundwater habitats (i.e., the Racovitzan shortfall). In recent years, environmental DNA (eDNA) methodologies, which leverage DNA shed by organisms into their surrounding habitats, have become increasingly popular complements to traditional approaches for aquatic species, representing a powerful new tool to detect and monitor biodiversity rapidly, nondestructively, and potentially cost-effectively, especially for taxa that are rare and of conservation concern. Here we review the use of eDNA approaches for monitoring and studying groundwater biodiversity, while highlighting our recent work in the southeastern United States and southeastern Alaska. We discuss the advantages of eDNA as an effective surveying and monitoring tool for groundwater biodiversity but also highlight some challenges of eDNA approaches when applied to groundwater ecosystems.

Assessing Patterns of Subterranean Biodiversity and Microclimates to Inform Cave Management and Conservation

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Abstract

Climate change is expected to increase average cave temperatures and alter subterranean hydrology and relative humidity. These changes may cause negative impacts for obligate and facultative cave-dwelling species, which are adapted to relatively stable subterranean climates and often have limited dispersal abilities and ranges. Fortunately, microclimates vary both within and among cave systems, and this variation may allow cave-dwelling species to persist within local climate refugia. Cave managers would like to identify and conserve such refugia. However, it is unclear which geological, geographical, or biological characteristics or processes create refugia and thus it is unclear which management actions can best conserve refugia. For example, forest cover is hypothesized to reduce solar radiation and thus mean cave temperatures, but how much of an impact could cave managers have on cave microclimates by conserving surface forest cover? In this project, we collaborate with federal, state, and non-governmental organizations across the southeastern United States to identify high priority caves for conservation; quantify how forest cover mediates cave microclimates; and create and evaluate a portfolio of management options for improving cave ecosystem resilience during future climate change. We are deploying newly designed cave climate monitoring technology in 60 caves across nine states. We also are conducting biosurveys in a subset of 30 caves, and have documented to date more than 150 taxa, representing five phyla, 15 classes, 45+ orders, and 80+ families. This project represents the first coordinated, regional effort to improve climate resilience in cave ecosystems across the southeastern United States, and we welcome new collaborations with other cave managers in the region.

Oral Presentations

Education Session

Chair: Amy Hourigan

Taking Conservation Education to a New Level at Great Basin National Park

Baker, Gretchen[1]; Jackson, Dave[2]

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Abstract

Education of the public is a crucial component of efforts to conserve species, caves, and aquifers. In the short term, education about specific conservation initiatives builds support among the public for these initiatives, helping citizens to understand the importance of conservation work and the role that the public can play in assisting with conservation. In the longer term, more generalized conservation education helps inspire children to consider careers in science and conservation, and inspires people of all ages to take a stand for conservation. Immersive educational experiences like CaveSim are designed to make learning about conservation fun and memorable. After years of planning and hard work, Great Basin National Park now has their own mobile CaveSim exhibit. The authors collaborated to make this possible, and they will discuss the project, including what they learned and how Great Basin National Park plans to use the mobile CaveSim system.

The Texas Hydro Geo Workshop

Schindel, Geary M., P.G.[1]*; Harris, Mike*[2]

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Abstract

The Texas Hydro Geo Workshop was created in 2014 to provide earth science and wildlife biology students with opportunities to obtain field experience within their respective majors. Participants work with practitioners and professors to obtain hands-on field experience in hydrology, geology, environmental science, wildlife, and aquatic biology.

Now in its 9th year, the Texas Hydro Geo Workshop attracts approximately 250 to 300 students from across Texas and the United States as well as internationally. The workshop offers 30 to 40 different modules ranging from 1 to 4 hours in length. Each module is offered by experts in the field and range from surface and borehole geophysics; stream gauging; dye tracing; soil, water and rock sample collection; application of various instrumentation types; working with drilling rigs; rock identification; field safety and field camp survival; caving; etc. There are contests for the students along with lightning talks, lectures, a keynote speaker, and a yodeling and hog calling contest.

The workshop is funded by a small attendance fee along with significant support from various community and professional organizations. Volunteers and module presenters do not pay to attend. The workshop could not occur without the support of volunteer cavers, students, and practitioners.

Workshop Overview

The Texas Hydro Geo Workshop was created in 2014 as an event to introduce earth science and wildlife and aquatic biology students to field data collection methods and data evaluation. The workshop has been held at Cave Without A Name (CWAN), a commercial cave and campground located near Boerne, Texas. CWAN has a large campground, pavilion, and restroom facilities that are used as the organizational location of the workshop. The pavilion is used for registration and to sign up for the various modules offered during the event. The Workshop is generally held in the fall (early October) over one weekend and starts on Friday afternoon and ends on Sunday at noon. Friday and Saturday evenings also include lightning talks on various topics and presented by students and practitioners. On Saturday evening, a keynote speaker presentation occurs within the main hall in CWAN.

Registration for the event ranges from $50 to $70 depending on when people register with price breaks for early registration. Participants receive a field guide, event T-shirt, camping, breakfast on Saturday and Sunday, dinner on Saturday night, a book donated by the National Speleological Society, keynote speech, and camping. The workshop includes three contests including rock and mineral identification, best field lunch (based on taste, presentation and bribes to the judge) and after the keynote talk, our ever popular yodeling and hog calling contest in the confines of the cave. Prizes are given to the winners of each contest – commonly a rock hammer donated by Estwing Company.

The event is also heavily sponsored by various groups including geological societies from across Texas, professional societies such as the Association of Environmental and Engineering Geologists, consulting firms, and vendors.

Modules

The main draw of the event is the series of modules that are presented all day on Saturday and until noon on Sunday. Modules are field based and involve hands-on opportunities for the students to experience various instruments and methods for field data collection. The modules offered each year are based on the availability of module presenters. The presenters determine the length for each module they present (usually one to four hours), the number of students they will accept, the topics to be covered and how many times they will present modules during the workshop. The presenters let us know what support they need and where they would like to present. Some modules occur in CWAN, on the surface on the large property owned by CWAN, at a nearby county park where access to the Guadalupe River is available, or in one of the nearby wild caves. Some instructors will present more than one module during the workshop. CWAN is open for public tours during the workshop and they have been very accommodating, and we've been able to work around their schedule.

Modules generally fall into a number of categories.

Basic Outdoor Skills

Many students have a field-based study that requires a field camp and extensive work in remote locations. Some of the students have limited outdoor and little or no camping experience. We have offered the following modules so they can better prepare for their field experience: Field Safety; Camping; and Knot Knowledge (Know Not, No Knot). Each module lasts one hour and ranges from identifying important gear, setting up tents, dealing with field hazards such as heat, cold, rain, insects, and critters.

Field Techniques and Career Development

The following modules have been offered in this area. The use of field instruments (map, compass, rock hammer); Environmental Data Presentation for Best Management Decisions; Developing Scientific and Field Notebooks; All Appropriate Inquire and Phase I Environmental Site Assessments; FLIR Infrared Camera and Radon Analysis; ArcGIS Mobile Data Collection Solutions; Career Development, Career Opportunities in the Oil and Gas Industry; and Low-Cost CO2 Monitoring in Karst Environments.

Students are encouraged to bring a resume and meet with industry representatives to obtain career advice. Many of the skills covered in the modules can be utilized in many of their courses and help direct career selection. We've had a number of participants that have obtained summer placements and jobs.

Well Drilling and Environmental Monitoring

We've been able to offer the participants a multi-hour module related to collection of data and installation of a monitoring well including the use of split spoon samples, safety and environmental monitoring instruments, soil and groundwater description and sampling, and water level measurements. The students are exposed to the operation of a drilling rig and how to work with the drilling crew to obtain the best samples.

Geophysics

We've been able to offer a number of geophysics modules over the years including Ground Penetrating Radar; Self-Potential Data Acquisition for Cave Applications; High Resolution 3D Resistivity Imaging to Location Caves and Voids; and Microgravity Instruments. The geophysics modules are performed in the field, commonly over known cave passage and karst features.

Water and Resource Management

We offer a wide range of water and resource management modules including the following: Groundwater Investigation Methods; PFAS Investigations and Remediation; Tracer Testing in Karst; Surface Water Quality Sampling; Climate Change, the Tipping Points of No Return; Low Impact Development; Stream Gauging; Groundwater Conservation Districts including measurement of groundwater levels; Potentiometric Surface Mapping; Water Quality Monitoring with Eureka Manta2 Sondes; and TCEQ's Clean Rivers Program: An Overview.

Field Biology

Our field and aquatic biology modules have expanded in the last couple of years and have included the following modules: Intro to Golden-checked Warbler Habitat Assessments and Surveying; Macroinvertebrates as Water Quality Indicators; Cave Biological Inventory; Freshwater Fish, Freshwater Mussel, and Aquatic/Semi-Aquatic Reptile and Amphibian Sampling Techniques; and Herpetological Field Survey Techniques. Golden-checked Warblers occur in the Texas Hill Country and are listed as endangered species with surveys required for the birds before development can occur.

Karst and Geological Evaluations

We have an extensive list of modules for karst and geological evaluations including Cave Geology; Karst Feature Evaluation Using the Texas Commission for Environmental Quality (TCEQ) Forms; Stalagmites as Paleoclimate Archives; Rock Identification; Regional Stratigraphy; and a Field Trip to Herff Falls at Cibolo Preserve. The TCEQ has regulations related to development on the Edwards Aquifer Recharge Zone and requires an extensive Geologic Assessment before construction begins.

Caving and the Cave Environment

The Bexar Grotto of the National Speleological Society has presented a series of cave related modules including Safety in the Vertical Environment; Cave Mapping and our ever-popular Field Trip to a Wild Cave. The wild cave trip involves taking students into a nearby cave where they wade upstream in the cave until they are chest deep in water – approximately 1,500 feet to observe the cave hydrology and biology. Most of the students have never been in a wild cave and are instructed in safe caving practices. Participants are outfitted with helmets, lights, gloves, and kneepads before entering the cave.

Lectures

The owner of Cave Without a Name has built a conference room which we've been able to utilize for a series of lectures in the last few years. The 2023 lectures including the following one-hour presentations: Climate Change, Understanding the Problem; How Climate Change Impacts Infrastructure; The Search for the Dog Valley Fault; and A Path from "Rocks for Jocks: to a Career in Engineering Geology." Three of these presentations were made by two Jahns distinguished lecturers sponsored by the Association of Environmental and Engineering Geologists.

Logistics

The Texas Hydro Geo Workshop is a section of the National Speleological Society (NSS) and is incorporated as a 501(c)(3) organization in the state of Texas. The workshop is governed by a steering committee and profits from the event are used to cover scholarship, student research, field trips, as well as conservation and education related activities. There are also scholarship opportunities to attend the workshop for participants based on need. Recipients of the workshop scholarship are requested to help set up, assist with serving food, and other tasks during the workshop.

The workshop is primarily staffed by volunteers from the Bexar Grotto of the National Speleological Society who handle most of the logistics for the event. The workshop has created a professional webpage and online registration system. Volunteers prepare a program guide describing the modules, number of participants, and schedule. The grotto has acquired some large tents and assorted items to help support the event. The NSS has provided a series of overstocked books that are given to the students and the workshop pays for shipping and provides the NSS with a donation. The workshop acquires its insurance for the event through the NSS by making an additional donation to the society.

Module presenters are volunteers that attend the event for free. They are given a T-shirt with the workshop logo, provided with meals, and can attend any of the modules if their schedule permits. Commonly, they bring instruments specific to their modules for use by the students. The presenters have a wide range of backgrounds, and most are practitioners in their field or college professors. Our keynote speaker on Saturday evening is a luminary in their respective field and presents their lecture in the large room in Cave Without a Name on Saturday night. After the keynote speaker, we have a yodeling and hog calling contest which has been wildly popular. The participants receive a nice prize and bragging rights for a year.

Food for the event is usually a spartan breakfast for both Saturday and Sunday composed of fruit, bagels, yogurt, etc. with a catered hot meal occurring on Saturday night. After the yodeling contest, lightning talks are presented in the pavilion and are well attended. Depending upon weather conditions, there may also be a campfire in the campground.

Conclusion

The Texas Hydro Geo Workshop would not be possible without the generous support of Tom Summers, owner of Cave Without a Name and his staff. We also want to thank our many volunteers including Mike Harris who serves as Co-Chair of the event, Jill Orr who prepares the Program Guide, Jess Chadwick who administers the online registration, our many module presenters who give so freely of their time and expertise, and the cavers of the Bexar Grotto.

Students keep coming back each year and the only complaint we've heard is that there are many more modules they want to take than they have time for. We're hoping our workshop model can be adopted in other areas of the country and we would be happy to provide them with advice and support.

Oral Presentations

Karst Studies Session

Chair: Amy Hourigan

Mountain Valley Pipeline: Karst Issues in Virginia 4 Years into Construction and the Preliminary Exploration and Protection of Calcite Turtle Cave

Orndorff, Wil[1], Malabad, Thomas[1]; Kosič Ficco, Katarina[1] ; Vorster, Penelope[1]

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Abstract

Construction began in 2018 on the 42-inch diameter, 1400 PSI Mountain Valley (MVP) and Atlantic Coast (ACP) pipelines to carry natural gas across Virginia's Appalachian Ridge and Valley province, where karst is extensively developed in Paleozoic carbonate bedrock. Sinking streams, sinkholes, caves, and springs are common. Each project developed karst hazard assessments and mitigation plans, and results from dye tracing informed monitoring. Regulatory obstacles and significant citizen opposition slowed construction. ACP was cancelled in July, 2020. As of 1 January, 2024 the 302 mile long MVP pipeline was over 95% complete. Final restoration was forecast for the spring/summer 2024 upon completion of jurisdictional stream crossings. Site access issues thwarted attempts to investigate a spring in Montgomery County that in 2018 became turbid following discharge of sediment from the right of way to sinkholes. The owner continued through at least early 2023 to report turbidity following precipitation events despite restoration of that section of the right of way in late 2018, since when erosion and sediment control measures have been largely effective across the karst. The four-mile section of MVP along Sinking Creek Mountain (Giles County) was in its sixth year of construction in 2023, and monitoring data at two karst springs had shown no indication of impacts to karst waters. However, the unrestored right of way continued to place underlying and downslope karst systems at increased risk through the spring of 2024, and to disrupt landowners' use of their property. MVP continued to coordinate with VDCR to investigate and limit impacts to newly discovered karst features, including Calcite Turtle Cave, discovered in the construction right-of-way in 2021 after being overlooked during the pre-construction karst resource inventory. By NCKMS 2023 (November), the now gated cave had been mapped to a length of 2800 feet and a depth of 512 ft. Through careful coordination with VDCR, slow methodical excavation, and undoubtedly some good luck, MVP was able to install the pipeline directly over mapped cave passage ~ 50 feet beneath the base of the trench with no discernible impact to the cave. Exploration continues into walking passage at the end of the current survey at -512 feet.

Introduction

Construction of the 42-inch diameter, 1400 PSI Mountain Valley Natural Gas Pipeline was continuing into its sixth year as of the fourth quarter of 2023. A similar, concurrent project – the Dominion Energy Transmission Atlantic Coast Pipeline – was cancelled by Dominion in July, 2020. Both projects crossed the karst of the Appalachians in West Virginia and

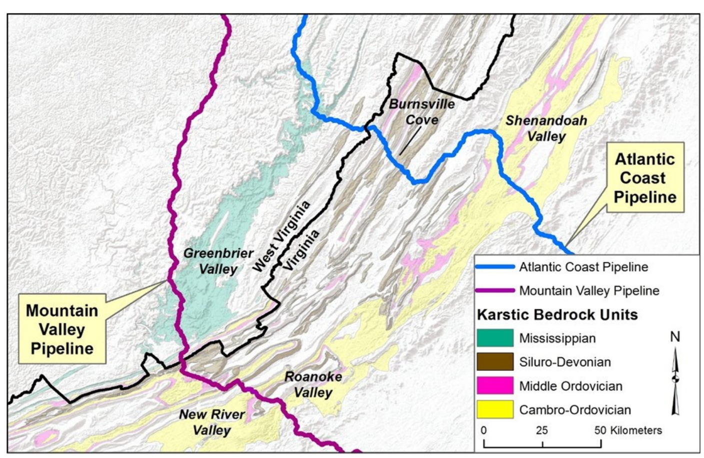

Figure 1. Proposed routes of Mountain Valley and Atlantic Coast high pressure natural gas transmission pipelines crossing the Appalachian Karst, VA and WV (Karst from Weary and Doctor, 2014)

Figure 2. Small cave in pipeline trench, August 2022. A-location of cave in trench on slope; B - cave entrance; C - full extent (15 feet) of cave, now destroyed.

Virginia (Figure 1). Significant adjustments to avoid documented, significant caves and karst features in the proposed routes for both projects were made during planning. In addition, karst resource inventories (Draper Aden Associates, 2017a; Geoconcepts, 2018b) and mitigation plans (Draper Aden Associates, 2017b; Geoconcepts, 2018a) were performed by consulting teams with extensive cave and karst experience. Additional studies were performed prior to and during construction as needed, and are summarized in previous NCKMS proceedings by Orndorff et al (2017), Orndorff et al (2020), and Orndorff et al (2022). Due to issues with private property access, no progress has been made on either remediating or determining the cause of turbidity spikes at Bottom Spring in Montgomery County, VA that began shortly after construction started, following storm events in May, 2018 (Orndorff et al, 2020).

This paper describes karst-related issues associated with construction of the Mountain Valley Pipeline since January, 2022. Most of these issues occurred where MVP crosses limestones of Middle Ordovician age in Giles County, Virginia, where most of the final phases of construction in Virginia occurred.

Spring monitoring

Monitoring of turbidity, pH, temperature, and specific conductivity of two springs (Steele Acres Spring and Canoe Cave Spring) along Sinking Creek Mountain in the vicinity of the pipeline continued as described in Orndorff et al, 2022, with no discernible impacts from construction. The dataset will be the subject of a future publication.

Small caves intersected during trenching

From January 2022 through the end of 2023, MVP reported two small cave entrances discovered during trench excavation to VDCR. Both turned out to be of little significance, though each exhibited speleothem development.

Newport Trench Cave (Figure 2) was reported to VDCR in August of 2022 and explored the next day by VDCR staff.

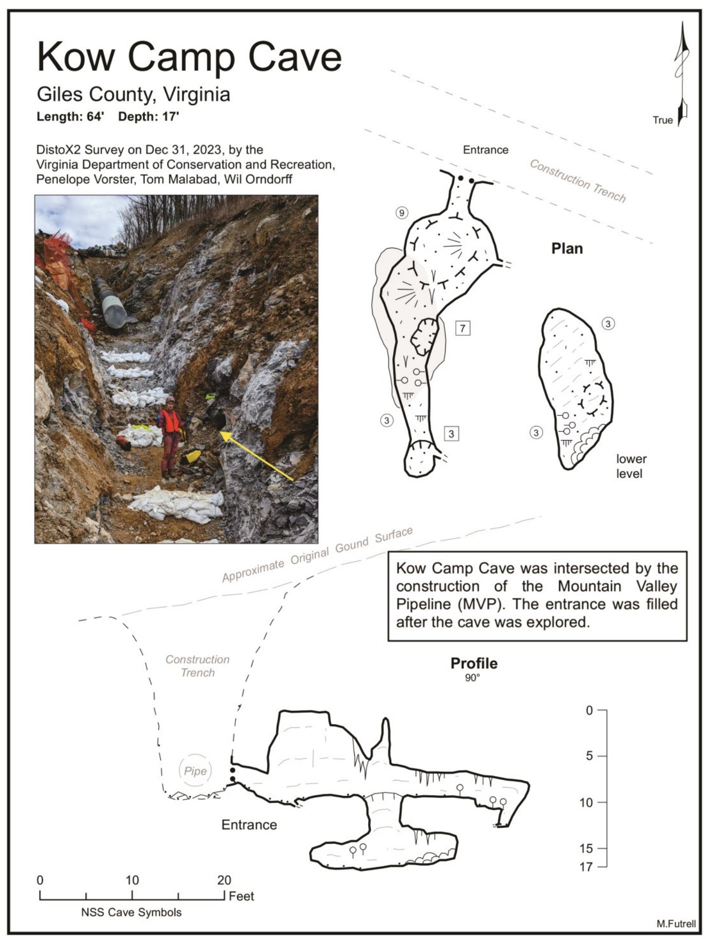

Figure 3. Kow Camp Cave, MVP Trench, Giles County, VA (cartography by Mike Futrell, Virginia Speleological Survey)

After exploration revealed the cave to be only 15 feet in length, the cave was completely destroyed by trench excavation.

A second entrance created by trench excavation led to a small cave developed in the middle Ordovician limestone in central Giles County, and was reported to VDCR on December 30, 2023. VDCR karst staff explored and mapped the cave on New Years Eve. The entrance was blocked when the pipe was installed in the trench, then backfilled, in early 2024. However, the cave was not filled, just the entrance blocked, preserving the cave in a state close to its pre-discovery condition. Kow Camp Cave surveyed to 64 feet in length and 17 feet in depth (Figure 3), and contained several pristine speleothems that persisted despite close proximity to trench excavations (Figure 4).

Figure 4. Images from Kow Camp Cave. A - spalling fractures near trench, B - formation gallery in back of cave, C - attractive, intact bacon drapery.

Conventional Bores versus Open Stream Crossings

The Army Corps of Engineers originally (2018) authorized jurisdictional stream crossings by general permit, but the US Fourth Circuit Court (Richmond, VA) twice declared the general permits invalid (2018, 2020). MVP applied for individual stream crossing pemits in 2021, and these permits were issued in June of 2023 after congressional authorization of MVP. However, the individual permits largely required conventional boring beneath jurisdicational streams rather than allowing open cut crossing. Horizontal directional drilling in karst was deemed too risky due to the potential loss of pressurized drilling fluids into karst voids, a well-documented phenomenon. MVP opted to apply in 2021 for conventional bore versus open cut simply because it was more likely to be approved by regulatory agencies and the court.

Unfortunately, many of the stream crossings in the karst of Giles County, Virginia proved to be extremely challenging to bore due to the presence in and beneath the stream bed of rounded cobbles and boulders of Silurian-aged orthoquartzite (Tuscarora and Kieffer formations). Not only are such boulders very hard, they also tend to deflect and/or capture the drill bit. In addition, conventional boring requires excavation of large (up to 20 feet deep) bore pits on either side of the stream. Boring generates a large amount of sediment laden water that must be pumped to constructed settling ponds prior to discharge back to surface waters. In many cases, water from the overlying streams entered the stream bores during construction through alluvial material in the stream bed. However, intersection of karst features during boring was minimal.

In some bizarre cases, permits required that MVP bore through quartzite cobbles and boulders beneath dry or nearly dry streambeds downstream of karst sinkpoints (swallets), as shown in Figure 5. By contrast, in places where open cut crossings were implemented, even on perennial streams, construction took place quickly with minimal if any impacts to surface or groundwaters (e.g. Canoe Cave Spring Run, Figure 6).

While boring beneath surface waters may in some cases be an appropriate, low-impact solution, it proved for many crossings associated with the Mountain Valley Pipeline to be not only more expensive, but more environmentally impactful than crossings using open cut methods. This is especially true in karst areas and/or areas with coarse quartzose sediment (cobbles and boulders) in and beneath the stream bed.

Exploration and Conservation of Calcite Turtle Cave

Calcite Turtle Cave was discovered in the permanent construction limits of disturbance (LOD) in May, 2021 (Orndorff et al, 2022), and MVP was unable to negotiate with the landowner to alter the route to avoid the cave. Thus it became necessary to try to avoid intersecting the cave while drilling within the approved 125’ wide construction corridor.

The first two survey trips in 2021 revealed that although the cave ran beneath the final pipeline trench location, it descended steeply reaching a depth of approximately 60-67 feet from cave ceiling to land surface at the deepest point beneath the construction right of way. MVP’s karst consultants (now with TRC, which purchased Draper Aden in June of 2022) ran electrical resistivity imaging (ERI) over the cave in the construction LOD to search for anomalies consistent with

Figure 5. Doe Creek Crossing (Direct bore). A. Looking down 70m long path of bore, arrow indicates channel. B. Dry stream channel of Doe Creek with quartzite cobbles, ~ 3 m wide.

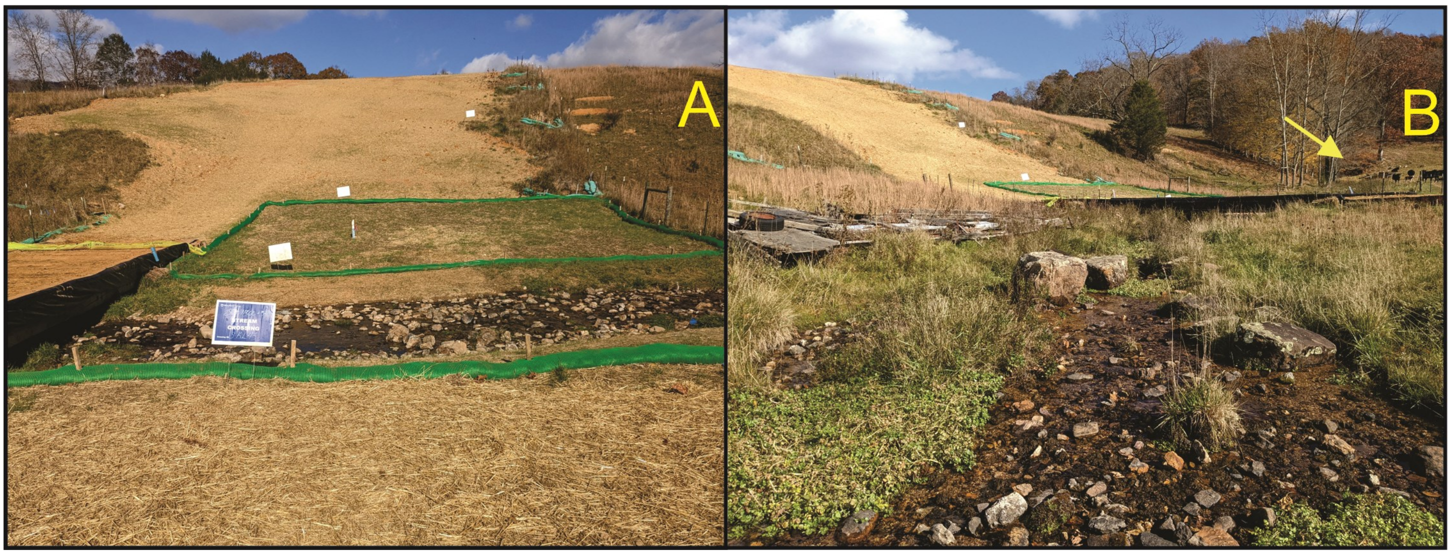

Figure 6. Conventional open-cut stream crossing of Canoe Cave Spring Run. A. View of the restored crossing, B. Clear water downstream of the crossing, Canoe Cave Spring at arrow in background.

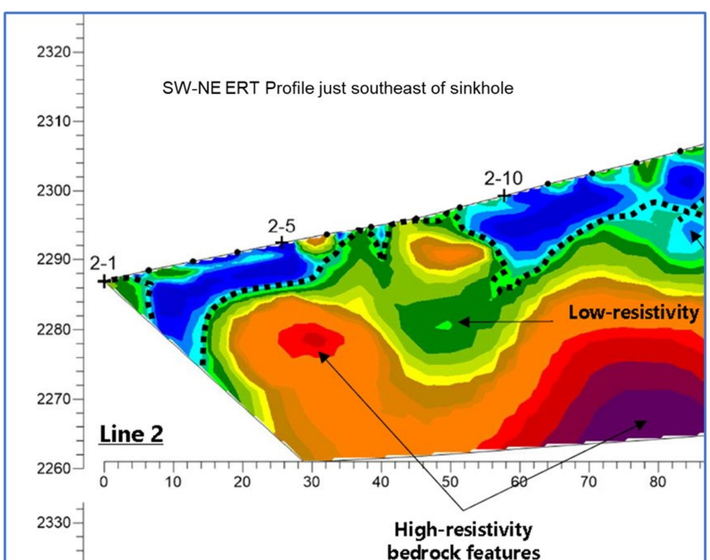

Figure 7. Example of ERT imaging across Calcite Turtle Cave, Mountain Valley Pipeline Construction Limits of Disturbance (courtesy of TRC, analysis by Chris Printz). Low resistivity anomalies indicate possible mud-filled voids. High resistivity anomalies indicate either dry bedrock or possible air-filled voids.

subsurface voids to better pin down the best possible location for the eight to ten foot deep trench. ERI revealed several anomalies with the potential to intersect the cave through blind ceiling connections (Figure 7).

Considering both the physical survey and the resistivity, VDCR and TRC/Draper Aden concurred that the best option (since avoidance was not an option on the table) was to deviate the centerline approximately forty feet to the south, as shown in Figure 8, which includes all cave survey data through 2023.

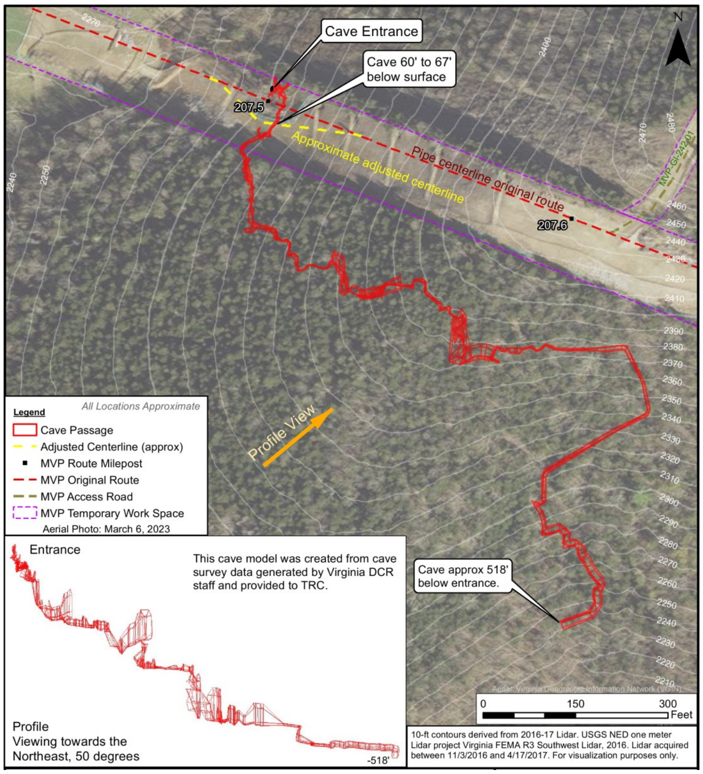

Figure 8. Calcite Turtle Cave and the Mountain Valley Pipeline at of 12/31/2023 (courtesy of TRC, GIS Model and graphics by Mike Futrell)

Exploration to date over five trips from May 2021 through the present revealed the cave to be extraordinarily beautiful (Figure 9-A), and explorers were surprised at how rapidly the cave descended via a series of vertical shafts (Figure 9-B) separated by short sections of horizontal canyon, all following the calcite saturated stream (with eponymous turtle) encountered just below the entrance. Exploration was suspended after the fourth trip in June, 2022 until a secure cave gate was installed to control access. Local spelunkers, possibly associated with pipeline opposition groups, had entered the cave without the landowner's permission, who then requested the cave be gated for both safety and conservation reasons. A bat-friendly cave gate was installed in 2023 (Figure 9-C), after which the fifth and most recent survey trip pushed the cave to its current length of 2802 feet and depth of 518 feet. That survey ended with the way on continuing as walking passage continuing to follow the small stream. Preliminary biological surveys revealed the cave to have several cave-limited invertebrates present, most notably blind cave beetles of the genus *Pseudanophthalmus*, not yet identified to species level. Bats have not yet been observed in the cave, but with the bat-friendly cave gate and extensive suitable habitat, future use by bats is likely.

The current end of exploration at the lowest point in the cave so far is at an elevation of ~1780 feet, and dye tracing (Figure 10) showed that the stream from Calcite Turtle joins water from other caves and stream sinks in the Doe Creek basin underground before resurging at Belle Spring on the New River ~ 2.5 miles west at an elevation of approximately 1650 feet. The cave has over 100' of vertical potential left, and has the potential to connect to cave passages carrying the other water that flows to Belle Spring.

The trench across Calcite Turtle Cave was excavated in November of 2023 (Figure 11 A-D). The process began with air track borings along the proposed centerline across the cave, which showed evidence of a couple of small voids as well as a mix of rock and soil fill indicating a cutter (soil-filled) and pinnacle (bedrock) surface. The decision was made to begin excavation using John Henry hydraulic rock hammers while a blasting plan for force assisted excavation was being developed. However, by the time the blast plan was developed, excavation of the trench was complete. VDCR and TRC staff were present to inspect the trench for the duration of excavation, and only a single, ~ 1 meter diameter void was intersected and, though filled with inactive speleothems, it did not appear connected to underlying passage in Calcite Turtle Cave. Once the trench was completed, a geosynthetic liner was placed in the bottom of the trench and covered with ~ 8" of pea gravel to discourage erosion and possible subsidence in the bottom of the trench. On December 12, 2023 members of the VDCR karst team entered the cave to look for evidence of impacts from the trenching above. No evidence of impacts to the cave was found. By early April, 2024, the pipe was installed in the trench, the trench was backfilled, and the right of way restored to grade and seeded.

Summary

While construction of the Mountain Valley Pipeline has had a combination of minor and transient impacts to karst resources,

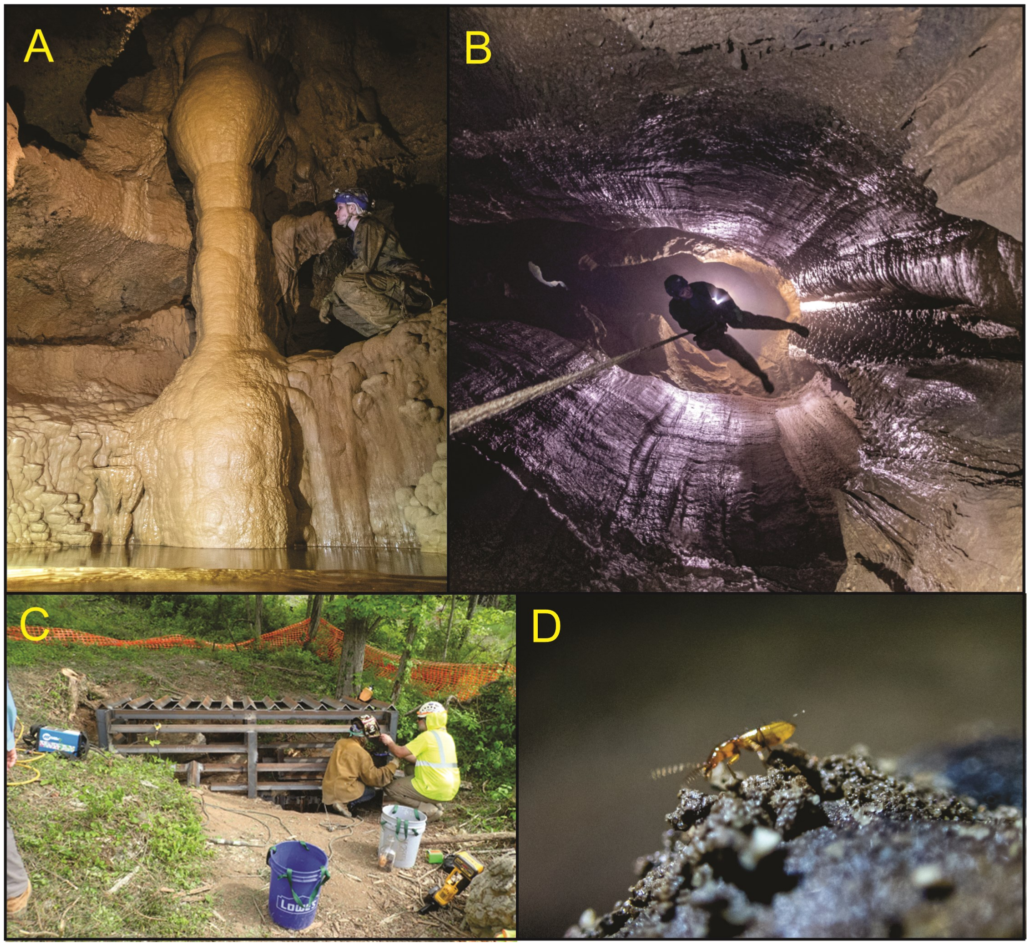

Figure 9. Calcite Turtle Cave. A - typical flowstone found throughout the cave; B - One of several sculpted shafts in the cave; C - installation of cave gate in 2023; D - Pseudanophthalmus sp. cave beetle.

Figure 10. Dye tracing to determine Calcite Turtle Cave resurgence. Geology from Schultz et al (1986).

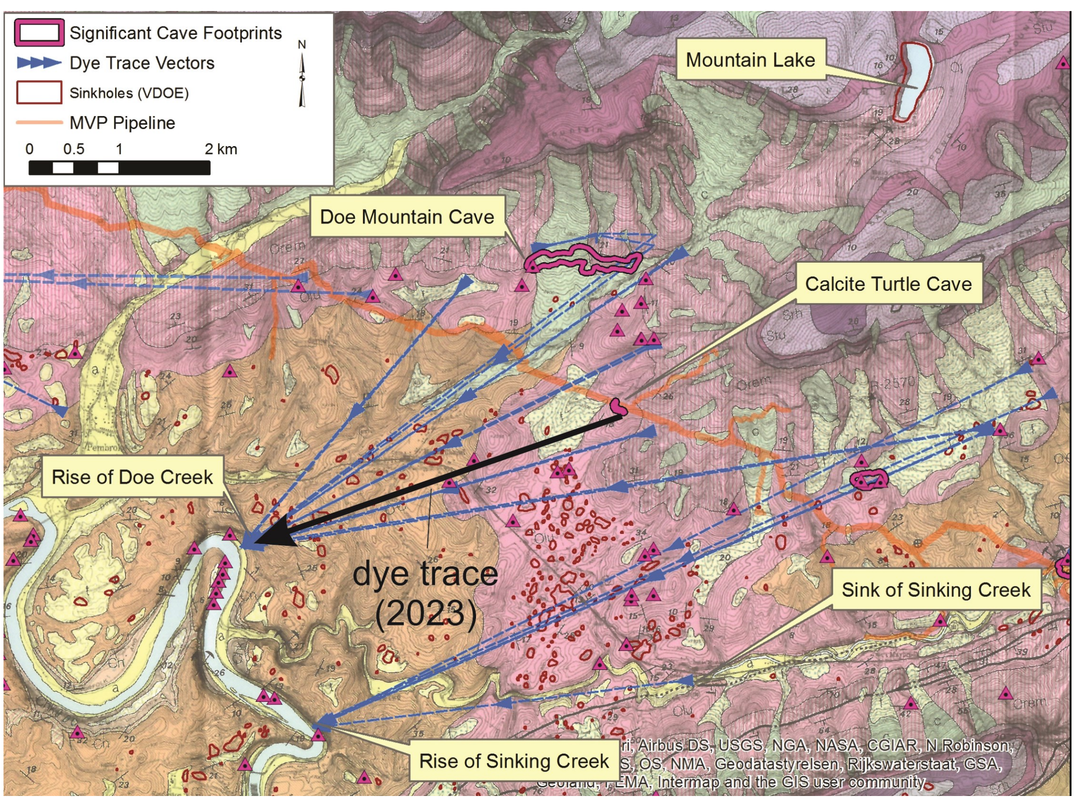

Figure 11. Trenching over Calcite Turtle Cave.

A - exploratory air-track boring over cave prior to excavation; B - Excavation of trench across underlying cave passage (marked by X); C - completed trench with geosynthetic and gravel bed liner; D – Right of way regraded and seeded, blue marks area over cave passage.

overall the impacts were small considering the scale and duration of the project. While a "no-build" option would by default have had fewer (no) impacts, in most cases this is not a realistic result. In the case of the Mountain Valley Pipeline, once the project was approved for construction, a collaborative rather than adversarial relationship between the company and Virginia DCR Karst Program staff resulted in a better outcome for the cave and karst resources in vicinity of the project. The combination of preliminary karst feature inventory; avoidance of cave and karst features during route selection; frequent inspections; responsiveness to agency recommendations; financial support for monitoring, land conservation, and exploration efforts; and facilitation of site access for VDCR staff, including to caves, undoubtedly reduced the project's impacts to cave and karst resources across the entire length of the project.

Acknowledgements

VDCR acknowledges the financial support over the course of this project from Mountain Valley Pipeline, LLC; the Cave Conservancy of the Virginias; and the New River Land Trust. We thank TRC staff Mike Futrell, Chris Printz, Andrea Futrell, Bill Balfour, Mike Cole, and Billy Newcomb for assistance in the field and in preparation of technical graphics. Most importantly, we'd like to thank the private landowners – whose use of their properties was impacted for several years by pipeline construction - for allowing access for monitoring, especially Georgia Haverty, owner of Doe Creek Farm where we discovered Calcite Turtle Cave.

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Significant Cave Exploration within the Easement of a Major Interstate Gas Pipeline: The Nexus of State Agencies, Cavers, Landowners, and the Mountain Valley Pipeline

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Abstract

In early 2018, construction began on the 303-mile-long Mountain Valley Pipeline (MVP) connecting Wetzel County, West Virginia, to Pittsylvania County, Virginia. MVP will transmit natural gas extracted from the Marcellus and Utica shales in a 42" pipe at 1400 PSI, crossing over multiple important karst areas in both Virginias. In the summer of 2015 Draper Aden and Associates (DAA) began karst assessments for MVP. In February of 2017, MVP submitted the DAA Karst Hazzard Assessment and FERC approved it finalizing the location of the corridor. On March 3, 2021, bat biologists reported a small opening in a previously identified sinkhole within construction limits. DAA visited the feature shortly after and informed the Virginia Department of Conservation and Recreation (VDCR) Karst Program that an opening too small for human entry, had been found. DAA performed an electrical resistivity survey identifying subsurface features possibly related to the opening. VDCR visited the site and performed an initial assessment and follow up on May 11 and 20, 2021. At the request of VDCR, MVP removed a boulder making the opening large enough for entry. Exploration of the cave by VDCR began on May 28, 2021. This is Calcite Turtle, Virginia's newest significant cave! Exploration yielded 2,802.36 feet of length with a depth of 517.98 feet as of September 15, 2023, making it the ninth deepest cave known in Virginia. The main route contains a small stream with 11 vertical drops connected by meandering fissures. The last survey trip turned around in walking passage.

Sinkhole Hazard Assessment Index and Risk Analysis to Inform Karst Policy and Mitigation Planning

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Abstract

Sinkholes are geologic hazards that occur in karst landscapes that can be highly destructive and costly. It is unknown how much sinkholes cost per year, and sinkhole-related policies are nonexistent on a federal level and nearly nonexistent at the state level. This is partly due to the need for a method to quantify and assess sinkhole cost and risk over time. A lack of awareness has led to the continuation of the development and urbanization of sinkhole-risk areas, which put lives and property at risk. This study will attempt to characterize sinkhole threats to aid in creating a method to quantify sinkhole potential cost and risk, including the morphometry and scale of bedrock collapse sinkholes, which are less common but highly destructive. In addition, comparison and contrast of existing sinkhole policies and regulations to assess how well they measure the characteristics of sinkhole hazards will occur; however, karst landscapes are inhomogeneous, and it is unlikely that a "one size fits all" policy approach will be found effective. The goal of this study is to create a method that can be used to quantify the risk associated with sinkholes to influence better development practices and policy implementation. Once the study is completed, a sinkhole hazard index tool will be created that can be used by developers, environmental managers, and policymakers to inform urban karst development decisions based on environmental, economic, and social factors.

Hydrological Dynamics of Surface-Groundwater Interactions between Major Springs of Mammoth Cave and the Green River, Kentucky, USA

Polk, Jason [1]; Cecil, Matthew[1]; Toomey, Rick[2]; Kambesis, Pat[1]; Lawler, Trayson[1]; Troxell, JT[1]; Hourigan, Amy[1]; DeCelle, Christian[1]; Wisenden, Matthew[1]; Maric, Nenad[3]

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Abstract

Mammoth Cave is one of the most studied caves in the world; yet, studies of the recharge/discharge dynamics of two of its primary spring outlets, Echo and Styx Springs, are still underway. These springs recharge to the Green River during normal flow, but can reverse flow under flooded conditions. Data collections occurred in 2021 and included almost a year of weekly water samples for isotope and geochemical analyses at 13 sites on the surface and in-cave and water levels at six sites. These data were used to determine the conditions during which river reversals occur at the two springs and how epikarst and surface rainfall recharge the system during storm events to create competing hydraulic head conditions. River reversals appear to be moderated by cave recharge dynamics during certain flow conditions to a threshold when the springs dominate the flow regime, while during high river discharge, the system can exceed this threshold and the Green reverses into the cave via the springs. The system responds within weeks to return to baseflow, except during anomalous flood conditions, which were captured in a February, 2021 major flooding event. Recharge points in the cave have varying geochemical signatures and indicate the complex residence time dynamics that control the discharge in the springs during different seasons and antecedent moisture conditions. These results have implications for the management of the cave system and adjacent Green River with respect to a variety of hydrologic and biological parameters, including the potential future response under a changing climate.

The Karst Springs Initiative - Five Years of Volunteer Karst Studies on the Cumberland Plateau of Tennessee

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Abstract

In 2015 the Karst Springs Initiative was formed as an informal, volunteer-based, effort to study some of the largest springs in Tennessee. The group sought to establish continuous monitoring stations on the largest accessible springs to determine the largest karst springs in the state. Continuous monitoring stations were established at five major springs and spring groups. Spring groups are areas where groundwater discharge occurs in a distributary fashion, further defining the local hydrology, often through main (perennial) and overflow (ephemeral) springs. For a large spring in the East Fork Obey River, a station was also established at the main sink point located seven miles upstream from the spring. Many discharge measurements were made over a five-year timespan in an effort to develop rating curves for eight continuously monitored springs and sinkpoints. In addition to streamflow studies, the group delineated recharge areas for two of the larger spring systems (Enchanted River and Grundy Big Spring) through the use of dye tracing. This tracing work has delineated some of the largest karst recharge areas in Tennessee. The Enchanted River recharge area exceeds 136 mi^2, while the recharge area for Grundy Big Spring/Collins Rise system is 154.5 mi^2. Data collected by the Karst Springs Initiative helps to better understand springs and karst landscapes along the Cumberland Plateau. This work has also helped to create an initial ranking of streamflow for the largest springs in Tennessee. Data from these studies will be further published and shared widely to encourage future karst studies in Tennessee.

KARST PROTECTION: How Do We Go from Words to Action?

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Abstract

Karst science has been advancing for over 400 years. However, advances in the protection and management of karst terrains remain sluggish. The slow progress may come as a surprise, considering how many guidelines and recommendations have been and continue to be developed on local, state, national, and international levels. Despite these efforts, governments worldwide still do not adequately address karst protection and management.

The question that arises is, why? Is the protection of these essential and valuable resources intentionally ignored? Are the guidelines difficult to understand or implement? Does the reason lie elsewhere?

Most guidelines are exceptionally comprehensive from a karst protection perspective, and following them would assure rigorous protection of karst terrains. However, economic, political, and social obstacles make implementation difficult. Interestingly, approaches accounting for these essential elements have been developed by karst scientists worldwide but are rarely considered during the development of guidelines. One example is the K-framework that will be explained in this study. Some other examples include A Process for Karst Hazard Mitigation Planning in Virginia by Belo, Disturbance Index for Karst Environments by Van Beynen, and several more.

It has become apparent that the only way to appropriately and successfully protect karst resources is through interdisciplinary approaches. In addition to the karst and natural science professionals, social scientists, legal scholars, and citizen and agency stakeholders should be included in the process. This study presents the obstacles entities attempting to regulate and protect karst are encountering and suggestions on how these obstacles may be overcome.

Poster Presentations

Community Interest and Involvement in Cave and Karst Protection

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[2] Crawford Hydrology Laboratory, Western Kentucky University

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Abstract

Public education and outreach have long been considered important facets of cave and karst conservation and protection. Such activities are conducted by various cave and karst related entities such as local grottos, cave conservancies, federal and state agencies that manage cave resources, cave/karst research related university programs and some show caves. Educational/outreach resources can include public lectures, brochures, websites, lesson plans and social media. In karst areas, combining citizen science and applied learning opportunities are also very effective methods in raising public interest and awareness in protecting local cave and karst resources. Three case studies (from Warren and Hart Counties, Kentucky and Robertson County, Tennessee,) are presented where local community members participated in assessing the cave and karst resources in their "neighborhoods". Participatory activities included cave mapping, dye tracing and monitoring, georeferencing cave entrances and sinkholes, and using simple geospatial resources such as Google Earth and ArcGIS Online. Participants came away not only with a greater appreciation of the caves on their properties but also the relationship between groundwater, caves and the karst landscape. That extra insight emboldened some community members to take action against development projects that threatened their local karst resources; helped landowners make informed decisions on land use changes to minimize impact to local caves, and inspired one land owner to dedicate caves on their property to cave/karst research and student learning.

Introduction

Public education and outreach have long been considered important facets of cave and karst conservation and protection. Such activities are conducted by various cave and karst related entities such as local grottos, cave conservancies, federal and state agencies that manage cave resources, cave/karst research related university programs and some show caves. Educational/ outreach resources can include public lectures, brochures, websites, lesson plans and social media. In karst areas, combining citizen science and applied learning opportunities are also very effective methods in raising public interest and awareness in protecting local cave and karst resources. Three case studies (from Warren and Hart Counties, Kentucky and Robertson County, Tennessee) are presented where local community members participated in assessing the cave and karst resources in their caves.

Bell Witch Cave, Robertson County, Tennessee

Landowners contacted WKU requesting a cave assessment and possible survey. Located near the Kentucky-Tennessee border, this show cave is in the Northern Highland Rim and its main tourist appeal is that it is a possible paranormal activity site. Landowners accompanied us on survey/inventory work and had many questions about geology, cave speleothems, the relationship of the cave to surface topography (Figure 1) and local hydrogeology (Figure 2). They have since decided to include more science-related information on their tours and would like it included on the map.

Coleys Cave, Warren County, Kentucky

Local landowners requested an assessment of caves on their properties. Upon visitation they revealed their concern for a new subdivision that was proposed in their neighborhood and its impact on sinkhole development and water quality.

Landowners accompanied us on survey trips (Figure 3) and expressed great interest in all aspects of their caves including biology, geology, water flow and sinkhole development. We did a biological inventory (Figure 4) of the cave and actually found a number of troglobites which were of great interest to

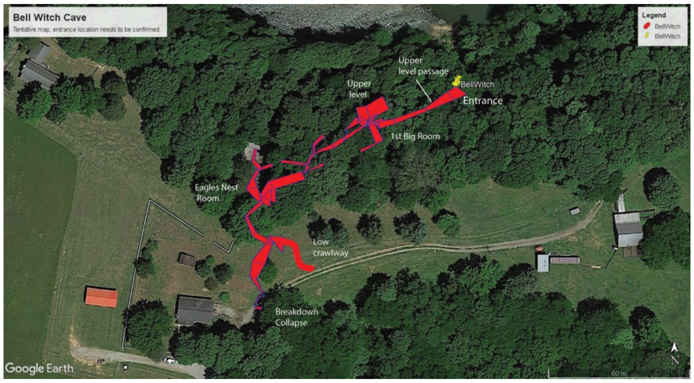

Figure 1 Topographic overlay of Bell Witch Cave

Figure 2 Local hydrogeology of Bell Witch Cave

Figure 3 Landowner on reconnaissance trip in Coleys Cave

Figure 4 Flatworm documented in Coleys Cave

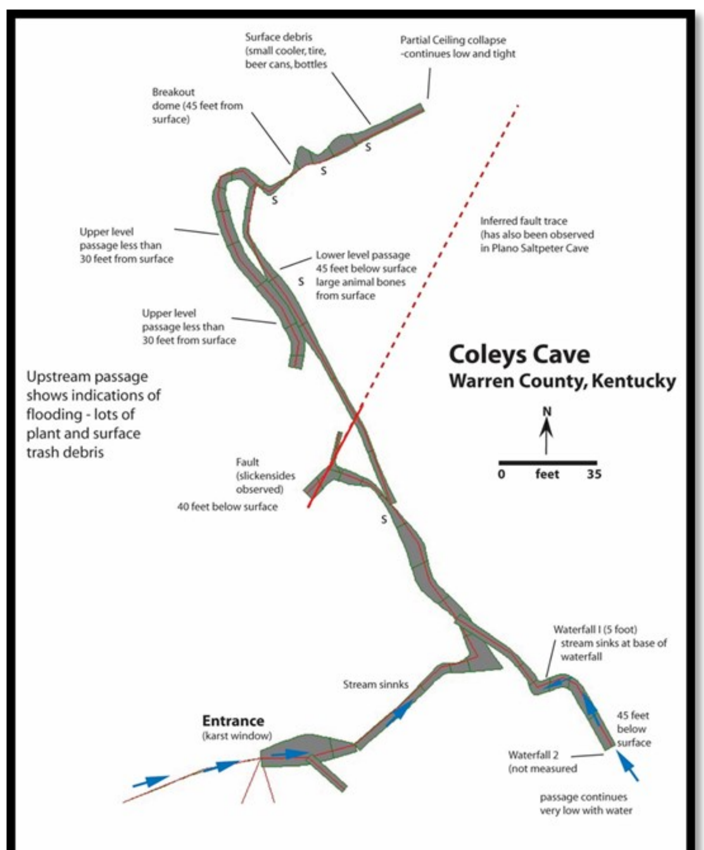

Figure 5 Map of Coleys Cave. The joint controlled nature of the cave is evident from the map.

Figure 6 Location map provided by landowner

the local landowners. The Coleys Cave survey resulted in 923 feet of surveyed passage (Figure 5).

Hydrogeological assessment of the cave revealed the cave to be on the boundary of two different karst groundwater basins. The largest of the two is the Lost River Groundwater basin; the second basin is smaller and is currently undocumented. Land owners have secured permission for us to access springs to monitor the progress of dye tracing efforts.

Our team was invited to make a presentation to local landowners and it was very well attended by local residents. They had many questions about caves in their neighborhood and caves in general.

Wendy's Cave, Warren County, Kentucky

Landowner contacted Cave Research Foundation to give an invitation to check out a cave on her property. They provided location information for the cave on their property (Figure 6). The landowner allowed access for a reconnaissance of the cave and surrounding area (Figure 7). We have since determined that the cave is undocumented. The landowner wants hydrogeological information about the cave since it directly impacts the property and has opened the cave and property for student research projects.

Discussion and Conclusions

In all cases, landowners reached out to local institutions involved in cave exploration and research and actively participated in the field work involving their caves. They came away with a greater appreciation of the caves on their properties but also the relationship between groundwater, caves and the karst landscape. That extra insight emboldened some community members to take action against development projects that threatened their local karst resources; helped landowners make informed decisions on land use changes to minimize impact to local caves and inspired a Warren County landowner to dedicate the caves on their property to cave/karst research and student learning.

Acknowledgement:

We would like to thank the landowners of Bell Witch Cave, Tennessee, the Plano community members in southern Warren County, Kentucky, and to the landowner in Bowling Green, Kentucky for inviting us to document their caves and for their interest in the protection of cave and karst resources.

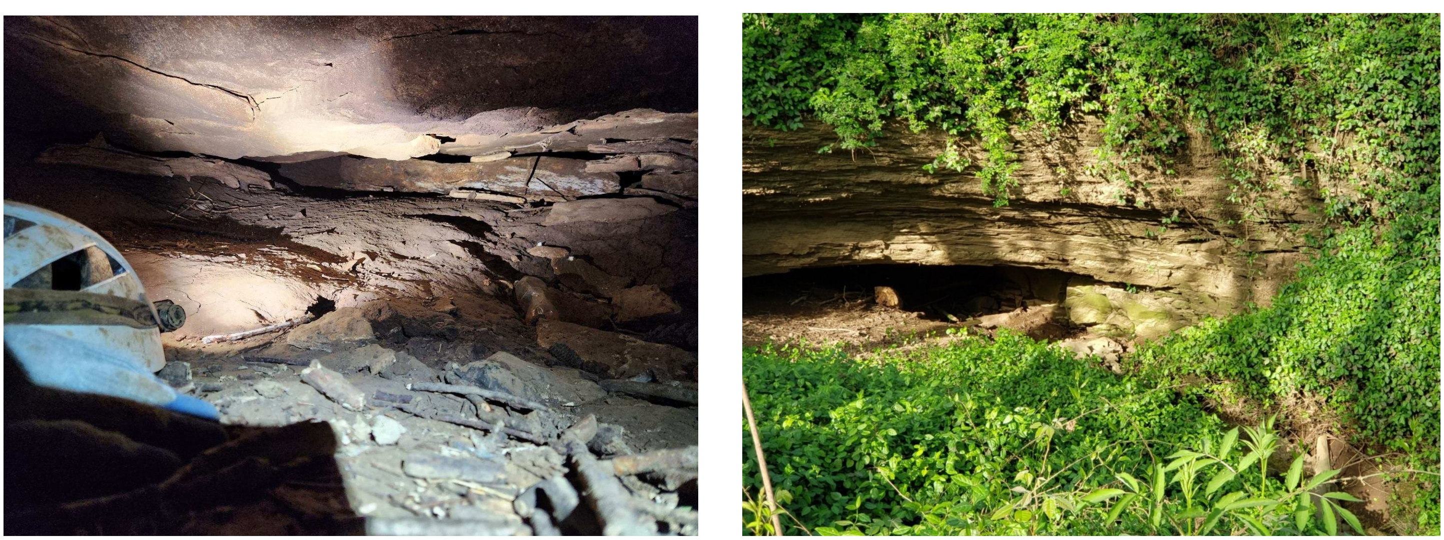

Figure 7 (Above left and right) Images from reconnaissance trip

Microplastics Contamination with the Hidden River Cave System, Hart County, Kentucky: Preliminary Results

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Abstract:

Caves are significant geological and geoheritage features that can contain important drinking water reserves, unique ecosystems, evidence of historical and archeological human use, and contain natural archives in the form of sediments that provide insight into past climate conditions. The interconnectivity of the surface and subsurface environments make caves highly susceptible to all types of contaminants and among those are microplastics (MPs). Though it is well documented that karst aquifers easily transport and store sediments, the impact of MPs on these sediments is an understudied topic. The goals of this study included: confirming the presence of microplastics at the study sites; documenting the presence, characteristics and abundance of microplastics in cave sediment; and comparing the concentrations of microplastics in a show cave vs. a wild cave. The area of interest for this study is the Hidden River groundwater basin located in Hart County, Kentucky. Specific study sites include L&N Cave, a wild cave; and the Hidden River Cave System, which is a show cave. Sediment samples were collected in both caves and analyzed for particle size and content, and inspected visually. Microplastics were present in the preliminary samples with higher amounts along the tourist paths in the show cave and in lesser amounts in the wild cave.

Introduction

Caves contain relatively stable environmental conditions due to the absence of seasonal variability and permanent darkness, and thus are considered conservative environments because they can preserve geological/environmental information over long time periods. Caves are also easily impacted by pollution and climate change, causing them to lose scientific information and natural habitats. Show caves undergo additional anthropogenic impact in the form of construction of tourist trails, lighting systems, and other tourism infrastructure that oftentimes modify the cave atmosphere and microclimate. Tourism brings in lint, dust, pollutants and organic materials. Since the 1970's, microplastic (MP) pollution has been found in just about all natural environments worldwide but has just recently come to the forefront as an environmental pollutant in caves. Previous studies that documented either MP or lint in caves found fiber content to be between 30%-85%. MPs can potentially endanger subterranean ecosystems, damage speleothems and pollute karst groundwater. The goals of this study were to determine if MPs are present in Hidden River Cave, a show cave in Hart County, Kentucky; and L&N Cave, a wild cave located 2 km due south of the show cave.

Site Description:

The Hidden River Cave System is a tributary and sub-basin within the greater Gorin Mill Groundwater Basin located in Hart County, Kentucky (Figure 1). The cave system is the focus of this study due to its history of significant contamination, its proximity to industrial development, and its relationship to the Mammoth Cave karst aquifer and the Green River. Hidden River Cave is a show cave that is owned and managed by the American Cave Conservation Association. The Hidden River groundwater sub-

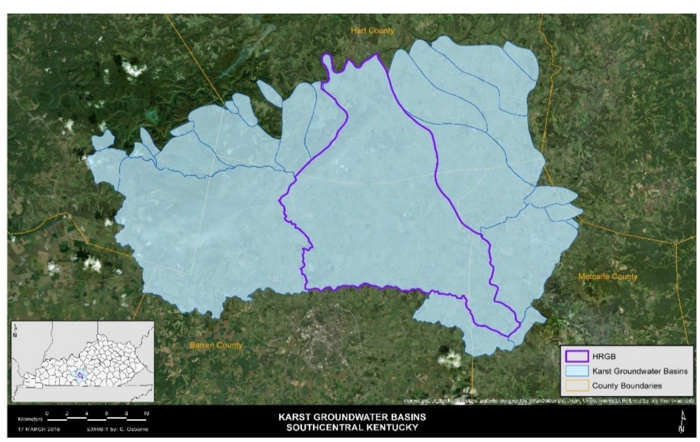

Figure 1. Greater Gorin Mill Groundwater Basin, Hidden River sub-basin outline in blue.

basin includes L&N Cave (surveyed at 3 km; 2 mi) in Cave City, Hidden River Cave (16 km; 10 mi) in Horse Cave, and the Hidden River Complex (32 km; 20 mi) situated near the Green River (Figure 2).

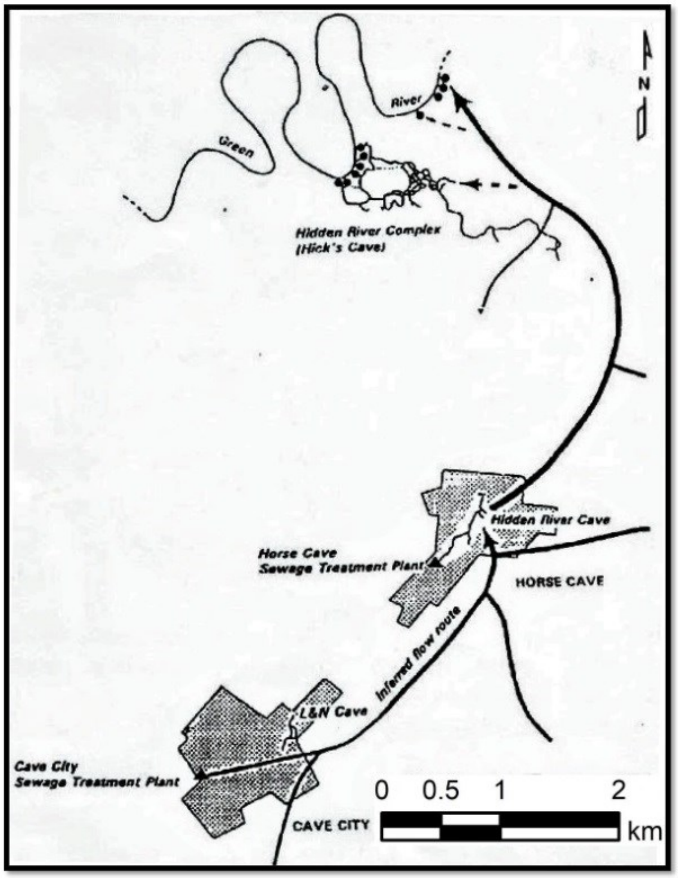

Figure 2. Components of the Hidden River Groundwater basin

The Hidden River groundwater subbasin exhibits distributary flow, where flooded, low-level conduits have created a system of interconnected passages that flow north toward Munfordville and resurge through 46 springs situated on the Green River. Land use in Horse Cave includes agricultural, residential, commercial, industrial districts, and a central business district. However, Hart County has become more focused on industrial growth and hosts a variety of industries located mostly in Munfordville and Horse Cave, Kentucky. Of particular interest to this study is a local industry that manufactures Styrofoam food containers. It is located on the sinkhole plain south of Hidden River Cave (Figure 3) and occupies ten buildings that cover nearly 27 ha (67 ac) of land in Horse Cave. The sinkhole plain is a significant recharge area for Horse Cave, Kentucky.

Methods

Field sampling: A total of eight sites, shown in Figure 4, were selected for sediment sampling for this study. Five samples

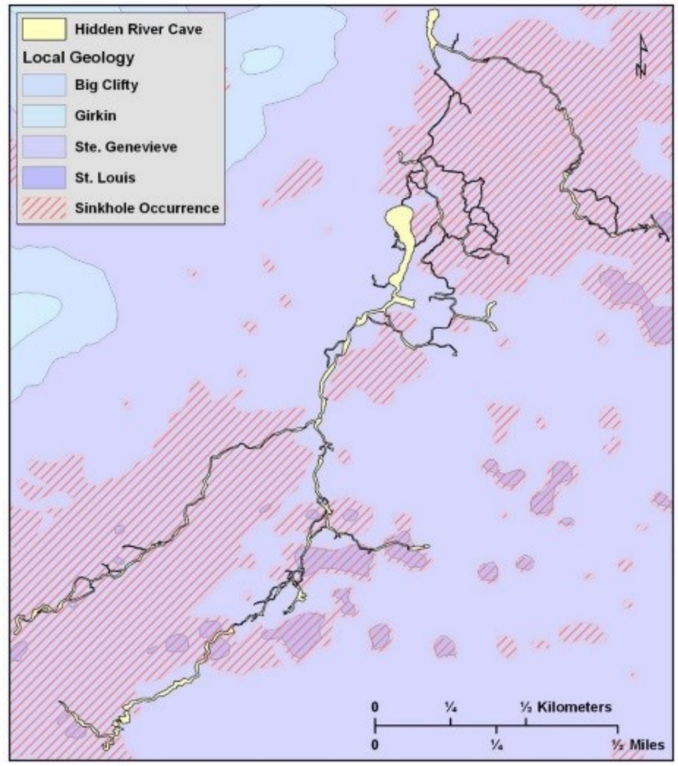

Figure 3. Sinkhole plain south of Horse Cave, Kentucky

were collected from 0.5 x 0.5 meters plots adjacent to the tourist trail and from two sites off the standard tourist trail.

Samples were taken with metal implements and stored in sterile glass jars to prevent further plastic contamination (Figure 5A-B). All sampling material was pre-cleaned with ethanol and distilled water. The samples were stored in the fridge at 6 °C until laboratory analysis. Three of the eight samples have been analyzed so far.

Laboratory methods: Microplastics (MP) laboratory analysis was done as a two-step process that included extraction/ purification (after Balestra and Bellopede, 2022) and identification (after Crawford and Quinn, 2017).

Extraction/purification methods:

Nitrile gloves and cotton lab coats were used to avoid additional plastic contamination. Working surfaces were cleaned with ethanol and distilled water. Plastic equipment was not used during the lab analyses.

- The sediments are placed in a metal pan, covered with aluminum foil and dried in an oven at 40^{o}C (104^{o}F) to constant weight (Figure 6a).
- 30 mg of sample was selected and poured into pre-cleaned glass beakers (Figure 6b).

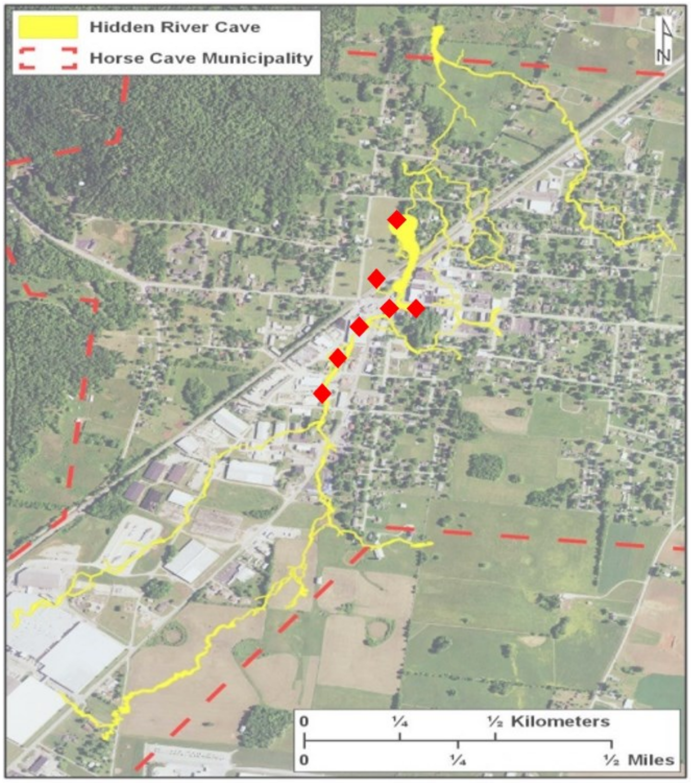

Figure 4. Sampling sites in Hidden River Cave. Numbered sites have been analyzed for this preliminary study

Figure 5a. In-caves sampling

Figure 5b. Samples collected in glass jars.

Figure 6a. Drying samples

Figure 6b. Samples ready for density separation

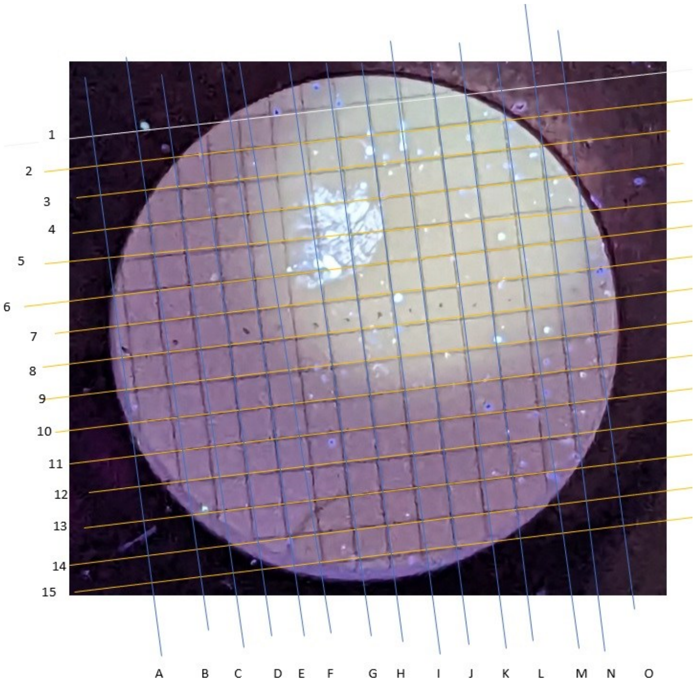

Figure 7a. Grid for sample

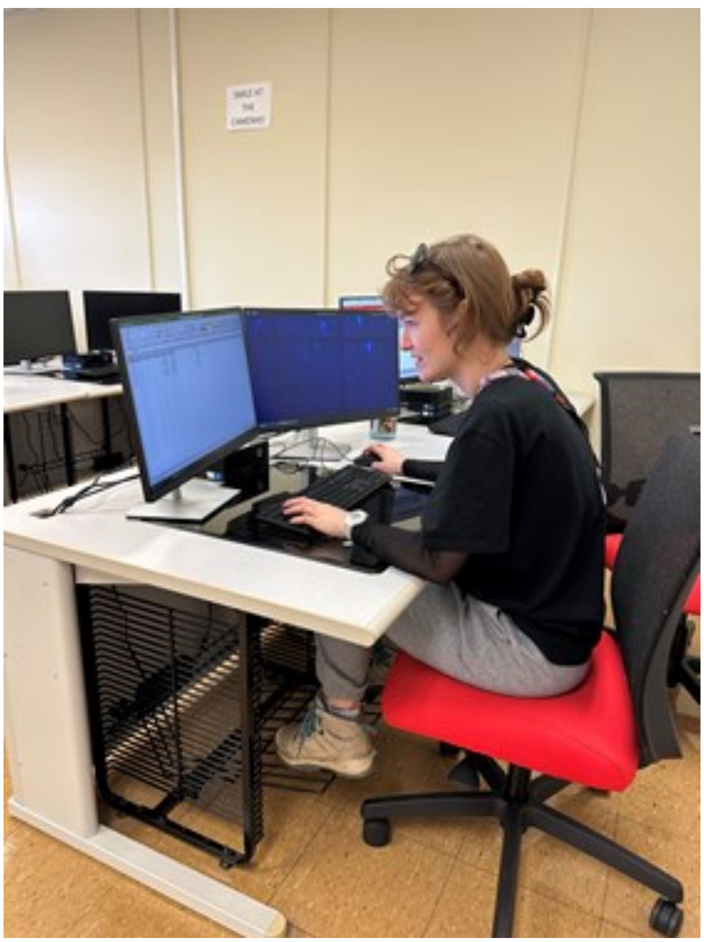

Figure 7b. Identifying and counting MPs

- After settling for 24 hours, 30 ml of supernatant was extracted with a glass pipette and filtered by a vacuum pump through a 1.2-µm pore size glass microfiber filter (Whatman, Ø 47 mm). Filters were placed on glass petri dishes covered with aluminum foil and dried in an oven at 40°C for 2 hours.
- Organic material was removed by applying 0.5 ml of 15% hydrogen peroxide solution, left to react for 30 min. The sediments were dried again for 1 hour at 50°C

Identification:

- Petri dishes containing the MPs on filters were placed on a grid that was used to facilitate counting. A UV flashlight set at a 45° degree angle (Alonefire SV10 365 nm UV flashlight 5W), was shined on each sample. 56 rectangular areas were defined to count MPs (Figure 7a) and photographed.
- MPs were counted via visual identification. The cut off particle size was >0.1 mm (Figure 7b)
- All counted MPs were described using standardized size and color sorting system (SCS) as per Balestra and Bellopede 2022.

Results and Discussion

Only three of the 8 total samples have been analyzed so far (Samples 1, 5, 8). Sample 1 was collected just beyond the dripline of the cave. Sample 5 was collected near the end of the tourist trail. This area is visited by adventure tours. Sample 8 was in the upstream section of L&N cave. Microplastic counts were recorded and totaled on an Excel spreadsheet and summarized in Table 1.

The total number of MPs found in all three samples was 644 microplastic pieces. Of these, 91% were of size 1mm or less and 9% were between 1-5 mm. Of the 644 pieces, 19% were fibers, 74% were fragments, and 7% were foam.

Sample 1 is located at the cave dripline but away from the tourist trail. The majority of the pieces were fragments less than 1mm in size (72% were fragments, and 28% were fibers). MP pollution in this area may have come from the roads located above the large sinkhole entrance.

Sample 5 was located adjacent to the tourist trail. Most of the pieces were less than 1mm in size (93%) and 7% were between 1-5mm. Fragments made up 74% of the total, fiber was 21%, and foam was 5%. The cave floods almost fully several times a year which may explain the large amount of fragments. Fiber, which is usually associated with tourist clothing, made up 21%.

The presence of foam may be from autogenic recharge from the Styrofoam container factory located within the sinkhole plain south of the cave.

Sample 8 is located in the upstream portion of L&N cave; 87% of the fragments were less than 1mm in size and 13% were between 1-5mm.

Conclusions

- Microplastics were present in the three preliminary samples with higher amounts along the tourist paths.
- Most of the particles were fluorescent under UV light.
- Small (less than 1mm), fragment-shapes dominate the samples possibly from major flooding events.
- Fibers were the next common type in the show cave suggesting that synthetic clothes could be a significant source of microplastic pollution in show caves.
- The occurrence of foam pieces are likely from the foam container factor in the recharge area.
- Microplastic monitoring in subterranean environments is a fundamental step to establish the base level of MP pollution and consequently to determine strategies for the protection and management of show caves.

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Crawford, C. B., & Quinn, B. (2017). Microplastics, standardisation and spatial distribution. *Microplastic pollutants*, *5*, 115-122.

Sample#	Size<1mm	Size: 1-5mm	Fiber	Fragment	Foam
Sample 1	105	0	29	76	0
Sample 5	254	22	58	205	13
Sample 8	229	34	34	197	32
Totals	588	56	121	478	45

Table 1. Sample counts and analyses

Importance of State Cave Surveys for Cave Resarch- Case Study: Tennessee Cave Survey as a Source of Speleological and Geological Data on Cave Type, Distribution, and Density as Indicators of Karstification on the Cumberland Plateau of Tennessee

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Abstract

State cave surveys can contain significant amounts of data besides cave locations. Metadata in the form of cave statistics, descriptive narratives, and maps provide valuable information for cave and karst research. The Tennessee Cave Survey has documented 11,756 caves (as of 2023) distributed over 11 physiographic provinces and occurring in rocks of Cambrian, Devonian, Silurian, Mississippian, and Pennsylvanian ages. Caves vary in length, depth, and geological units within which they formed. This study analyzed available data on geographic location, geological distribution, density of caves, and local hydrogeology, which provided insight into cave development and karstification in Tennessee. For this phase of the study, analysis focused on the sub-physiographic provinces of the Cumberland Plateau including the Cumberland Plateau proper, its Eastern and Western escarpments, and the Sequatchie Valley, which cover a 16-county area and contain 61% of the known caves of Tennessee. The majority of cave development on the Cumberland Plateau (95%) occurs on the Eastern and Western escarpments where exposed Mississippian limestones abound. Cave development on the Cumberland Plateau Proper (2%) is sparse which is to be expected due to caprock lithology. The Sequatchie Valley (3%) also has comparatively few caves but that is due to the morphology of the valley rather than unfavorable lithology. Analysis of existing cave maps (also archived by the TCS) provided insights about local hydrogeological conditions that resulted in the formation of a variety of cave types whose morphology and distribution reveal the processes that formed them.

Introduction

State cave surveys can contain a significant amount of data besides just cave locations. Metadata in the form of cave statistics, geology, descriptive narratives, and maps provide valuable information for cave and karst research. The Tennessee Cave Survey (TCS) has archived 11,756 caves as of 2023, that are distributed over 11 physiographic provinces. Figure 1 is a heat map showing the density and distribution of caves in Tennessee (Sutherland 2023). The purpose of this study was to use the existing state survey data to understand the distribution of caves on the Cumberland Plateau and how those distributions are influenced by regional hydrogeology, geologic units, and elevation.

Site Description

This study analyzed the Cumberland Plateau (CP) parsed into its sub-physiographic provinces that include the Cumberland Plateau Proper, Eastern and Western Escarpments, and the Sequatchie Valley (Figure 2), all which cover a 16-county area. The plateau is drained by two regional drainage basins: the Cumberland and Tennessee River basins. The Cumberland Plateau proper is capped with resistant sandstones, interbedded with shale and coal of the Pennsylvanian age. The lower slopes of the eastern and western sides of the plateau make up the Cumberland Escarpments and are underlain by Mississippian-age limestones. The Sequatchie Valley caves are predominantly in Mississippian-age limestones though caves have also been documented at the valley bottom in units that are Ordovician in age.

Methods

TCS provides data in Excel and comma delimited text format (CSV) to its members. Maps and narrative files are provided in PDF format. TCS also provides state-wide statistics on caves. For this phase of the study, analysis focused on the Cumberland Plateau region. This study sorted and analyzed available data via sub-physiographic province, regional hydrogeology, geology, and elevation, and mapped the results using ArcGIS Online.

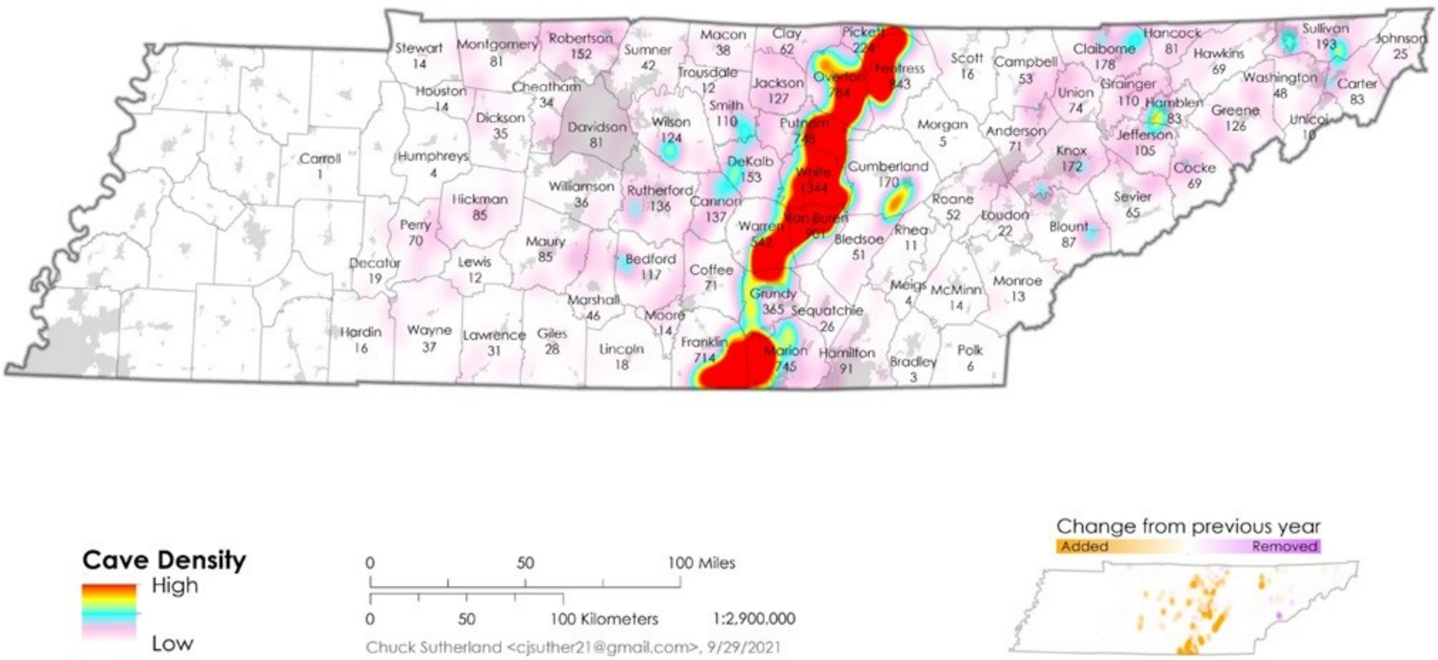

Figure 1: Heat map showing cave distribution in Tennessee. The "hot" area (in red) depicts the Cumberland Plateau. Map by Chuck Sutherland

Analysis of existing cave maps (also archived by the TCS) provided insights about local hydrogeological conditions that resulted in the formation of a variety of cave types whose morphology and distribution reveal the processes that formed them.

Results and Discussion

Geologic distribution

Of the Cumberland Plateau sub-provinces (Figure 3), the Cumberland Plateau Proper holds 2% of the known caves. This area is composed of conglomerates and sandstones, interbedded with shale and coal of the Pennsylvanian age that function as a caprock to the underlying limestones. These units are impermeable though there are locations where the caprock has been breached and cave development has occurred, but these are rare. At the edges of the caprock erosion and sapping exposed the Mississippian-aged limestones that make up the Western and Eastern escarpments and hold the majority of Cumberland Plateau region caves (75% on the Western escarpment and 20% on the Eastern). As the caprock continues to retreat it leaves behind outliers of limestone that are heavily karstified.

The Sequatchie Valley contains 3% of Cumberland Plateau caves. Sequatchie Valley is a long, linear geological feature called an anticline and erosion has exposed the rocks in the middle. The margins of the Sequatchie anticline are composed of Mississippian-age rocks whereas the center of the anticline exposes Ordovician-age rocks which are much older than Mississippian age and explains the two different ages of the caves formed within the feature. Cave development in this area is more structurally influenced due to the close proximity to the structurally complex Valley and Ridge physiographic province to the east.

Hydrogeology

Regional hydrogeology (Figure 4) is extremely important in terms of erosional impact on the Plateau areas and cave development. The Cumberland plateau is encompassed by two regional river basins. The Cumberland River basin in the north-northwest drains the heavily karstified Western Escarpment and associated caves. The caves of the Eastern Escarpment and the Sequatchie Valley are included in the upper and middle portions of the Tennessee River basin. The Cumberland River was significantly affected by Pleistocene glaciations which completely changed the configuration of the greater Ohio River basin and is reflected in the "Cumberland Style" caves (Figure 5) of the region (Anthony & Granger, 2004). The effect of glaciation on the caves of the Tennessee River basin is an understudied topic.

Caves in terms of depth

The Cumberland Plateau has 51 caves with vertical extents that range from 91 to 286 meters. Of those, 23 extend through the geological sections of Bangor-Hartselle-Monteagle-St. Louis-

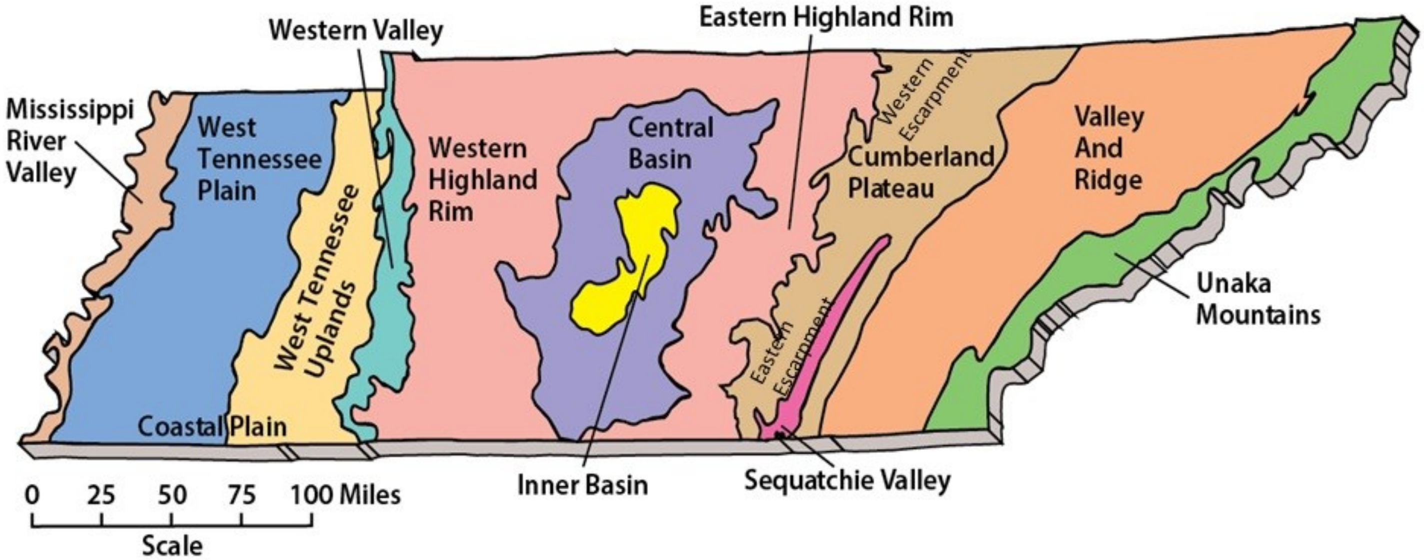

Figure 2: Physiographic provinces of Tennessee from https://tnsoshistory.com/chapter1

Warsaw and take the form of the "classic" deep Plateau Margin Cave (Figure 6). These cave types sap away the margin of the Cumberland Plateau and open it to further erosion. The caves occur predominantly in the highly dissected Eastern Escarpment, in the Grassy Cove area of the Sequatchie Valley, and the middle Western Escarpment of the Cumberland Plateau (Figure 7).

There are a total of 851 caves with vertical extents between 15-90 meters that occupy the western escarpments of the Cumberland Plateau and the Sequatchie Valley. An additional 4800 caves have extents of less than 15 meters. They all start either at the Bangor limestone or at the Hartselle Formation. These account for the great density of caves on the Western and Eastern Escarpments of CP (Figure 8).

Caves in terms of length

The Cumberland Plateau area has six caves with lengths between 25 and 66 kilometers and containing large-size passages (Figure 9). These caves tend to be closer to the Eastern Highland Rim than other Cumberland Plateau caves and based on cosmogenic dating, some of them predate the first glaciations of the Pleistocene. These caves initially formed during times of stable base level before the cyclic glaciations that had a profound effect on landscape evolution in the Cumberland River Basin. Called Cumberland-style caves, the cave depicted in Figure 5 is an example.

There are a total of 118 caves with lengths between 2-16 km in the Cumberland Plateau area (Figure 10). Many of these caves are located on the edges of coves which are plentiful in the Cumberland Plateau area. They have a linear morphology and tend to parallel the coves and may be the result of stress release fracturing – a phenomenon that happens as erosion unloads the plateau and isostatic rebound forms many fractures and fissures in the brittle carbonate units (Sasowsky & White, 1994).

There are over 6000 caves that are less than 2 km in length on the Cumberland Plateau (Figure 11). They contribute to the "clutter" of caves on CP related areas though they are mostly concentrated along the margins of the many coves that charac-

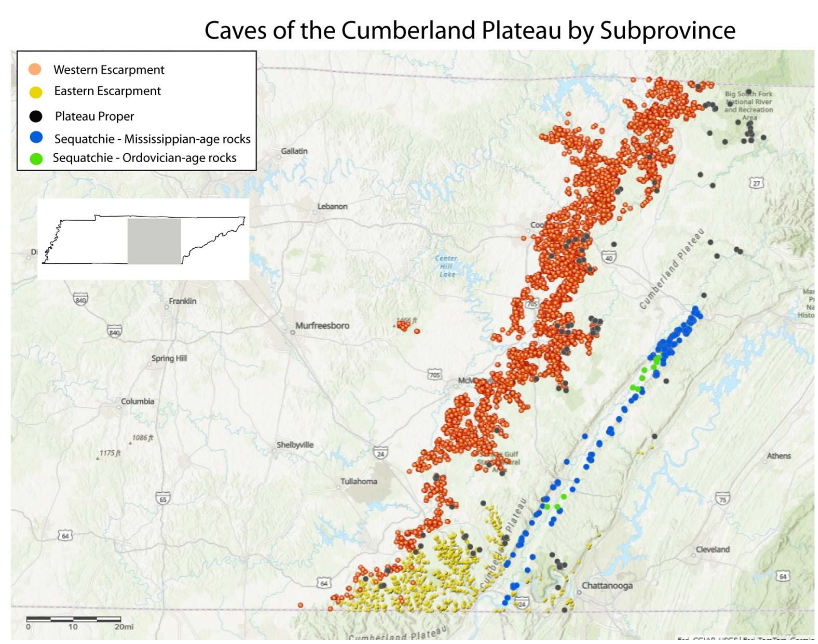

Figure 3: Caves of the Cumberland Plateau by Subprovince

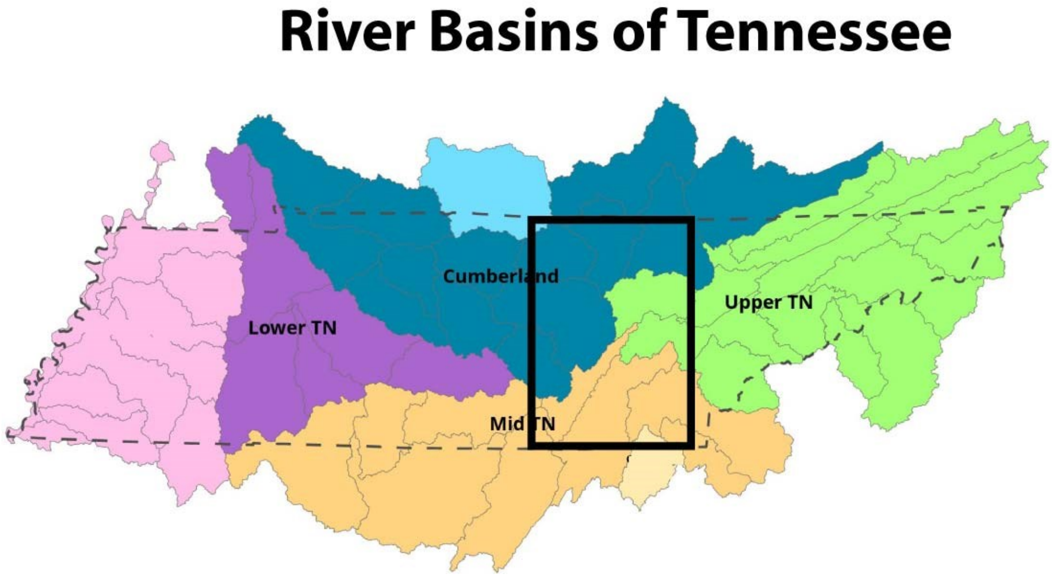

Figure 4: Cumberland and Tennessee River basins of Tennessee. Black rectangle represents the Cumberland Plateau region.

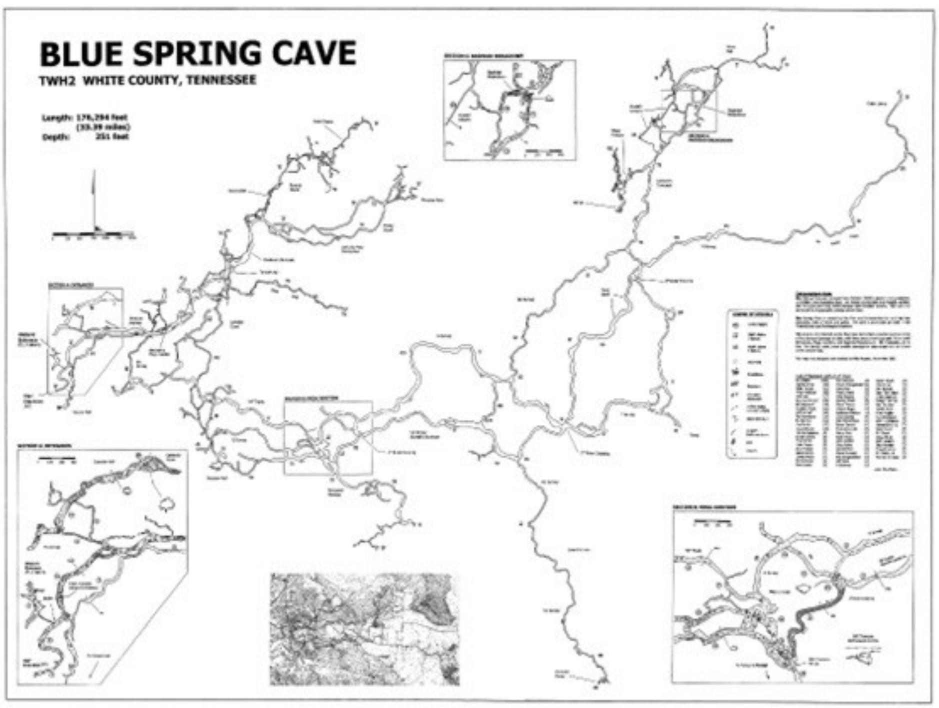

Figure 5: Example of a Cumberland-style cave

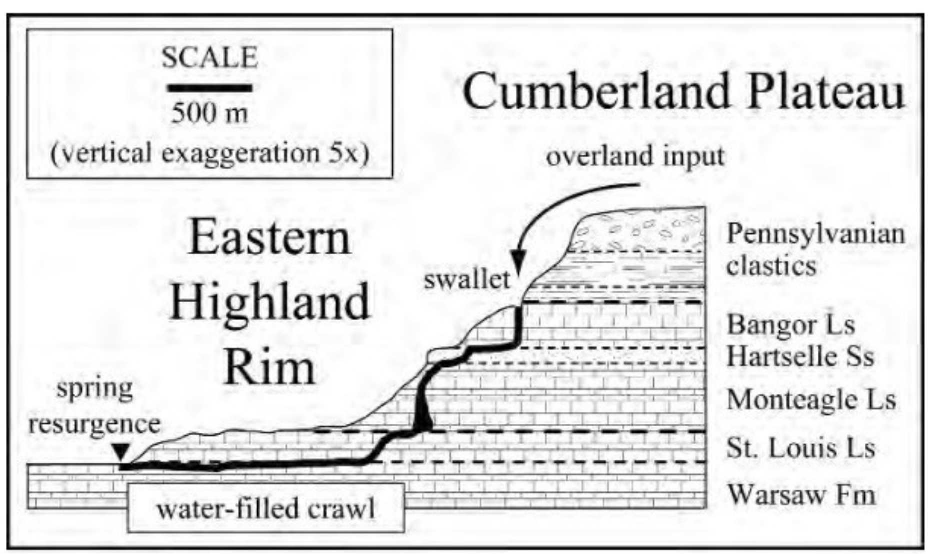

Figure 6: Plateau Margin Cave Model after Crawford 1984.

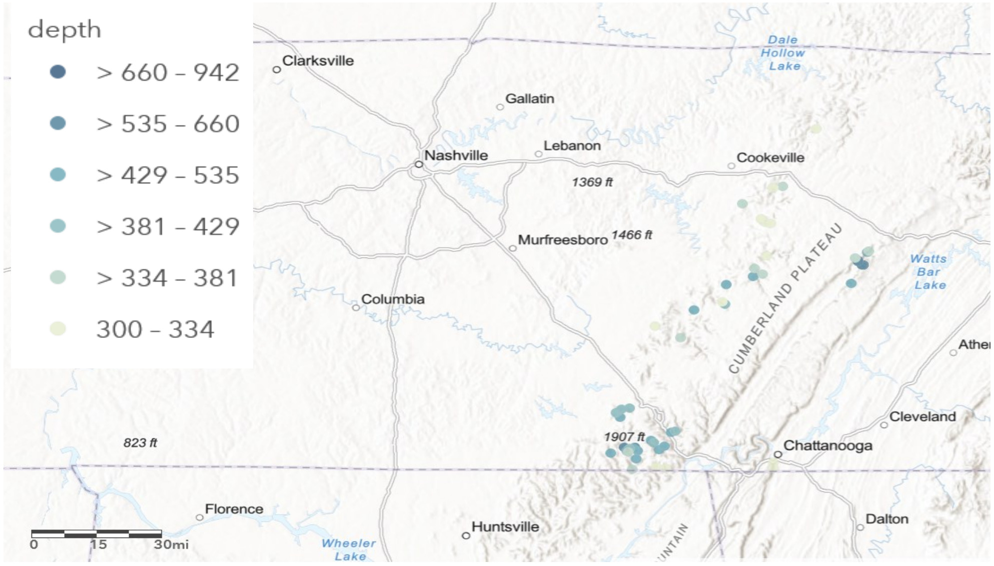

Figure 7: Distribution of "deep" caves of the Cumberland Plateau (vertical extents between 300 feet (91m) and 902 feet (286m).

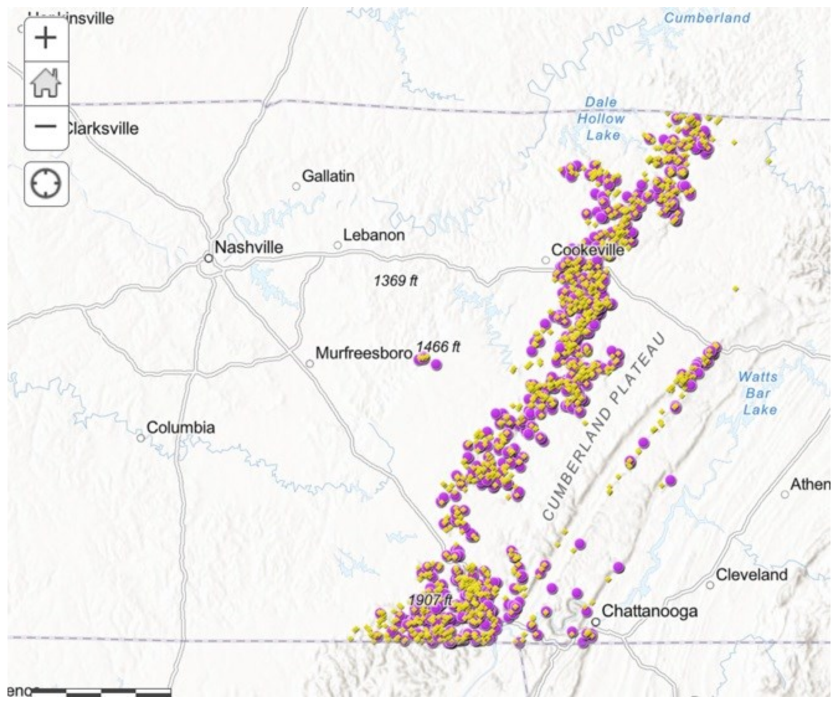

Figure 8: Distribution of caves with vertical extents between 15 and 30 meters (purple dots) and less than 15 meters (yellow dots).

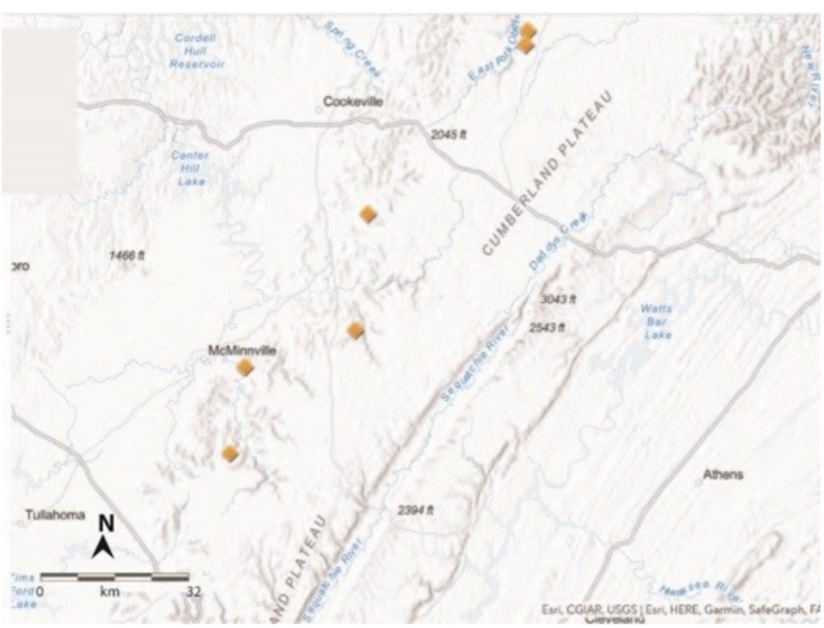

Figure 9: Distribution of longest caves of the Cumberland Plateau

terize the plateau. Stress release fracturing may also be the reason for their existence and as such they also contribute to the continued erosion and sapping of bedrock in the Cumberland Plateau area.

Conclusion

The metadata collected and archived by the Tennessee Cave Survey, along with additional statistical analyses of the data and existing cave maps (also archived by the TCS), provided insights about local hydrogeological conditions that resulted in the formation of a variety of cave types, whose morphology and distribution reveal the processes that formed them and prove to be extremely useful in understanding the geologic history and karstification of the Cumberland Plateau and its related areas.

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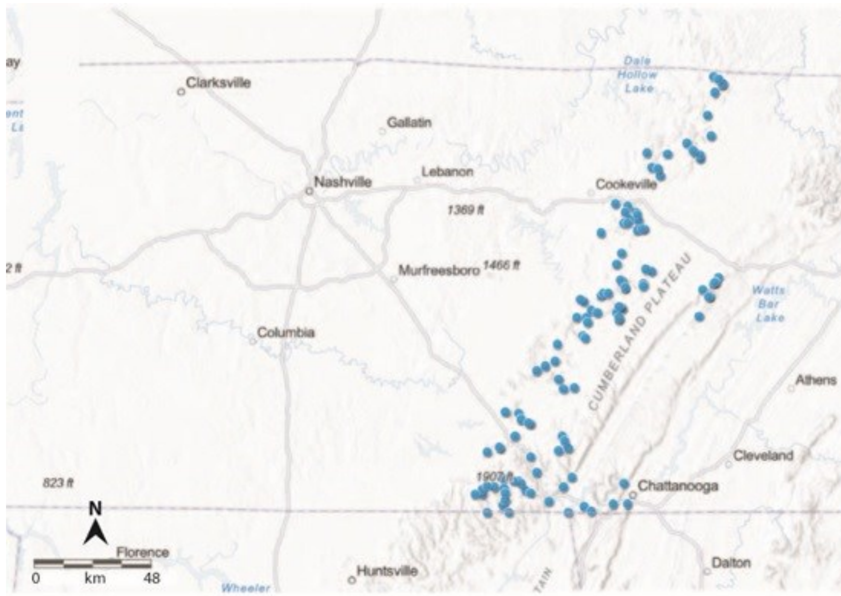
Figure 10: Caves of lengths between 2 – 16 km which may have formed due to stress release fracturing.



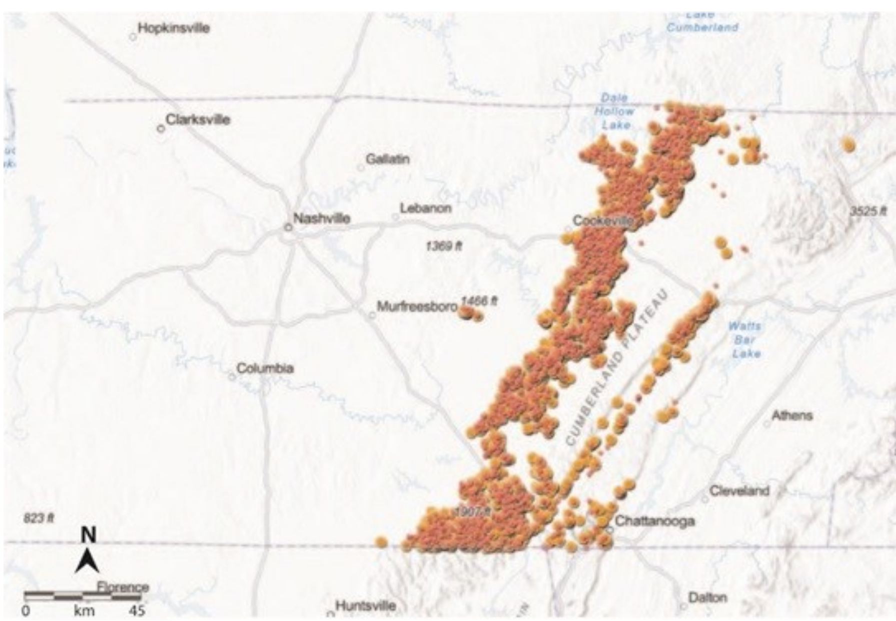


Figure 11: Caves less than 2 km in length

Mapping Karst Groundwater Flow Paths and Delineating Recharge Areas for Fern Cave, Alabama, Through the Use of Dye Tracing

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Abstract

Fern Cave in Jackson County, Alabama, is a 15.6-mile-long (25.1-kilometer) cave system, managed by the U.S. Fish and Wildlife Service and Southeastern Cave Conservancy, that has the second highest biodiversity of any cave in the southeastern United States. Groundwater in karst ecosystems is known to be susceptible to impacts from human-induced land-use activities in watersheds that contribute recharge to the groundwater system. To provide the U.S. Fish and Wildlife Service with necessary baseline information on the groundwater flow system in Fern Cave, the U.S. Geological Survey and the Kentucky Geological Survey conducted a series of dye traces during 2019–21 to delineate the watershed recharging the cave system. The dye traces identified two separate streams that flow through the cave and a recharge area of 1.73 square miles (4.48 square kilometers) draining to the cave system. Current land use within the recharge area is dominated by deciduous forest with minimal additional land use types, indicating a low potential for undesirable effects to the cave by anthropogenic sources.

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