24th National Cave and Karst Management Symposium Proceedings

Endangered Species - Caves - Aquifers

1-5 November 2021 - San Marcos, Texas

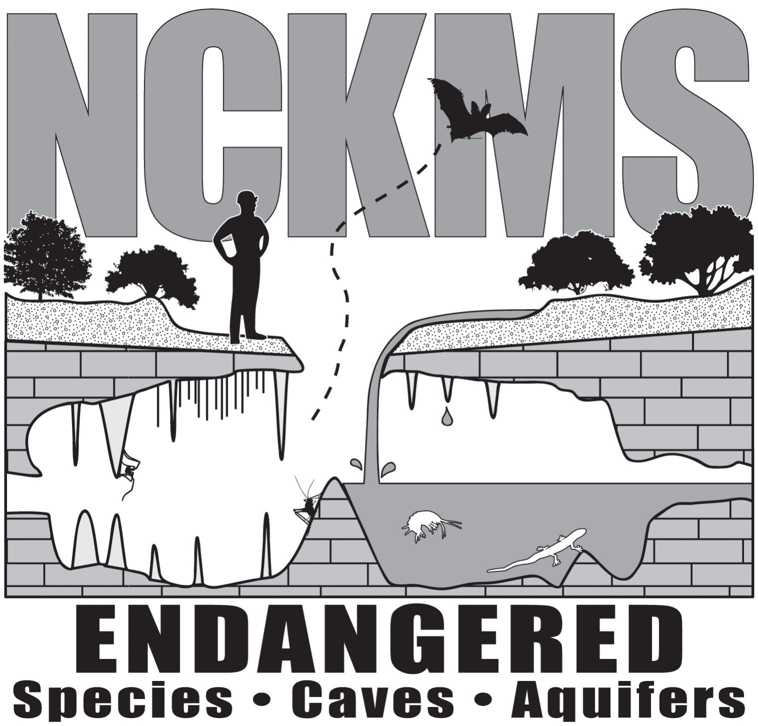
NATIONAL CAVE AND KARST MANAGEMENT SYMPOSIUM

Proceedings of the Twenty-Fourth Symposium

NCKMS: Endangered Species, Endangered Caves, Endangered Aquifers

1–5 November 2021
San Marcos, Texas

Editor: Gerald L. Atkinson



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Cover Photo: A base level stream cave in the Hill Country of Texas. The cave reportedly had cave salamanders before a massive oil leak from a nearby broken pipeline or storage tank occurred in the 1950s. No salamanders have been observed since and the cave still bears the scars of the incident to this day. Photo by Bennett Lee.

Table of Contents

ORAL PRESENTATIONS

Biology Sessions

Chair: Benjamin Hutchins

Collaboration in Karst Knowledge Session

Chair: Devra Heyer

Geotechnical Solutions in Karst Session

Chair: George Veni

Management and Monitoring in Karst Session

Chair: John Hickman

POSTER PRESENTATIONS

Foreword

Welcome to San Marcos and NCKMS 2021!

We heartily welcome all cavers, cave owners, cave conservancies, cave managers, cave researchers, cave educators, and cave lovers to the 23rd biennial meeting of the National Cave and Karst Management Symposium (NCKMS), in San Marcos, Texas on 1–5 November 2021. Roughly 20%, or 53,720 square miles, of Texas is karst, including the urban corridor of Waco through San Marcos, south to San Antonio. The last (and only) NCKMS held in Texas was in New Braunfels, in 1989. Our state's population (and number of caves!) has grown rapidly since then, leading to inevitable management conflicts. Hence our theme 'Endangered Species, Endangered Caves, Endangered Aquifers'. In beautiful San Marcos, that theme surfaces as clearly as the waters of the karstic Edwards Aquifer: a water source for over 2 million people, source of the culturally and economically important San Marcos River, and habitat for a number of federally endangered species inhabiting caves and springs in San Marcos and beyond. San Marcos is touted as one of the oldest continuously inhabited sites in the Americas. With its college-town character, bars and restaurants, proximity to caves and karst features of the Balcones Escarpment and Edwards Plateau, and abundance of natural areas like Spring Lake and Purgatory Creek, we thought it the perfect location for the 2021 NCKMS.

As is characteristic of symposia past, the 2021 NCKMS features a diversity of presentations, reflected in our interdisciplinary sessions, titled Biology, Collaboration in Karst Knowledge, Geotechnical Solutions in Karst, and Management and Monitoring in Karst. We are particularly honored to be hosting NCKMS during the International Year of Caves and Karst. Our keynote speaker, Dr. George Veni, will discuss how the international year is a beginning, and we are confident that the knowledge shared and connections made during the 2021 NCKMS will serve as a springboard for increased exploration, understanding, and protection of caves and karst in the United States and beyond. And few people have more authority to talk about exploration, understanding, and protection than our featured speaker, Dale Pate, a native Texan and Texas State University - San Marcos alum (formally Southwest Texas State University). Dale's years of experience caving in the U.S. and beyond, and managing karst resources for the National Park Service, will provide perspective and an undoubtedly enjoyable evening.

We are excited to have Austin Water – Balcones Canyonlands Preserve as our host this year! Some other goodies we have lined up include a Monday Social and glass-bottom boat tour of Spring Lake, where karst waters well up from San Marcos Springs to form the head of the San Marcos River, and a tour of nearby Natural Bridge Cavers, site of the Tuesday Howdy Party. We'll have field trips all day Wednesday, focusing on the hydrology, biology, and land use conflicts of central Texas karst. Some field trip options even include short visits inside non-commercial caves, so please bring your properly decontaminated cave gear. But remember that this is Texas, so even in November, a T-shirt and jeans (with knee and elbow pads!) will be sufficient underground clothing. As 2021 is the International Year of Caves and Karst, we have also incorporated public outreach activities during our conference.

So once again, welcome to San Marcos and the 2021 NCKMS!

Jim Kennedy
Chair 2021 National Cave and Karst Management Symposium

NCKMS 2021 Host

Austin Water – Balcones Canyonlands Preserve

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- Benjamin Hutchins: Biology
- Devra Heyer: Collaboration in Karst Knowledge
- George Veni: Geotechnical Solutions in Karst
- John Hickman: Management and Monitoring in Karst

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Workshops

Workshop 1: Project Underground

Description: Project Underground is a K-12 environmental education curriculum and activity guide focused on caves and karst through the topics of geology, biology, and history. Learn methods to educate about the world beneath our feet in this workshop. Formal educators (classroom) and non-formal educators (nature centers, parks, camps) are encouraged to attend. Hands-on activities are required. This is not a passive lecture. Participants will receive an activity book and certificate at the end of the workshop.

Instructor: Christine Walkey

Workshop 2: The Survey and Inventory of Cave and Karst Features

Description: Baseline resource inventories and annual monitoring are two of the most important, if not the most important, activities in cave and karst management. They inform the "what and where" component of the cave and karst resource strategy and allow one to gauge the effectiveness of management decisions/actions through time. This short course will cover the design and execution of baseline inventories and annual monitoring activities as they apply to cave and karst resources. The course will also explore various methods to derive more understanding and visualization of cave data and surface/subsurface karst field data. 25-person limit.

Instructors: Kyle Rybacki, Pat Kambesis

Workshop 3: Cave Management Considerations for Bats

Description: Bats have long been associated with cave habitats, but throughout history this association has not always benefited these cryptic mammals. In fact, our cave-dwelling bat species have suffered some of the most catastrophic population declines. Fortunately, we now have a far better understanding of the complexities in underground environments and their importance to bats. We begin with a glimpse of the variety of underground environments and how to determine their suitability to different bat species at all stages of their life cycles. Bat natural history and the history of cave exploration and human use is combined to highlight the important biological implications of cave study and protection. Case studies of cave conservation are presented which will illustrate many of the successful efforts to balance human and bat needs on the landscape. 20-person limit.

Instructors: Janet Tyburec, John Chenger

Workshop 4: Developing Stewards: Cave and Karst Management Through Accessible Education

Description: How do we develop future stewards of cave and karst resources? This workshop will explore the idea of management through the development of education programs that will build future stewards of cave and karst resources. Participants will further look at how to build an accessible program from its infancy to completion so that educational outreach is accessible to all audiences. This will be an interactive workshop mixing both small group discussions and whole-group activities to enable participants to freely discuss issues they are having as cave and karst managers and to develop solutions through discussion and reflection. 50-person limit.

Instructor: Brad Barker

Workshop 5: Cave and Karst Hydrology

Description: Karst terrains and underlying caves are part of the hydrologic cycle. Karst has many unique aspects that are commonly misunderstood by non-specialists. This workshop will discuss different conceptual models to better understand the karst hydrologic cycle from rainfall to sinkholes and caves to springs. Several tools will be discussed that are useful to help better understand and manage these unique environments including water quality monitoring parameters and frequency, water quality instrumentation, use of tracer (dye) testing to delineate spring sheds, and general discussion of geophysics in karst settings. 25-person limit.

Instructors: Geary M. Schindel, Dr. Mustafa Saribudak, Alf Hawkins

Field Trips

Trip 1: Cave Restorations on the Urban Frontier

Trip leader: Drew Thompson

Synopsis: See the City of Austin's cave restoration and stabilization projects of the past decade in South Austin. Our urban karst landscapes have taken many hardships throughout its recent history from deforestation and overgrazing to the purposeful filling in of caves and sprawling urban expansion. Witness firsthand the City of Austin's efforts to reopen and restore our valuable resources increasing clean water recharge, healthy biological habitat, and creating a safe environment to educate the public about the benefits of caves and their contribution to the Edwards Aquifer.

Trip 2: From Recharge to Rivers: Groundwater Fauna Sampling Across Flowpaths

Trip leader: Benjamin Hutchins

Synopsis: See representative/ important groundwater fauna sites in the San Marcos area as we move from the Contributing Zone of the Edwards Aquifer down a flowpath that even takes us off of the karst but never outside its influence to see aquatic habitats, management issues, and sampling techniques for rare groundwater species.

Trip 3: South Austin Wild Cave Tour: Management to Protect Cave Ecosystems

Trip leaders: Rich Zarria, Mark Sanders

Synopsis: Tour of South Austin Cave Preserves that are ecosystems for rare cave species and serve as educational/ recreational resources for thousands each year. Each has different entrance security measures to protect the cave and the public, depending on site-specific conditions. There are efforts to establish sufficiently large karst preserves to protect cave cricket foraging areas and water source areas to sustain cave ecosystems. Several decades ago, a large maternity bat colony in Goat Cave was eliminated by a cave gate in response to concerns from a new growing neighborhood. Once trash and ranch fill were removed from Wildflower and LaCrosse caves, their ecosystems are rebounding including nutrient providing bats and cave crickets, despite the shared use with up to 2000 school kids and other explorers each year.

Trip 4: Finding Caves in North Hays County: Recognition of Caves in an Environment of Widespread Filling

Trip leader: Nico M. Hauwert

Synopsis: This field trip examines common reasons why most caves were filled across the area and provides tools for recognizing filled caves. A common misconception is that caves are found open and can readily be identified by a geologist trained in karst terrains. The reality is that caves were widespread filled for a variety of reasons that will be examined in this field trip. Caves known today generally were excavated by cavers. Caves, especially when filled, are generally not identified prior to development of sites, and are more likely discovered during construction or later catastrophic collapse. However, features that are highly likely to be caves can be identified by experienced cave stewards through geophysics, surface contour maps, LiDAR, and occasionally on aerial photographs. Where caves are filled, the actual discovery of caves and understanding their importance necessitates excavation. We will discuss how historical practices affected recharge to aquifers, potential groundwater contamination, flooding potential, habitat for wildlife, education/recreational resources, historical records archived in cave deposits, and the loss of heritage features for the public to experience. This trip will also examine sinkhole morphology and the geologic factors affecting cave development and cave density. The trip is dedicated in memory of Bill Russell, my mentor in finding caves and one with an amazing record for finding concealed caves.

Trip 5: A Cross Section of Cave and Karst Management: Show Caves, Preserves, and Private Property

Trip leader: George Veni

Synopsis: Many styles of cave and karst management occur to fit their diversity and needs. The styles also vary according to the type of ownership and general land use. This trip spotlights three styles of ownership/management. It will first visit a small, lovely, privately owned show cave where management is focused on public access, education, and safety. Next is a public nature center with an attached private nature preserve where natural resource protection is the primary focus, followed by public education, access, and research. The final stop is on a privately owned ranch trying to protect over 150 years of family stewardship from now rapidly encroaching suburban development. The trip is designed for people interested in contrasting landscape-wide and site-specific approaches to cave and karst management.

Oral Presentations

Biology Sessions

Chair: Benjamin Hutchins

Monograph of the Groundwater Isopods of Virginia

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Abstract
A monograph (in preparation) of the groundwater isopods of Virginia encompasses over 50 species found in caves, springs, seeps, wells, and drain tiles. Twenty of these species are being described as new to science; mostly narrow endemics. A large percentage of the karst-associated biodiversity is in springs, not caves. We emphasize the importance of sampling springs, frequently passed over by biologists in favor of entering the caves discharging the water. In Virginia, the cave and spring fauna are interwoven into a complex evolutionary fabric, and evaluating both helps our understanding of how the subterranean obligate fauna fits into the bigger picture. Two of the karst species are listed as federally endangered or threatened, and a third is being evaluated for placement. Critical review of past records of these and other Virginia isopod species leads to the seemingly obvious conclusion that one should enlist the best taxonomic expertise available. Much of the Virginia material has been identified by folks who weren't isopod specialists, resulting in misidentifications, confusion, and the need to revisit. Likewise, we have found molecular work is critical for recognition of cryptic species. Traditional morphological taxonomic characteristics alone are not always sufficient for species delineation, resulting in significantly underestimated species diversity. However, in most cases, other morphological characteristics vary consistently between species in such a way that once a species is recognized, determinations based on morphology can be made. A by-product of the molecular work is the discovery of more syntopy than previously recognized from morphology alone.

Over the course of the last 50 years, it has become apparent that the Commonwealth of Virginia is inhabited by an array of groundwater isopod crustaceans that is of global significance in its diversity. Although the best known of the subterranean isopods in Virginia are those inhabiting caves in the karst associated with the Appalachian Valley and Ridge in the western part of the state, groundwater isopods are actually known from across much of Virginia (Figure 1). In particular, an assemblage of ten or so species are now known from the coastal plain area, where they occur in shallow groundwater habitats that are not associated with karst. Instead, they occur in seeps, soil tubes, saturated soil interstices, etc. That notwithstanding, the focus here will be on the fauna found in the extensive karst regions of Virginia.

The accumulation of species being described has been gradual, starting with *Mancasellus brachyurus* (Harger, 1876), and then adding one or two new species periodically. A milestone along the path included the first compilation of the fauna as an assemblage, and was presented by Steeves (1969), who looked at cavernicolous asellid isopods of the southern Appalachians. Among that fauna, he discussed five obligate subterranean species that were known to occur in Virginia caves at that time. Holsinger and Culver (1988) increased this to 13 species in the list

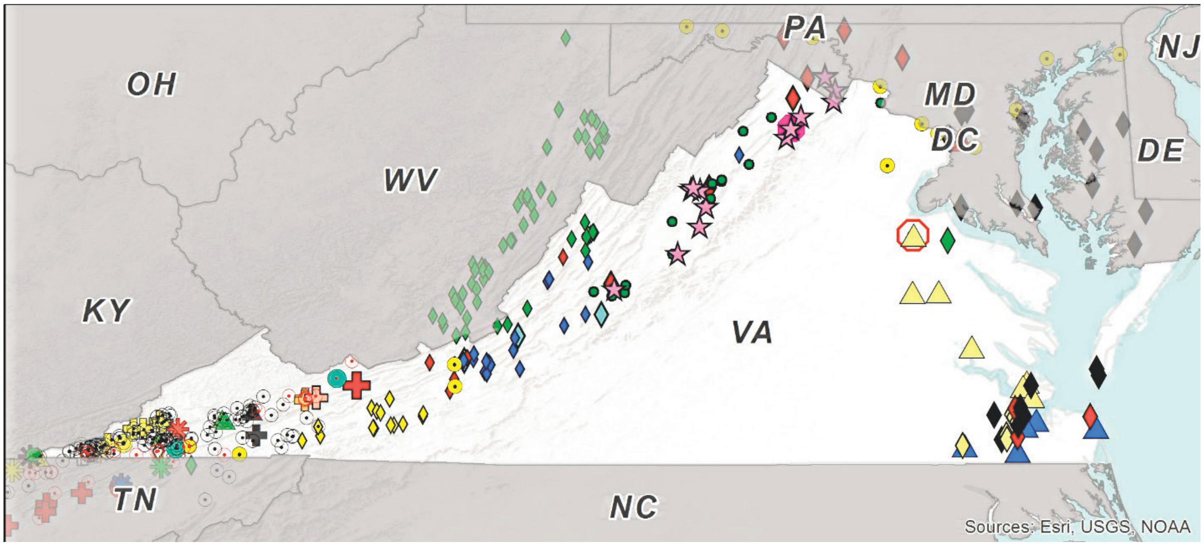

Figure 1. Distribution of the groundwater isopods of Virginia.

of Virginia cave fauna. Lewis (2009) described three more new species from Virginia groundwaters, and summarized the asellid isopods reported from the state, bringing the total to 24 asellid species. Now a monograph is in the final stages of preparation that encompasses all of the groundwater isopods of Virginia, reporting 50 species inhabiting caves, springs and spring runs, seeps, wells, and drain tiles. Of these 50, 49 are asellids currently assigned to the genera *Caecidotea* and *Lirceus,* plus the unique cirolanid isopod *Antrolana lira*.

The taxonomic scope of the monograph focuses on the asellids, since *Antrolana lira* was well described by Bowman (1964) and requires no further elaboration. Of the 49 species of asellid cited above, 40 occur in Virginia, with the others found in adjacent West Virginia, Tennessee, Georgia, Alabama, or the District of Columbia. A total of 24 species are being described as new to science, of which 19 are endemic to Virginia. This represents the largest leap forward in our knowledge of the isopod fauna of Virginia in particular, and the Appalachians in general, in the history of the group.

Thirty-five of the 49 asellid species are associated with karst habitats; primarily caves and springs. Although historically, the greatest diversity among karst asellids has been associated with eyeless, unpigmented stygobiontic species, 40% of the karst-associated biodiversity are pigmented species occurring in springs, not caves. We emphasize the importance of sampling springs, frequently passed over by biologists in favor of entering the caves discharging the water. Of the 24 new species being described in the monograph, 13 of them are entirely or primarily found in springs.

In Virginia, the cave and spring fauna are interwoven into a complex evolutionary fabric. Evaluating them as a whole helps our understanding of how the subterranean obligate fauna fits into the bigger picture. After the discovery of the two previously known Virginia stygobionts of the genus *Lirceus*, (*L. usdagalun* in Lee County (Holsinger and Bowman, 1973) and *L. culveri* in Scott County (Estes and Holsinger, 1976)), no further cavernicolous species were discovered. The monograph includes five additional new species that appear to be restricted to caves. One of these, endemic to the Maiden Spring area of Tazewell County, Virginia, was recognized as "*Lirceus* sp. B" by Holsinger and Bowman (1973), and another had been collected from a cave in Washington County by Holsinger in 1967, but not recognized for what it was until rediscovered in the Smithsonian collection by us in 2016. The seven stygobiont species now recognized inhabiting Virginia caves exhibit a broad range of troglomorphisms, with four of the species retaining varying degrees of vestigial eyes and pigmentation, and three that are completely eyeless and unpigmented. Examples of the broad spectrum of troglomorphisms exhibited in newly discovered species of *Lirceus* are shown in Figure 2.

Critical review of past records of these and other Virginia isopod species leads to the seemingly obvious conclusion that one should enlist the best taxonomic expertise available (and this applies to any group of animals, not just isopods). A problem that we have encountered is that much of the Virginia material was identified by folks who weren't isopod specialists, resulting in misidentifications and confusion. A significant amount of the field work for the project has been revisiting sites where it was thought that the fauna was well known and accurately identified in

Figure 2. Four new species of isopods of the genus Lirceus from southwestern Virginia, exhibiting a range of morphological adaptation to caves. At far left, a spring-inhabiting species from Cave Spring, Lee County; and obligate cavernicolous species (from second left to right) from Lane Cave, Scott County; Hugh Young Cave, Tazewell County; and Litton Cave No. 1, Lee County.

order to obtain adequate collections for examination (Figure 3). Likewise, we have found molecular work is critical for recognition of cryptic species, and these methods have required revisiting many sites to collect fresh specimens that have been chemically fixed in such a way that the DNA is preserved for analysis. After initial fixation in 100% ethanol, specimens are maintained out of sunlight (i.e., UV radiation) and in an ice-filled cooler. Later in the day of collection, the ethanol used for fixation is replaced with fresh 100% ethanol for preservation. Upon reaching the lab, samples of typically 3 to 10 specimens are placed in fresh 100% ethanol and refrigerated pending shipment for DNA isolation, PCR, and sequencing. Typically, four genes are analyzed, including mitochondrial 16S and CO1.

The molecular phylogenetic analysis has proved invaluable because traditional morphological taxonomic characteristics alone are not always sufficient for species delineation, resulting in significantly underestimated species diversity. The paradigm of identification of asellid isopod species by relying on the morphology of the male genitalia has proved to be inadequate to the task in separating cryptic species. However, in most cases, other morphological characteristics vary consistently between species in such a way that once a species is recognized, descriptions based on morphology of new species can be prepared. Likewise, diagnoses and keys are being presented to allow identification of species without the necessity of DNA sequencing.

A byproduct of the molecular work is the discovery of more syntopy than previously recognized from morphology alone. In east-central Tennessee, we have discovered that some springs are inhabited by two species of epigean *Lirceus* that are very similar in appearance. This has produced at least one collection in which *Lirceus hargeri* and an undescribed species of *Lirceus* are co-mingled. In some sites in Virginia, like Flanary Bridge Springs, two species of *Lirceus* have been found, but are readily separated because one of them is an unpigmented stygobiont. Both the Powell and Clinch river valleys have one relatively widespread epigean species inhabiting springs, i.e., found over stretches of as much as 20 to 30 miles. It would not be surprising to discover sites where one of these more widespread species co-occurs with one of the rare endemic species. Furthermore, in some sites, a species of *Caecidotea* is also present, making for aquatic communities in which three species of asellids are present and living in the same habitats.

As suggested by Hubricht and Mackin (1949), the pigmentation patterns of species in the genus *Lirceus* have proved to be an important component of characterizing species. A great deal of effort has been expended on collecting living isopods and making macrophotographs to obtain accurate representations of their appearance before preservation. This can be more complicated than it might seem. For example, for the isopods that occur in Lane Cave in Scott County, the isopods were collected into plastic, breakproof containers in which a couple pieces of hosiery fabric had been inserted for the animals to cling upon. They were then placed in our packs and transported to the surface, which included the trip back out of the cave and ascending

Figure 3. Collecting two new species of stygobiont isopods (a Caecidotea and a Lirceus) from Lane Cave, Scott County, Virginia (left to right, Salisa Lewis, Zenah Orndorff, Wil Orndorff).

the short entrance pit on rope. Once reaching the surface, the animals were photographed immediately in our "isopod photo studio" (Figure 4), which consists of a small custom-built glass aquarium. The construction of this "studio" is such that it sandwiches the animals between two pieces of glass in a space only a few millimeters wide, which limits some of the depth of focus problems as well as how far they can wander off.

From a conservation standpoint, two of the karst species are listed as either federally endangered (*Lirceus usdagalun*), or threatened (*Antrolana lira*), and a third is a candidate species (*Lirceus culveri*). Ironically, several of the new species of *Lirceus* (in an assemblage of cryptic species related to *L. hargeri*) are single-site endemics that are probably much more restricted in their distribution than the federally endangered *L. usdagalun*. Luckily, one of the new *Lirceus* species as well as another new species currently assignable to the *Cannulus* species group of the genus *Caecidotea*, are endemic to Cumberland Gap and Shenandoah national parks, respectively. The presence of another of the new species, a *Lirceus* endemic to Flanary Bridge Springs (Lee County), was a key element of the acquisition of the property and addition to the Cedars Natural Area owned and protected by the state of Virginia. Other species are known only from caves and springs on private property, and will present new challenges to management.

Acknowledgements

The preparation of the description of the new species for the monographic revision of groundwater isopods of Virginia has been primarily funded by a grant from the Karst Program of the Virginia Department of Conservation and Recreation. Other significant funding has been provided for the description of new species from the Cave Conservancy of the Virginias and the U.S. Fish and Wildlife Service.

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Figure 4. Photo documentation of isopod pigmentation patterns (or lack thereof) in the "isopod photo studio," consisting of a V-shaped glass aquarium with a cardboard box spray-painted black as a backdrop. A macro lens is used on a 35mm camera, with either natural light or off-camera flash (J. Lewis in photo).

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Groundwater Snail Biodiversity and Conservation in the United States and Mexico

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Abstract

Among the many taxonomic groups to successfully adapt to life in groundwater habitats are freshwater snails. However, snails that inhabit groundwater systems are generally understudied because of sampling difficulty and lack of taxonomic expertise. We conducted a literature review to assess the biodiversity, geographic associations, current threats, conservation and management activities associated with each species, and current environmental policies that may offer protections for groundwater snails. We identified 39 species among several taxonomic families that have been described from karst regions across the United States and Mexico, representing one of the most biodiverse subterranean fauna. Owing to the often short-range endemicity and proximity to a range of anthropogenic disturbances such as increased sedimentation, groundwater extraction, or physical alteration of subsurface passages, most groundwater-restricted snail species are at an elevated extinction risk. Of the 39 known species, 32 have been assessed as imperiled under NatureServe criteria, and 10 species have been assessed as threatened under International Union for Conservation of Nature (IUCN) criteria. However, only three species are federally listed in either the U.S. or Mexico, and current laws regulating wildlife and water pollution at the state and federal level may not adequately provide protections for most groundwater snails. Since groundwater systems will be increasingly manipulated and relied upon for human water demands, we advocate for increased study of this diverse groundwater fauna so that conservation efforts can continue to be enhanced.

Predicting Surface Abundance of Federally Threatened Jollyville Plateau Salamanders (*Eurycea tonkawae*) to Inform Management Activities at a Highly Modified Urban Spring

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Abstract
Urban expansion has contributed to the loss of habitat for range-restricted species across the globe. Managing wildlife populations within these urban settings presents the challenge of balancing human and wildlife needs. Almost the entire range of the Jollyville Plateau Salamander (*Eurycea tonkawae*) is embedded in the Austin, Cedar Park, and Round Rock metropolitan areas of Travis and Williamson counties, Texas. Among *E. tonkawae* occupied sites, Brushy Creek Spring has undergone some of the most extensive anthropogenic disturbance. Today, the site consists of small groundwater outlets that emerge in the seams within a concrete culvert underlying a highway, yet salamanders persist within this system though they are rarely observed. Here, we predict the occurrence of salamanders within the surface habitat of Brushy Creek Spring in response to accumulated rainfall using generalized linear models. Our results indicate that, while rare, salamanders do occur within this modified habitat. Additionally, we present evidence of reproduction, recruitment, and subterranean movement by *E. tonkawae* throughout this site. Information on the conditions that result in salamander observations at this site should be used to schedule site management, maintenance, or repair, when the occurrence of salamanders is not predicted to be likely.

Development, Validation, and Application of an Environmental DNA Assay to Detect Federally Threatened Groundwater Salamanders in Central Texas

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Abstract
The molecular detection of DNA fragments that are shed into the environment (eDNA) has become an increasingly applied tool used to inventory biological communities and to perform targeted species surveys. This method is particularly useful in habitats that are difficult or not practical to physically survey. Central Texas Eurycea salamanders are species of concern throughout most of their distributions and can inhabit both surface (e.g., springs) and subsurface (e.g., aquifer) aquatic environments. Subsurface surveys are challenging, and the detection of salamander eDNA in water samples is an appealing survey technique for these situations. Here, we develop, validate, and apply an eDNA assay using quantitative PCR for Salado Salamanders (*E. chisholmensis*), Georgetown Salamanders (*E. naufragia*), and Jollyville Plateau Salamanders (*E. tonkawae*). These three species are federally threatened and constitute the Septentriomolge clade that occurs in the northern segment of the Edwards Aquifer. We demonstrate that the assay is specific to the target taxa and amplifies Septentriomolge eDNA from salamander positive water and known-occupied field sites. We did not detect Septentriomolge eDNA at any sites with historically rare detections or in second order creeks downstream of occupied sites. We explore the effects of site and sample covariates on these results, and we discuss future research needed to refine this method and understand its limitations before practical application and incorporation into formal survey protocols for these taxa.

Austin Cave Restoration

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Abstract

Historical widespread filling of Central Texas caves has left many features obscured by trash and fill, often resembling trash dumps rather than caves. There is much restoration work needed to return these caves to their original states. Restoration produces an increase in habitat for rare species, improves recharge to the aquifer, and provides educational opportunities for the public and the next generation of cave conservationists. There are many examples of caves in the Austin, Texas area that have been negatively impacted either by filling, by being built over, or by vandalism. Some of these include Midnight Cave, Dead Dog Cave, Salamander Mountain Cave, and District Park Cave. One of the saddest aspects of this widespread degradation of Central Texas caves is that these caves are home to an extremely diverse community of cave fauna. One of the factors that support this diverse community is the ability of nutrients from the surface to enter the subterranean environment. Cave crickets play a critical role in this by transporting nutrients into cave systems in the form of their eggs, their own bodies, and from their nutrient-rich droppings which feed fungus and bacteria that provide food for springtails, millipedes, and other cave organisms. Cave entrances are biologically important since they are the portals allowing nutrients from the surface to enter the nutrient deficient cave ecosystem. I will give detailed histories of some previous and ongoing Austin cave restoration projects. These include Wildflower Cave, La Crosse Cave, and Persephone Caverns.

Historical Filling of Caves

There has been widespread filling of caves across the United States, in part due to ranching activity for trash disposal, fall hazards to livestock, the creation of stock ponds for livestock, erosion of sediment from ranching activities, filling in low lying features, access road rutting, vegetation removal (especially widespread "cedar chopping"), filling in stream features to keep stream flow at the surface for mills, perceived aesthetics, the creation of swimming holes, removal of perceived public safety and nuisance hazards, and making future development land more marketable (Veni, 2000; Hauwert, 2009; Austin Geological Society, 2015; Veni and Hauwert, 2016). Experienced cave explorers have learned that many caves likely resemble rock piles, trash piles, and soil-covered depressions that require hand excavation in their karst evaluations. Areas of thick soil, trash, and exotic rock fill surrounded by circular rock outcrops frequently suggest filled sinkholes that can be verified and characterized through excavation to reveal sinkhole morphology and cave apertures (Hauwert, 2019).

Caves that are identified are more likely to be considered for protective measures than caves that are not and are therefore afforded no protection, even if encountered later during development construction. The public display of many unsecured cave locations almost invariably leads to greater risk to public safety as the inexperienced and ill-equipped public seeks to enter caves, resulting in increased trespassing and damage to the cave ecosystem. Widespread release of unsecured cave locations generally requires that expensive cave gates are eventually installed that can potentially have a detrimental effect on the cave ecosystem (Hauwert, 2019). Prior to the gating of District Park Cave, it became a party location with abundant trash and many broken formations. Some work was done to repair the broken formations, but it will never be restored to what it was before uncontrolled visitation (Figure 1).

On the other hand, if the general public, land managers, scientists, and other stakeholders are not aware of the prevalence of local caves, they will not advocate for them, and the caves are not likely to be discovered and preserved. There are also public safety risks involved with building infrastructure over subsurface cavities that were not discovered and preserved in advance. A local example of this is when Cambria Cavern was discovered in February 2018 when part of Cambria Drive in North Austin collapsed into the 22-ft tall chamber. The best solution is a diligent search for filled caves with individuals experienced in karst survey techniques, cave excavation and restoration, and a history of cave discovery and remediation. Where potential conflicts of interest exist, such as when a geoscientist is paid by the landowner or

Figure 1. District Park Cave graffiti, and speleothem repair.

developer seeking to develop the property, filled caves are not as likely to be discovered or properly assessed. Sufficient resources should be allocated to identifying and restoring filled caves. Once discovered and reopened, the cave should be buffered in a cave preserve. In this way, it would be expected that nearly every neighborhood located over a significant karst recharge zone would have a local cave preserve amenity, some of which may be appropriate for guided tours and public education (Hauwert, 2019).

Local Cave Filling

As of 1989, 20 percent of the known caves in Travis County had been destroyed in the last 20 years due to land use changes and urban expansion. At that rate, William Elliott and James Reddell estimated that less than 80 percent of the presently known caves in Travis County would remain by the turn of the century (Elliott and Reddell, 1989). Caves on ranch land like Wildflower Cave and La Crosse Cave were filled with eroded sediment and ranch trash. Other nearby caves on the same ranch such as Midnight Cave and Pipeline Cave were utilized as trash dumps for household waste for years. (Figures 2 & 3).

Other caves were built over during development such as Dead Dog Cave near MoPac and Salamander Mountain Cave in Circle C Ranch (Figures 4 & 5).

During construction of large neighborhoods, countless karst features and many caves were filled in with heavy machinery and built on top of. For the caves that remain, the adverse effects of pollution, vegetation alteration, and water flow changes from urban encroachment are major challenges. Since so many caves have been destroyed or impaired, it is critical to not only protect but to restore those that remain.

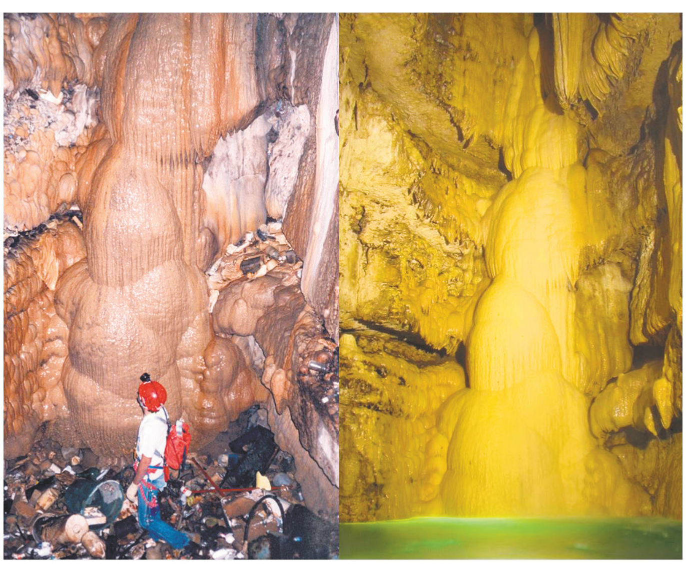

Figure 2. Midnight Cave before and after cleanup. Left photo by Nico Hauwert, right photo by Jeff Nichols.

Figure 3. Pipeline Cave entrance room, August 8th, 2018. Photo by Colin Strickland.

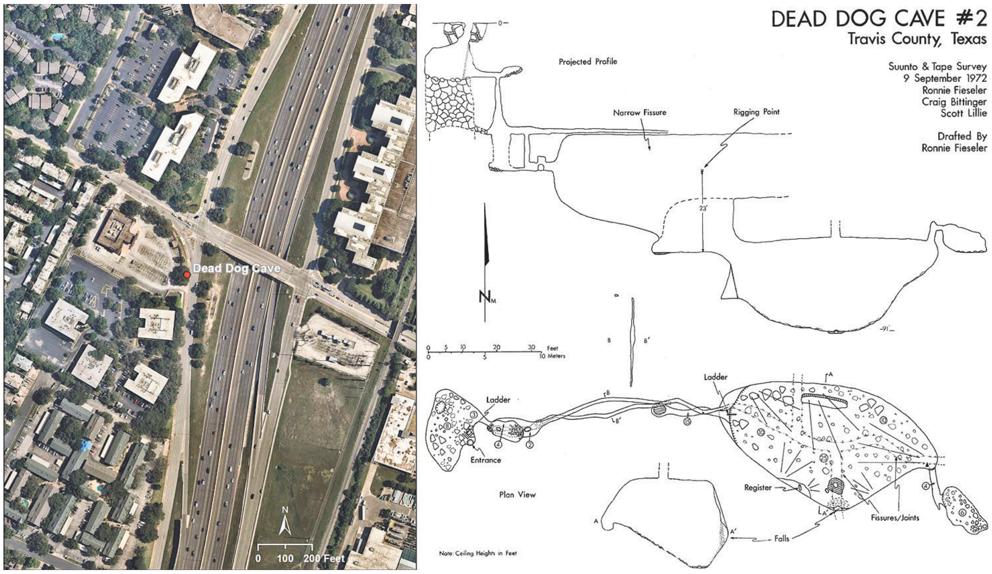

Figure 4. Dead Dog Cave location and cave map.

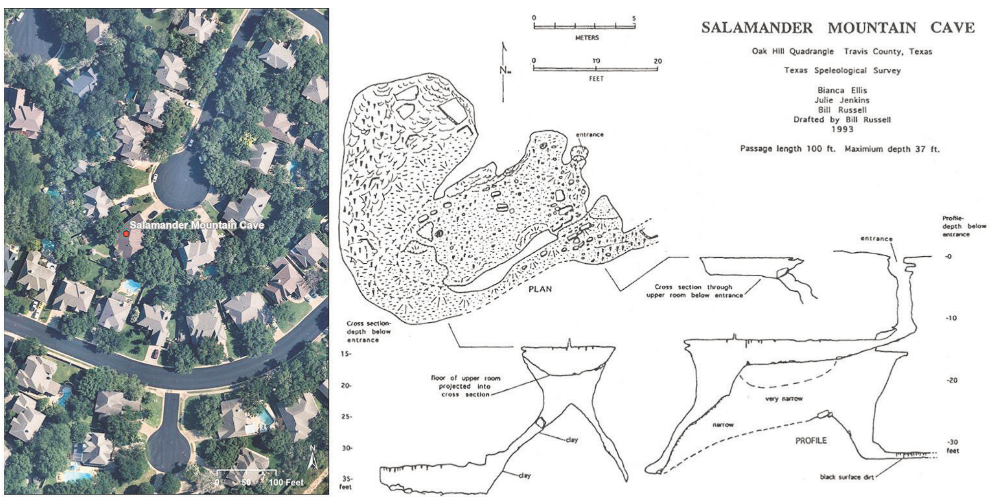

Figure 5. Salamander Mountain Cave location and cave map.

Cave Fauna Diversity

The Balcones Fault Zone has a very diverse cave fauna. This faunal region constitutes a transitional zone between the Coastal Plain and the Edwards Plateau. River and canyon incision and complex faulting have resulted in isolated exposures of cavernous limestone. As a result, several faunal groups have speciated to form numerous closely related species within a comparatively short distance. Some of these include spiders in the genera *Cicurina*, *Tayshaneta*, and *Eidmannella*; pseudoscorpions of the genus *Tartarocreagris*; harvestmen of the genus *Texella*; millipedes of the genus *Speodesmus*; ground beetles of the genus *Rhadine*; and mold beetles of the genus *Batrisodes* (Reddell, 1994). These isolated areas of limestone can be thought of as islands separating their inhabitants from their neighbors. This isolation not only allowed them to evolve into separate species, but it makes them very susceptible to extinction due to the extremely limited ranges of each species. Some species are only known from one or a few caves in Austin. Driving across Austin, you pass over many of the extremely small ranges of closely related species. Figure 6 shows the ranges of *Tartarocreagris* pseudoscorpions in the Austin area (Veni and Jones, 2021).

Cave Crickets

In Central Texas, cave crickets are a critical element in cave ecosystems, emerging at night to feed and returning to the caves to roost during the day. They lay eggs in cave sediments and the nymphs emerge. Troglobitic *Rhadine* beetles prey on cricket eggs, and the cricket nymphs serve as prey for other active predators such as spiders and pseudoscorpions. Their droppings serve either directly as food or as a medium for the growth of fungus on which millipedes, collembolans, and other species feed (Reddell, 1994). These cave crickets are keystone species

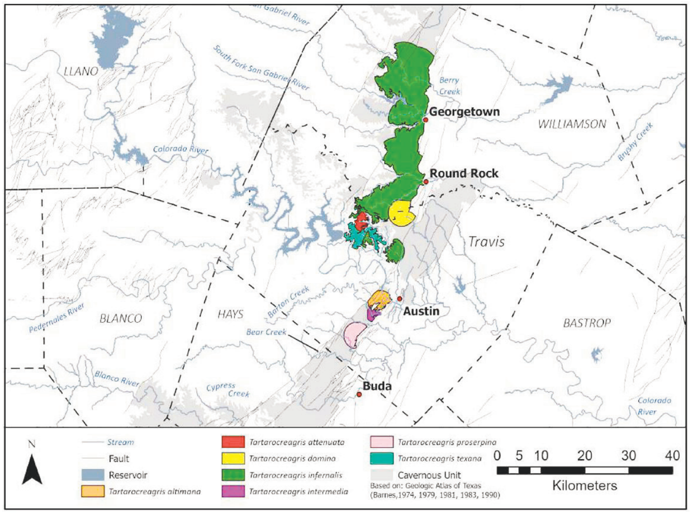

Figure 6. Ranges of Tartarocreagris species (pseudoscorpion) from Veni and Jones (2021), modified by Colin Strickland.

in the subterranean community. The most abundant is *Cuethophilus secretus*, the Texas Cave Cricket, which is found in large numbers in healthy caves (Figures 7 & 8). There is another undescribed *Ceuthophilus* species known as "Species B", that tends to be less numerous than *C. secretus*. These crickets are a good bioindicator of cave ecosystem health; if the crickets are doing well, it is a safe bet the troglobites that depend on them are also doing well.

Biological Importance of Cave Entrances

There is a misconception that covering the entrance of a cave would somehow protect it. The reasoning is that it would block pollution from being able to enter the cave and eventually the aquifer. This is not only an ineffective means of blocking pollutant infiltration, but it is devastating to the cave fauna. Due to the lack of plant life underground, the subterranean environment is extremely nutrient poor. The only way nutrients enter this ecosystem is by falling or washing into entrances or by being brought in by trogloxenes (cave visitors), such as cave crickets, bats, raccoons, possums, etc. One way to think about the subterranean environment is like a desert where instead of lacking moisture, it is lacking in nutrients. A cave, no matter how large, will have little biological activity without an input of nutrients from the surface. The cave entrances can be thought of as oases of abundant nutrients in the underground nutrient desert. When surveying a cave for life, most of the organisms are found only a short distance from the entrance. A biological comparison of an open cave in a natural landscape to a filled cave in an urban landscape can be seen in Figures 9 & 10.

Troglobites are found in higher numbers in areas with more nutrients. In long caves such as Airman's Cave in South Austin, the number of organisms found far from the entrance are few, and many times are only found in areas with external nutrient input such as raccoon scat, which may be crawling with hundreds of springtails and dozens of millipedes. Troglobites are found throughout the cavernous limestone of Central Texas; able to travel through interstitial spaces far too small for humans, but most of the individuals are likely relatively close to cave entrances that provide the nutrients to survive and multiply. If large numbers of cave entrances are sealed by filling with sediments, or being built on or paved over, it reduces the amount of nutrients entering the subterranean ecosystem, which will in turn lead to fewer individuals of each species. Also, depending on the geographical extent of the cave filling, it could isolate populations that before could easily travel from one nutrient-rich entrance area to another over a large area, but now are restricted to one or a few cave entrances. They are potentially separated from other members of their species by a vast nutrient-poor desert in

Figure 7. Ceuthophilus secretus, Pipeline Cave, May 20th, 2019. Photo by Colin Strickland.

Figure 8. Ceuthophilus secretus roost, Beard Ranch Cave, August 25th, 2021. Photo by Colin Strickland.

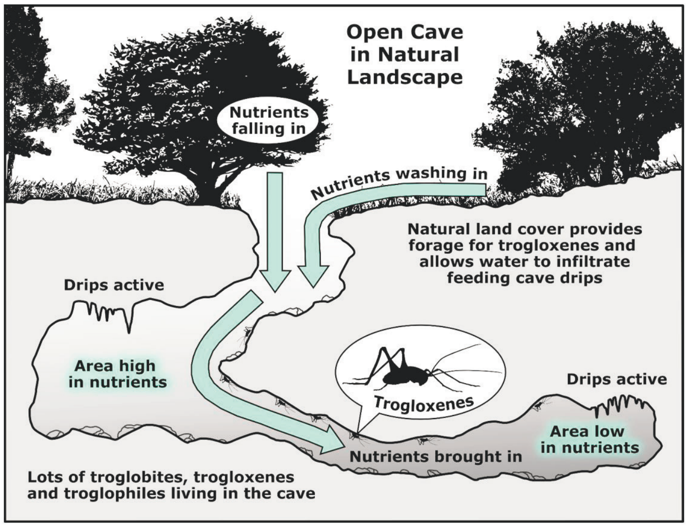

Figure 9. Open cave in natural landscape.

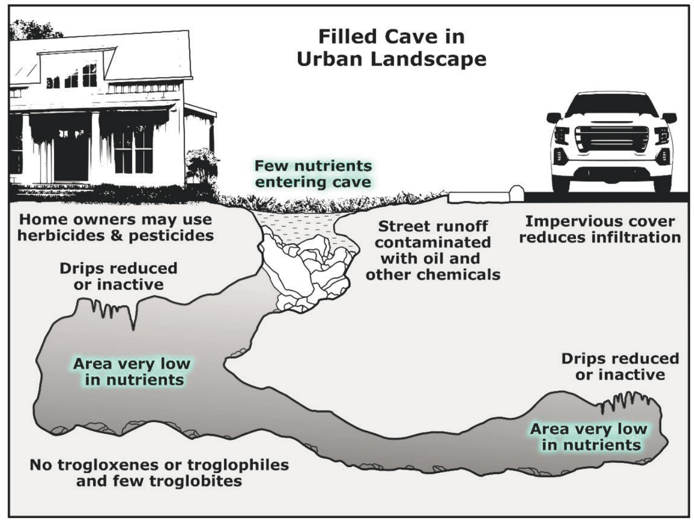

Figure 10. Filled cave in urban landscape.

the form of endless neighborhoods and strip malls on top of filled caves. The resulting reductions in gene flow make these organisms with already limited ranges even more susceptible to local extinctions.

Cave Entrance Size

Depending on the size of the cave entrance, the troglobites will stay the appropriate distance away from the entrance to remain in areas with near 100 percent humidity. In caves with constricted entrances, troglobites are often found very close to the entrance; whereas in caves with very large entrances, they will be found farther in where the humidity is higher (Elliott, 1997). A good example of a constricted entrance is Amber Cave (Figure 11).

This small cave has an unusually high richness of fauna because its small opening maintains humidity and allows the troglobitic fauna to access an area enriched with both leaf litter washed in from the surface and guano from the numerous cave crickets that reside within. When excavating caves, care should be taken to not enlarge the entrance more than necessary. Biologically speaking, the cave entrance really only needs to be large enough for crickets to come in and out. There are multiple reasons to enlarge it more than that though. First, being large enough for leaf litter to fall in and allowing mammal trogloxenes such as bats, raccoons, and opossums to enter helps diversify the types of nutrients available. Second, very small entrances can be hazardous to cave crickets because it allows predators such as spiders, scorpions, foxes, and ringtails to feast on them as they pour out of a small opening with nowhere else to go (Figure 12). Having enough room to spread out and exit in different areas simultaneously helps more crickets make it out alive. And last, but most importantly, if a human cannot fit inside, then we have no way of knowing what species reside within since bait traps are not effective at trapping certain species such as *Texella* spp. Much work is still needed to define the ranges

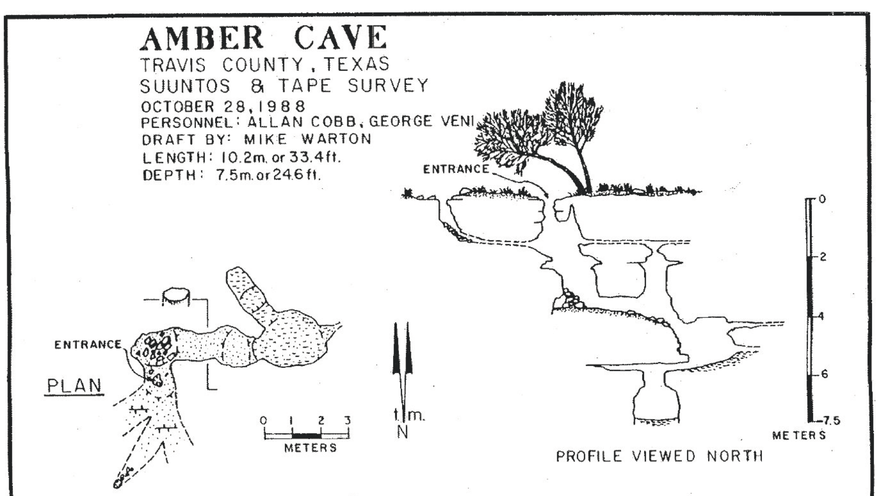

Figure 11. Amber Cave map.

of these hard to reach creatures, and there are more species yet to be discovered, but that can only happen if the caves can be explored and documented. A cave may harbor rare or endangered species, but if no one knows, it is far less likely that it will be protected.

Wildflower Cave

From the 1800s to the early 1900s, Wildflower Cave was situated on a ranch and likely received sediment runoff from ranching practices. From the 1950s to the 1970s, it was used as a trash dump. A photo of the entrance was taken by Mark Sanders in the late 1980s (Figure 13).

In 1993, Nico Hauwert, then with the Barton Springs/ Edwards Aquifer Conservation District, did a site inspection and noted the location of Wildflower Cave. On March 6th, 1994, there was a cleanup of the cave lead by Mark Sanders where they encountered an abundance of

Figure 12. Fox hunting cave crickets at Jester Estates Cave. Camera setup by Mark Sanders.

Figure 13. Entrance to Wildflower Cave in the late 1980s. Photo by Mark Sanders.

tractor/car batteries and lots of salamanders. In early 1995, the Lady Bird Johnson Wildflower Center acquired the 42 acres which included Wildflower Cave. On April 22nd, 1995, an Earth Day cleanup event of Wildflower Cave was led by Justin Shaw (Figure 14). Volunteers filled three trucks with trash including glass bottles, plastic bottles, and Clorox bottles.

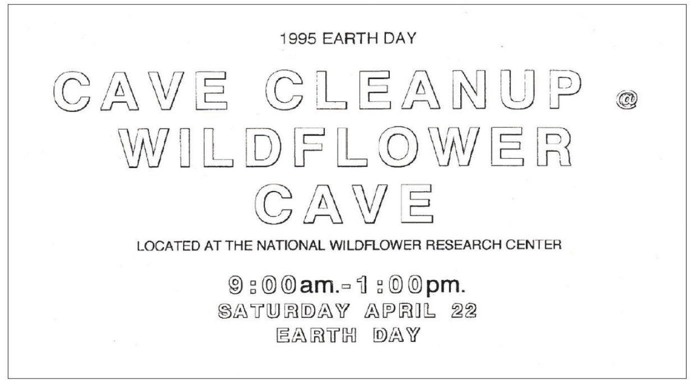

Figure 14. Upper portion of 1995 Earth Day cave cleanup flyer.

In 1999, the Wildflower Center acquired an additional 137 acres. In 2002, Stratus Properties donated 103 acres, bringing the Wildflower Center's total acreage to its current 284 acres. In 2002, the City of Austin Watershed Protection Department started using Wildflower Cave for its Earth Camp Program (Figure 15). The first year, 524 students visited the cave. The number of visitors continued to increase to 1,121 in 2007, 1,572 in 2013, and 2,160 in 2019, the last full year before the pandemic.

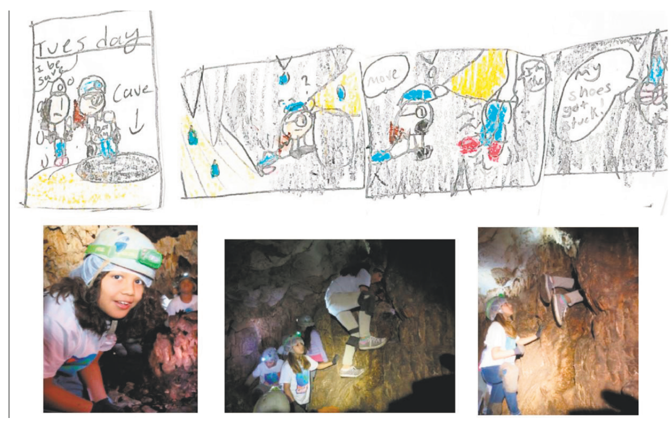

Figure 15. Images from Watershed Protection Department school outreach report.

In 2013, the Watershed Protection Department Cave Team led by Bev Shade removed a large amount of sediment and rock from the cave (Figures 16 & 17).

This opened access to the lower levels of the cave. In 2013, the cave was surveyed by David Ochel, Bev Shade and Justin Shaw, and a map was drafted David Ochel (Figure 18).

Figure 16. Watershed Protection Department Cave Team, led by Bev Shade, removing fill.

Figure 17. Material removed from Wildflower Cave, February 8th, 2013. Photo by Justin Shaw.

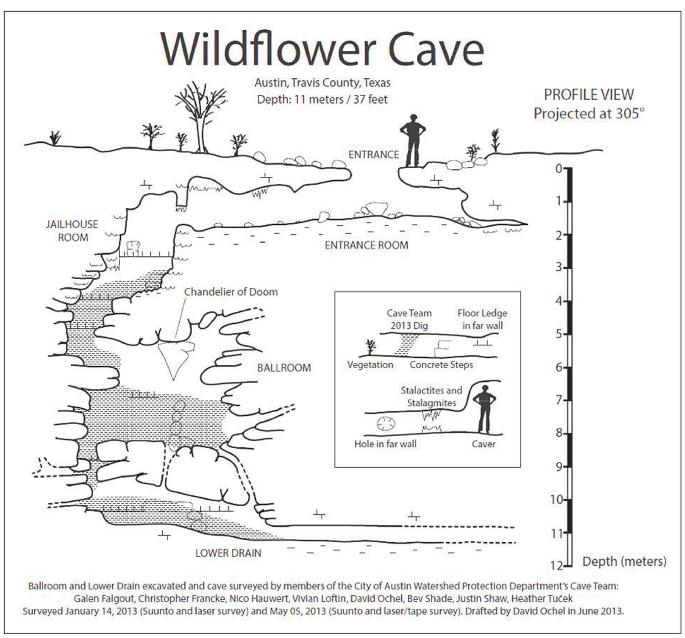

Figure 18. Profile view portion of Wildflower Cave map drafted by David Ochel, modified by Colin Strickland.

In 2013, a Tricolored bat (*Perimyotis subflavus*) was observed by Justin Shaw in the Jailhouse Room of the cave (Figure 19). They are presently seen there on a regular basis during winter through early spring and care is taken by Earth Camp participants to not disturb them.

*Figure 19. Tricolored bat (*Perimyotis subflavus*), Wildflower Cave, February 11th, 2013. Photo by Justin Shaw.*

In 2018, the Wildflower Center hosted its first Austin Cave Festival; a free public event held annually in February (Figures 20 & 21). Tours are given to children and adults in Wildflower Cave and nearby La Crosse Cave.

La Crosse Cave

La Crosse Cave is located on the Wildflower Center near La Crosse Avenue. In 1992, it was mostly filled with soil and ranch trash (Figure 22).

In his 1992 report of karst features in the area, Mike Warton wrote, "The entrance area contains a lot of ranching debris and refuse (rusted rolls of wire, pieces of tin, old cans, etc.)" (Warton, 1992). In 2000, Bill Russell received permission from the Wildflower Center, after their acquisition of the parcel containing La Crosse Cave, to conduct an initial cave cleanup (Nico Hauwert personal communication, 2021). In February 2003, The Texas Cave Management Association held a cave cleanup lead by Bill Russell that removed most of the remaining ranch trash from the cave entrance (Russell and Jenkins, 2003). In January 2012, Mark Sanders did a faunal survey, but since only a small portion of the cave near the entrance was accessible at that time, he found no troglobites. His notes state, "I did not observe any cave-adapted species, in my opinion this cave is too shallow and dry to harbor any troglobitic species" (Sanders, 2012). In 2012, the Watershed Protection Field Operations staff under the direction of Nico Hauwert used a crane to start excavating La Crosse Cave over a one-week period, which was followed up with more extensive cave team excavation from 2013 to 2016 (Nico Hauwert personal communication, 2021) (Figure 23). Members

Figure 20. Austin Cave Festival 2019 flyer. Image from www.hillcountryalliance.org.

Figure 21. Child entering Wildflower Cave, Austin Cave Festival, February 24th, 2020. Photo by Willow Cohn.

Figure 23. Members of the Watershed Protection Cave Team filling buckets in La Crosse Cave, September 16th, 2013.

Figure 22. Entrance to La Crosse Cave in 1992. Photo by Mark Sanders.

Figure 24. Volunteers from the Underground Texas Grotto assisting with rock removal at La Crosse Cave, July 30th, 2013.

of the Underground Texas Grotto would periodically volunteer with the excavation efforts (Figure 24).

The cave was gated in 2014, and then steps and guardrails were installed (Figure 25). Once the steps were in place, the Watershed Protection Department started using the cave for its Earth Camp Program. The cave is also used for cave tours during the annual Austin Cave Festival (Figure 26). The cave was surveyed from 2013 to 2015 and a map was drafted by Bev Shade in 2018 (Figure 27).

Figure 25. Installed gate, steps and guardrails at La Crosse Cave. Photo by Nico Hauwert.

Figure 26. Visitors in La Crosse Cave during the 2019 Austin Cave Festival. Photo from www.wildflower.org.

As can be seen on the map, fill was blocking access to the lower sections of the cave. In 2012, Mark Sanders was only able to access down to the 2003 floor level. On January 23rd, 2018, I did the first faunal survey in the lower levels of the cave and found multiple troglobitic species including two species of concern (SOC), *Cicurina bandida,* an eyeless cave spider, and *Rhadine austinica*, a troglobitic ground beetle (Figure 28). Additionally, I found *Cambala speobia*, a troglobitic millipede, and *Texella mulaiki*, a troglobitic harvestman. If the fill in the entrance room had not been removed, we would have had no way of knowing these species were present. Another way in which the cave ecosystem has benefited from the removal of fill is the use of the cave by bats. No bats were ever seen before the fill was removed. Caves with low ceiling are dangerous to bats since raccoons can simply grab them off

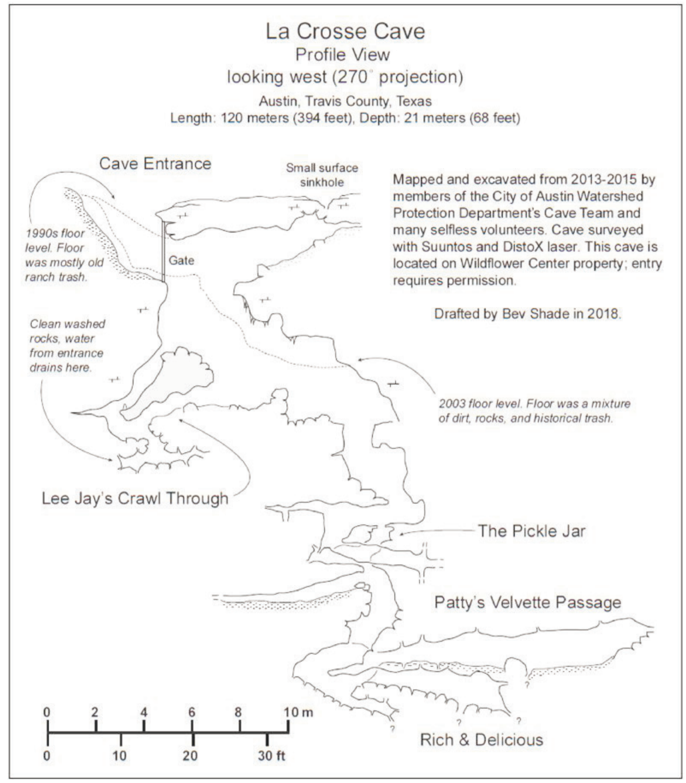

Figure 27. Profile map of La Crosse Cave drafted by Bev Shade, modified by Colin Strickland.

Figure 28. Cicurina bandida and Rhadine austinica, La Crosse Cave, January 23rd, 2018. Photos by Colin Strickland.

the ceiling. Now Tricolored bats are often seen roosting in the lower portion of the entrance room.

Persephone Caverns

Unlike the above caves that were only partially filled, Persephone Caverns is a good example of the benefits of restoring a completely filled cave. When I first found the feature, it was a crack approximately 8 ft long, 1 ft wide, and 2 ft deep. I had originally named it Canyon Creek Crevasse but later renamed it once its significance was determined (Figure 29).

Rich Zarria and his crew started excavating the cave on January 12th, 2021. The crack narrowed and they had to use a hammer drill and bull pins to widen the entrance to

Figure 29. Filled entrance of Persephone Caverns, February 5th, 2019. Photo by Colin Strickland.

continue. Eventually, they could lower a camera down into a room and spin it around for a view. They finally broke into the room on February 8th, 2021. I performed an initial faunal survey on February 10th, 2021. After dropping 17 ft down the crack to the floor, there was a room with a dome that you could stand in, and from there, low rooms continued to the north and south (Figures 30 & 31). I could see into further passages to both the north and south, but some material would need to be moved for access.

During the first faunal survey, I found multiple troglobitic species including *Speodesmus* sp. millipedes, *Cicurina travisae*, an eyeless cave spider that is a species of concern (SOC), *Eidmenella reclusa*, an eyeless cave spider, also a SOC, and *Texella reyesi*, the endangered Bone Cave harvestman (Figure 32).

Rich and his team excavated into the north section of the cave on February 23rd, 2021, and into the south section two days later. I conducted faunal surveys in the new sections and then delineated faunal survey zones for quarterly surveys to be repeated for at least the first two years, and eventually dropping to biannual surveys. A timeline of the initial exploration and faunal surveys is shown in Figure 33.

Andy Edwards is currently working on a map of the cave and Figure 34 is a preliminary version of the map with only the plan view. The cave currently has around 600 ft of passage, which currently makes it the most extensive cave known on the Jollyville Plateau.

The northern section of the cave includes a tunnel and multiple domes you can stand in (Figures 35 & 36).

The southern section is even more impressive with a large room around 60 ft long you can stand in with nice formations named Julia's Junction (Figures 37 & 38).

Increased Diversity After Opening Filled Entrance

The changing biology of Persephone Caverns became apparent as I did more faunal surveys. The only known entrance had been plugged with around 10 ft of soil and rocks. Very few organisms were entering or exiting, and no leaf litter was falling in before it was excavated. Ideally, I would have been able to research the cave immediately after the dirt plug was removed to document the faunal diversity, but unfortunately, they broke through the dirt plug into the room in late January 2021 but were unable to enter it until they enlarged the entrance shaft on February 8th. I then performed a faunal survey on February 10th, but by that time, the cave had been open to cave cricket colonization for almost two weeks. It is likely there were few or no cave crickets in the cave before the opening of the entrance, but by February 10th, I found around 100 *Ceuthophilus* sp. subadults and around 50 nymphs and 10 *Ceuthophilus* Species B. When I initially entered the cave, there was no cricket guano or leaf litter. This lack of nutrients meant there were few springtails. As time progressed, this changed. Large numbers of crickets began

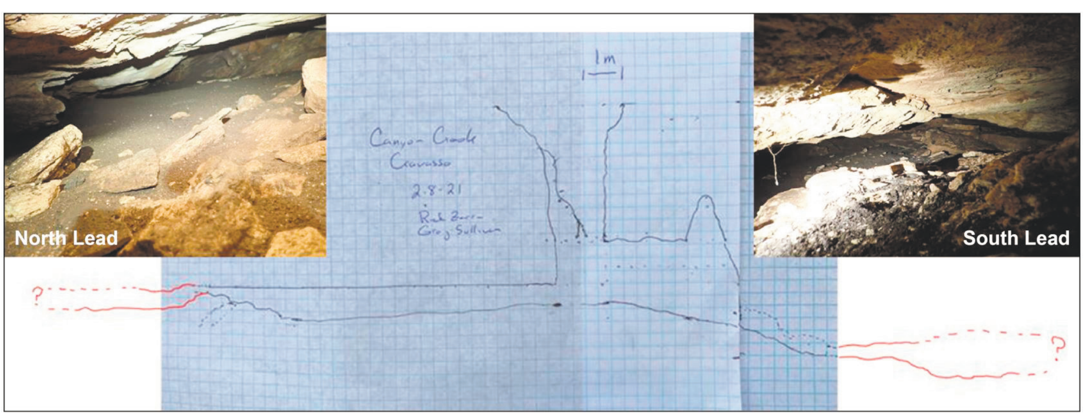

Figure 30. Initial profile sketch of Persephone Caverns by Rich Zarria. Photos and drawings of cave leads (red) by Colin Strickland.

Figure 31. Excavated entrance to Persephone Caverns. Photo by Colin Strickland.

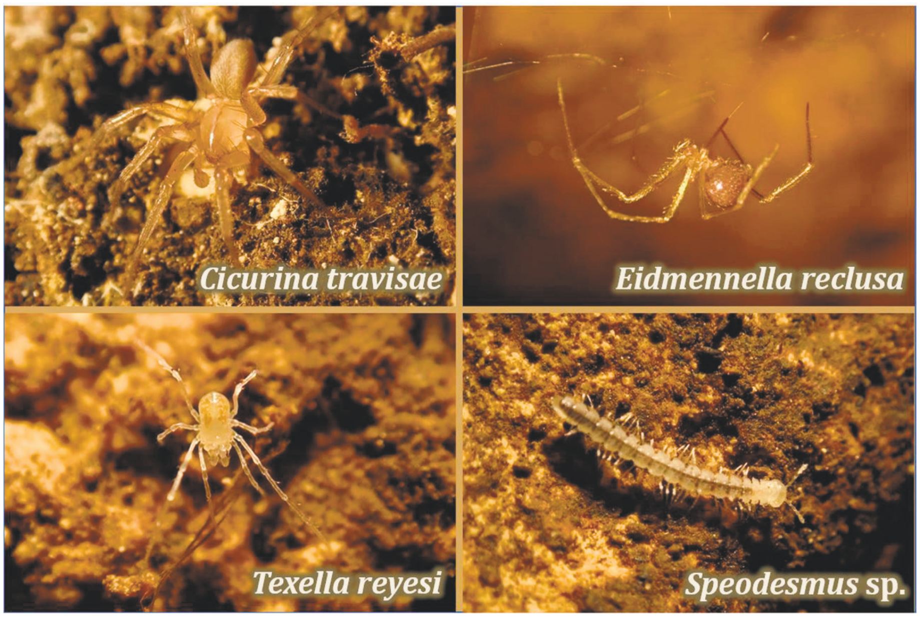

Figure 32. Troglobitic species found during first faunal survey of Persephone Caverns. Photos by Colin Strickland.

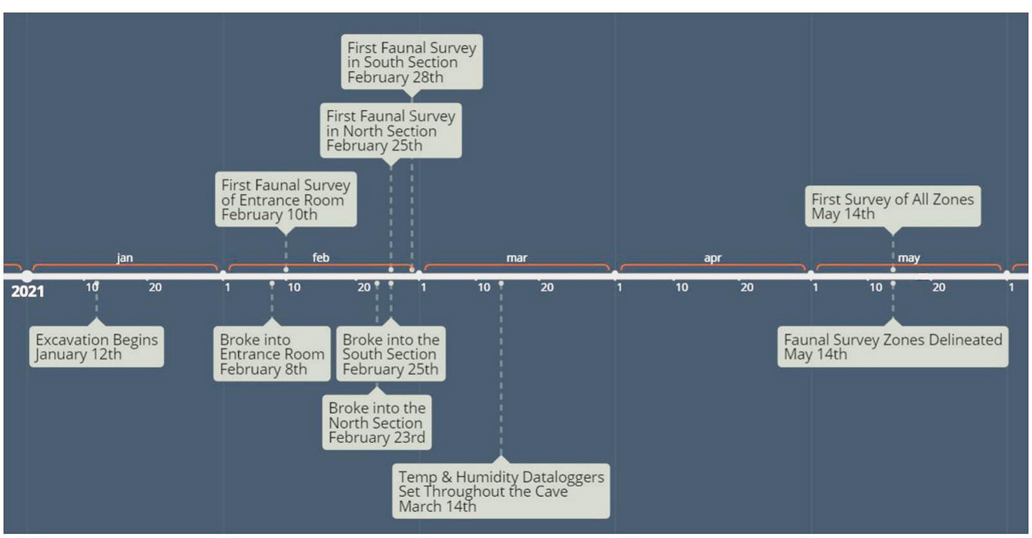

Figure 33. Timeline of Persephone Caverns' initial exploration and faunal surveys.

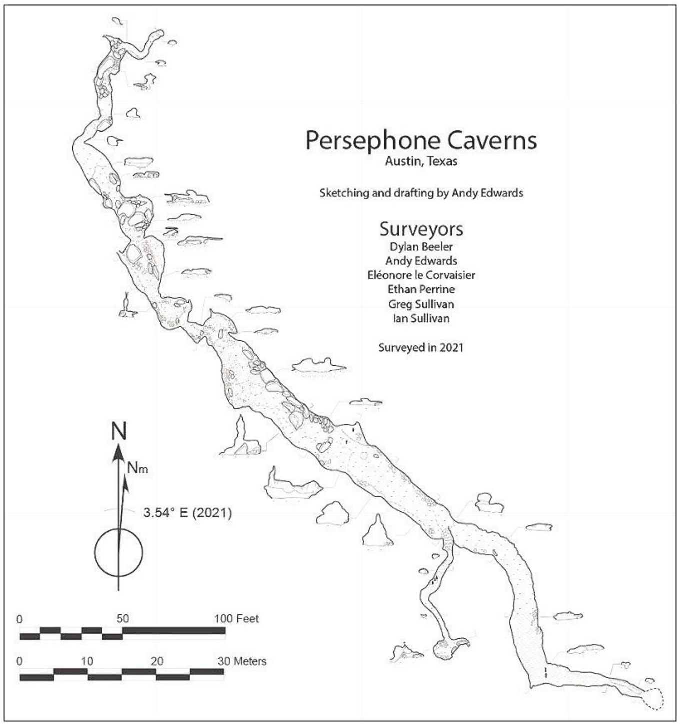

Figure 34. Preliminary plan view portion of Persephone Caverns map by Andy Edwards, modified by Colin Strickland.

Figure 35. Passage in northern section of Persephone Caverns. Photo by Colin Strickland.

Figure 36. Dome in northern section of Persephone Caverns. Photo by Colin Strickland.

Figure 37. Julia's Junction in Persephone Caverns. Photo by Rich Zarria.

roosting in the entrance room and in the various domes in the cave. They rain down nutrient-rich guano upon which fungus grows and provides food for springtails, snails, millipedes, and others (Figures 39 & 40). Though exact counts are hard to do with springtails, their numbers seemed to have approximately tripled in the entrance room from February 10th to May 14th, 2021. These springtails are prey for predatory troglobites, and with an increased number of prey, the number of troglobites, including eyeless spiders and pseudoscorpions, will also increase.

On the initial surveys of the cave in February 2021, I found no Western Slimy salamanders (*Plethodon albagula*), but by May 14th, they were plentiful with over 40 seen throughout the cave, mostly large adults (Figure 41). While traversing Julia's Junction and the long crawlway between faunal survey zones three and four, I saw about 20 large adults running away from me and hiding in cracks in the walls.

Another example of organisms moving into the newly opened cave is the Cliff Chirping frogs (*Eleutherodactylus marnokii*). When I first surveyed the entrance room on February 10th, I found one Cliff Chirping frog, but on the August 19th survey, I found 17 in the entrance room, mostly juveniles (Figure 42).

After the entrance was opened, I placed a game camera inside to watch for trespassers, but also to document trogloxene mammals entering and exiting. So far, no climbing mammals have made it in, but on April 29th and May 4th, 2021, my camera captured video of a bat flying around the entrance room. I look forward to seeing

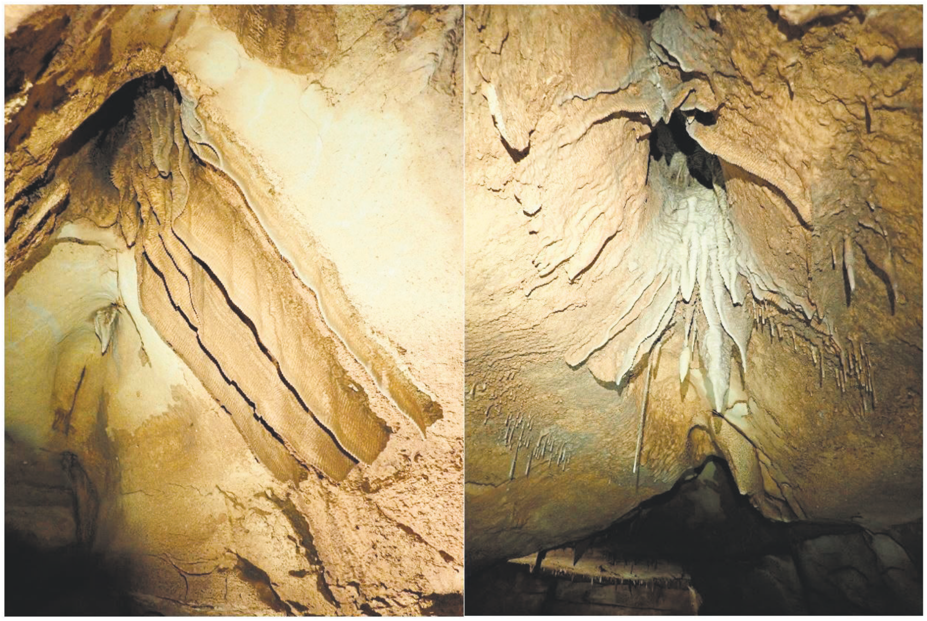

Figure 38. Formations in Julia's Junction, Persephone Caverns. Photos by Colin Strickland.

Figure 39. Left: Cricket guano covered in fungus in Persephone Caverns. Right: Psuedosinella violenta *(springtail) in Persephone Caverns, May 14th, 2021. Photos by Colin Strickland.*

how the cave's ecology changes as we do more surveys in the months and years to come. So far, the species list has grown quite large (Table 1). This species list includes three endangered species (ES), *Rhadine persephone* (Tooth Cave ground beetle), *Texella reyesi* (Bone Cave harvestman), and *Texamaurops reddelli* (Kretschmarr Cave mold beetle), as well as three species of concern, *Cicurina travisae* (troglobitic spider), *Eidmennella reclusa* (troglobitic spider), and *Rhadine subterranea* (troglobitic ground beetle) (Figure 43).

Another rare species found here is the pseudoscorpion *Tartarocreagris attenuata* which, though it is not an ES or SOC, it probably should be due to its extremely limited range (Figures 6 & 44).

We continue to locate filled caves throughout the Austin area and evaluate which should be restored; so lots more cave restorations to come. We will never be able to replace the caves that have been destroyed but we can restore and protect those that remain for future generations of both cave organisms and humans to enjoy.

Figure 40. Ceuthophilus secretus *roosting in dome, Persephone Caverns, August 19th, 2021. Photo by Colin Strickland.*

Figure 41. Juvenile and adult Plethodon albagula*, Persephone Caverns, May 14th, 2021. Photos by Colin Strickland.*

Figure 42. Juvenile Cliff Chirping frog in entrance room, Persephone Caverns, August 19th, 2021. Photo by Colin Strickland.

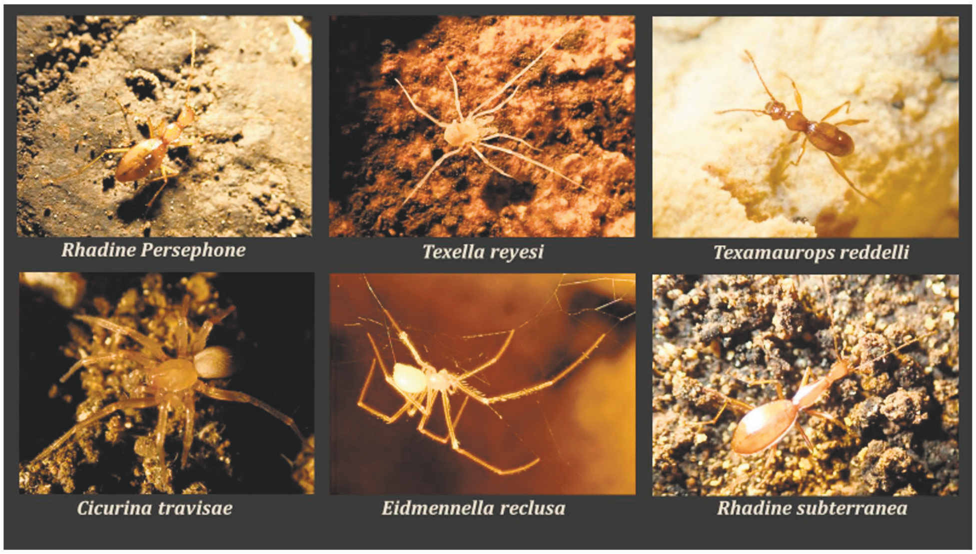

Figure 43. Top row: Three endangered species (ES) from Persephone Caverns. Bottom row: Three species of concern (SOC) from Persephone Caverns. Photos by Colin Strickland.

Figure 44. Tartarocreagris attenuata*, (pseudoscorpion), Persephone Caverns, February 28th, 2021. Photo by Colin Strickland.*

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Table 1. Persephone Caverns species list.

Taxonomic Name	Common Name
Acari	Mite
Armadillidae	Pill bug
Batrisodes sp.	Mold beetle
Cambala speobia	Troglobitic millipede
Campodeidae	Dipluran
Ceuthophilus cunicularis	Cave cricket
Ceuthophilus secretus	Texas cave cricket
Ceuthophilus Species B	Cave cricket
Cicadellidae	Leaf hopper
Cicurina travisae	Troglobitic spider
Cicurina varians	Troglophilic spider
Coleoptera	Beetle
Culicidae	Mosquito
Diptera	Fly
Eidmannella reclusa	Troglobitic scaffold web spider
Eleutherodactylus marnoki	Cliff Chirping Frog
Formicidae	Ant
Haplotaxidae	Earth Worm
Helicodiscus eigenmanni	Blind snail
Leiobunum townsendi	Harvestman
Lepidoptera	Moth
Lithobiidae	Stone centipede
Lycosidae	Wolf spider
Mycetophilidae	Fungus gnat
Peromyscus	Deer mouse
Plethodon albagula	Western slimy salamander
Pseudosinella violenta	Slender springtail
Pseudouroctonus reddelli	Texas cave scorpion
Rhadine persephone	Tooth Cave ground beetle
Rhadine subterranea	Troglobitic ground beetle
Speodesmus sp.	Troglobitic millipede
Staphylinidae	Rove beetle
Symphyla	Garden centipede
Tartarocreagris attenuata	Troglobitic pseudoscorpion
Texamaurops reddelli	Kretschmarr Cave mold beetle
Texella reyesi	Bone Cave harvestman
Texoredellia sp.	Troglobitic silverfish
Trichoniscidae sp.	Woodlouse
Vespertilionidae	Bat

Military Bases May Be Vital for Preserving Key Components of Karst Habitat: An Evaluation of Karst Preserves at Camp Bullis, San Antonio, Texas.

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Abstract

Joint Base San Antonio Camp Bullis has established Karst Preserve Areas for the management of 83 significant caves on the base, including 32 caves known to contain endangered species. The land use and management regime at Camp Bullis and at other field-based military installations is uncommon in today's urban landscape and presents some unique considerations for karst preserve assessment. In 2021, Zara Environmental, LLC evaluated Karst Preserve Areas for 34 of the caves based on recommendations for karst preserve design published by the U.S. Fish and Wildlife Service. Abiotic and biotic components of the karst ecosystem associated with the 34 study caves were assessed, resulting in a spectrum of low quality to high quality rankings for each cave preserve. Of these, one cave preserve ranked low quality, two preserves ranked low to medium quality, nine preserves ranked medium quality, seven preserves ranked medium to high quality, and 15 preserves were ranked high quality. The uncommonly high number of medium to high quality preserves reflects a low density of urban development and a high density of caves and karst features on the base. This enables many Karst Preserve Areas to overlap and create large contiguous preserve areas that exceed U.S. Fish and Wildlife Service standards for karst preserve size.

Introduction

Joint Base San Antonio (JBSA) Camp Bullis is a military installation and training facility located in northern San Antonio, Bexar and Comal counties, Texas (Figure 1). Camp Bullis occupies approximately 11,331 hectares (ha) (28,000 acres) of largely undeveloped land in the Texas hill country dedicated to the completion of field-based training exercises. As such, Camp Bullis boasts one of the most substantial expanses of underdeveloped land that remains in San Antonio's continually urbanizing landscape today. Natural resource managers at Camp Bullis have the remarkable opportunity to manage the land for conservation purposes, while simultaneously supporting the installation's overall training mission. They practice adaptive management strategies, which promote responding to changes in the ecosystem based on regular monitoring and scientific studies that further understanding of the natural resources and associated management needs. Camp Bullis has a long history of multi-agency and interdisciplinary natural resource work across a variety of fields including wildlife biology, geology, hydrogeology, archeology, and paleontology; many centered around the significant caves and karst features on the base.

Geologic and Biologic Setting

The richness of the karst resources on Camp Bullis can be attributed to its geologic history. Faulting in the southern portion of Camp Bullis juxtaposed the Edwards Limestone Group of the Edwards Aquifer with the Trinity Group of the Trinity Aquifer, both of which develop karst terrain (Figure 1). There are over 1,500 known karst features on Camp Bullis including 112 enterable caves. Many of the biologically significant caves exist in bedrock of the Edwards Limestone Group, which is a highly cavernous unit extending beyond the installation to the northeast and southwest (GAT, 2010).

As geologic units were isolated from each other through faulting and erosional downcutting, karst species were also isolated, and their ranges were confined to relatively small geographic areas. According to the JBSA's Integrated Natural Resource Management Plan (INRMP), Camp Bullis is home to at least 12 endemic karst invertebrate species, two state listed threatened *Eurycea* salamanders, and three federally listed endangered karst invertebrate species (JBSA, 2020). The three federally listed endangered species include two ground beetles with no common names, *Rhadine exilis* and *Rhadine infernalis,* and the eyeless Madla Cave meshweaver spider, *Cicurina madla*.

Karst Management and Preserve Design

Camp Bullis' Rare and Endangered Species Management Plan delineates karst preserve areas (KPAs) for biologically significant caves and incorporates adaptive management strategies as new scientific understandings become

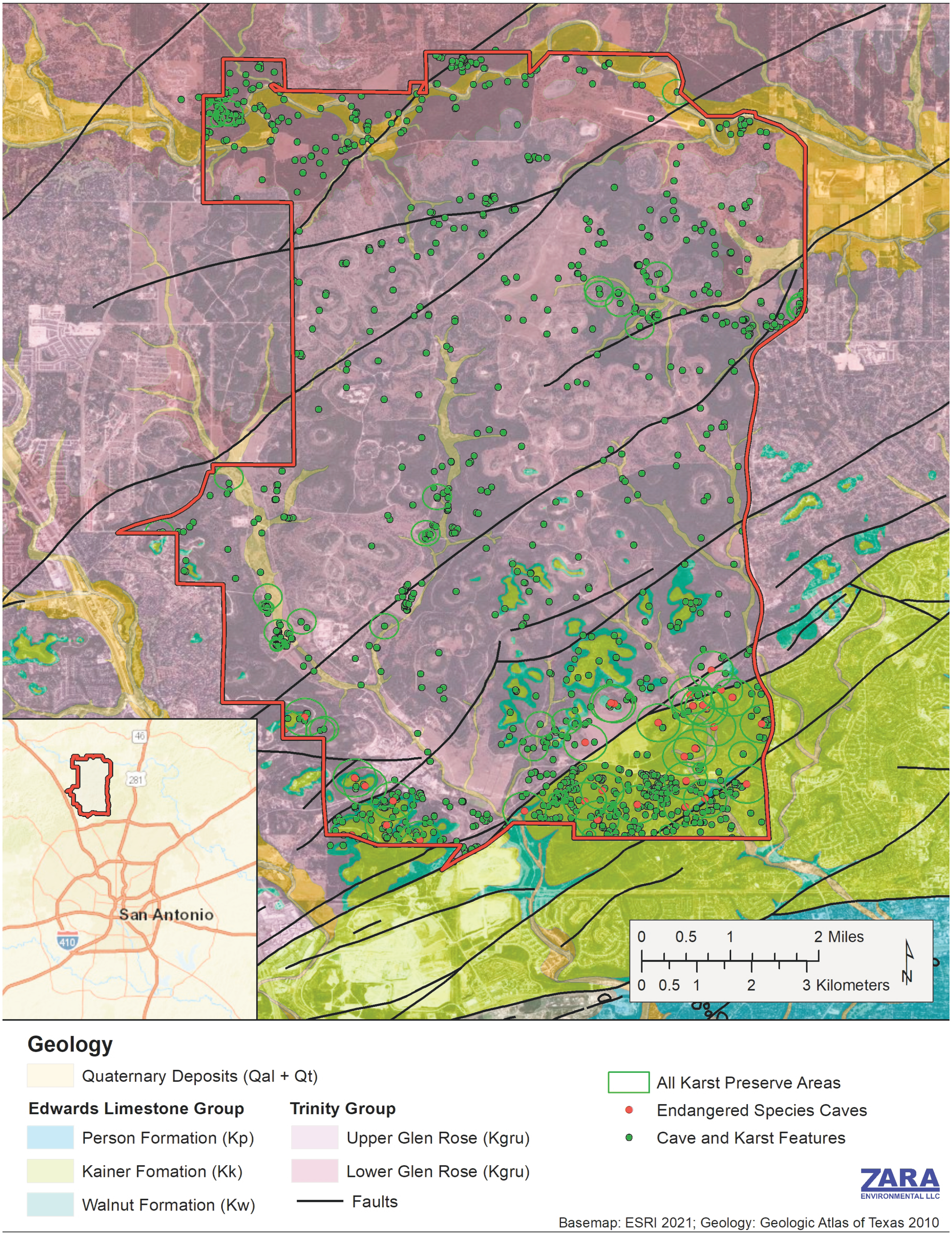

Figure 1. Camp Bullis is located in northern San Antonio and has a high density of significant caves and karst features known to contain rare, threatened, and endangered species, especially in the southern portion of the base where faulting has led to isolation of the Edwards Limestone Group and subsequent isolation of karst species.

available (Veni et al., 1999). The current management plan considers the United States Fish and Wildlife Service (USFWS) Karst Preserve Management and Monitoring Recommendations (USFWS, 2014) that aim to ensure continued survival and recovery of federally listed karst invertebrates in central Texas. The ultimate goals of the recommendations are to support the Bexar County Karst Invertebrate Recovery Plan with the objectives of down listing and delisting protected species through preservation of their habitat (USFWS, 2011). Camp Bullis KPA development was guided by USFWS Karst Preserve Design Recommendations (USFWS, 2012) to ensure components of the karst ecosystem are preserved to the best extent possible while remaining mission focused as a military training facility.

The USFWS Karst Preserve Design Recommendations outline a series of considerations that are largely based on principals of landscape ecology and include the preservation of biotic and abiotic contributors to overall cave health (USFWS, 2012). Landscape-level considerations include the size, shape, and configuration of a karst preserve, and the density, size, and depth of the karst resources. Biological components of the karst ecosystem include nutrient inputs from cave crickets and mammals, as well as the native vegetation communities that provide foraging habitat and climatic buffers against changes to temperature, humidity, and water availability. Abiotic components of the karst ecosystem include surface and subsurface drainage basins and mesocavernous connectivity that allows for nutrient and water flow as well as the dynamics of population genetics to occur. Additional abiotic components include the restriction of incompatible land uses within preserves and legally binding protections to preclude future impacts to the extent possible.

With these considerations, Camp Bullis has established 83 karst preserves of varying sizes and management practices depending on the significance of each cave. There are 23 caves that are considered biologically significant but do not contain endemic or endangered species (mesocaves). These 23 mesocaves are assigned 3.4-ha (8.5-acre) KPAs centered around the cave entrance that correspond to the documented 105-m (345-ft) foraging range for *Ceuthophilus* crickets (Taylor et al., 2005). There are 28 caves known to contain endemic species that are assigned 16-ha (40-acre) KPAs, and 32 caves known to contain endangered karst invertebrate species that have been assigned 36.4-ha (90-acre) KPAs, all centered around the cave entrance. Due to the density of significant cave resources on Camp Bullis, many of the preserves overlap, creating conglomerates of contiguous karst preserve areas that often exceed 40 ha (100 acres) (Figure 1).

Our recent work evaluated the quality of KPAs surrounding 34 caves at Camp Bullis to help understand if the current protection measures are adequate or if adaptive management strategies could be employed to improve the karst ecosystem supporting these caves. With detailed information regarding the quality of individual karst preserve components, managers can respond by directly targeting specific preserve components for improvements as needed.

Methodology

Quality Definitions of Karst Preserve Areas

The quality of individual karst preserves was ranked from low to high using criteria detailed in the USFWS Karst Preserve Design Recommendations (USFWS, 2012) as a guide. The document explicitly defines preserve quality because it can be used as an indicator of the likelihood of long-term survival of a species. Low quality preserves are less than 16 ha (40 acres) and are not considered to contribute to the karst invertebrate recovery plan. Medium and high quality preserves share the same components, include the entire surface and subsurface drainage basins, have healthy native plant and animal communities, and contain the entire 105-m (345-ft) cricket foraging range extending outward from the cave footprint. The main difference between medium and high ranking preserves is the overall size. A medium quality preserve encompasses 16 to 40 ha (40 to 99 acres), whereas a high quality preserve encompasses more than 40 ha (100 acres); a distinction based on data obtained from minimum viable population analyses for native vegetation communities that are key to the central Texas karst ecosystem (USFWS, 2012). Without a sufficient preserve size, the native woodland and grassland communities cannot sustain themselves over decadal and millennial timescales and begin to slowly erode from the edges inward.

The assessment of KPA quality that we present here deviates from these definitions due to inherent difficulties in applying these criteria to the land use and management regime in place at Camp Bullis. It is problematic to apply criterion that were designed to assess one to a few caves at a time in an area where development demand is high, to an area that has an extremely high density of occupied caves, yet a relatively low demand for development and can offer large contiguous expanses of mildly impacted natural landscape. Thus, we implemented a carefully modified approach to KPA evaluation. Our evaluation necessitated an extensive review of decades of existing data and GIS analyses, as well as new fieldwork to delineate estimated drainage basins for several caves. To assist in the qualitative comparison of KPAs, we evaluated three major elements of each preserve: 1) the karst preserve components; 2) monitoring and management activities; and 3) incompatible land uses, restrictions, or other legally binding protective mechanisms.

Karst Preserve Components

Analysis of the karst preserve components relied heavily upon GIS visualization and analysis to determine the extent to which the abiotic and biotic components were within preserved areas. Visualization of the spatial components for comparison and assessment allowed for better understanding of the preserve adequacy and overall quality; however, it is necessary for many of the components to be geographically delineated, or at a minimum, estimated. The initial step required obtaining cave survey maps to create cave footprints and projecting the known cave passages to the land surface through scaling and digitization of the data. This was followed by multiple other steps that allowed for review of the biological components of the karst ecosystem. We created a buffer that extended 105 m (345 ft) beyond the cave footprint to represent the cricket foraging range. Native plant communities were reviewed using aerial imagery, knowledge of site conditions from previous visits, and recent fieldwork performed to evaluate drainage basins (discussed in following sections). Foraging habitat for crickets and small-to-medium sized mammals was assumed based on the vegetation composition and quality surrounding the cave entrance.

Abiotic components of the karst ecosystem that were assessed include the surface and subsurface drainage basins. As there has been no widespread effort to empirically delineate surface or subsurface drainage basins at Camp Bullis, the drainage basins used for analysis are presented as estimates based on topographic and geologic field observations. Twenty of the caves had existing drainage basin estimates by Veni (2003), while all but two of the remaining caves received estimated drainage basins as a product of this study (Zara, 2021). Specific methods used for drainage basin estimates are described in the referenced reports. Surface drainage basins generally exhibit overland flow or channelized flow. Caves that receive channelized flow can have surface drainage basins that extend to a watershed scale, encompassing expansive portions of the landscape, as intermittent drainages can convey surface runoff from distal areas into cave entrances during high flow events. Special consideration was given to caves that had surface drainage basins extending well beyond the preserve area, as the drainage basins frequently included both undisturbed native lands and cleared training facilities used as firing ranges, which have a higher potential for contamination related to heavy metals and other land uses that may be incompatible with preserves.

Other considerations regarding the preserve components included the overall size, shape, and configuration of the preserves relative to each other. For endangered species caves, JBSA assigned circular KPAs that were 36.4 ha (90 acres) centered on the cave entrance. However, preserves were not circular where the geographic boundary of Camp Bullis truncated the preserve and augmented the shape and size. These preserves were assessed on a case-by-case basis as land use on the opposite side of the Camp Bullis boundary varied and could range from undisturbed to a highway or dense residential subdivisions with high impervious cover. Due to the density of significant caves at Camp Bullis, many of the KPAs overlapped to create large contiguous preserved areas that could be greater than 40 ha (100 acres) in some cases. The largest contiguous preserved area created by overlapping KPAs included 15 endangered species caves and encompassed 268 ha (662 acres). Given that preserve size is a major component contributing to the long-term survival of the endangered species, this was a significant consideration in our ranking of the quality of each preserve. We also recognized when land surrounding the preserves was less fragmented and provided quality ecosystem services due to not being heavily modified.

Management and Monitoring

The USFWS Karst Preserve Management and Monitoring Recommendations (USFWS, 2014) are designed to ensure preserves are managed in a way that is most conducive to survival of endangered karst invertebrates in perpetuity. Management considerations include: 1) whether red imported fire ants (RIFA) populations are being controlled, as they pose a direct threat to karst invertebrates and cave crickets (USFWS, 2011), 2) whether a cave entrance is fenced or gated to prevent unauthorized entry, which could result in inadvertent death of karst invertebrates by being stepped on and/or soil compaction or other habitat degradation, and 3) whether native vegetation is managed in a way such that the plant communities are sustainable and are not at excessive risk of devastation from threats like wildfire, invasives, or oak wilt. Karst preserve monitoring can provide valuable data and can track changes that may occur to the karst ecosystem over time. Monitoring should include regular biological surveys, cave cricket exit counts as a proxy for the nutrient inputs available for any given system (Taylor et al., 2007), and vegetation monitoring to assess changes that could result in reduction of foraging habitat quality and/or climatic buffers that moderate temperature, humidity, and water availability in a cave. Routine inspections and monitoring allow for resource managers to implement adaptive management if the data suggests conditions are degrading. We reviewed management and monitoring practices at each study cave to determine their adequacy per USFWS (2014) recommendations.

Land Uses and Protective Provisions

Incompatible land uses can change the behavior and conditions of the biotic and abiotic components of the karst ecosystem and, thus, should be restricted as possible. Alterations to vegetation matrices and linear fragmentation resulting from land clearing and impervious cover can affect foraging areas and corridors used by animal communities as well as surface and subsurface drainage basin flow dynamics. At Camp Bullis, primary land uses that are incompatible with karst preserves include buildings, paved and unpaved roads, concealed infrastructure such as pipelines or underground storage tanks, and training grounds where activities that could introduce contaminants into the system are performed, namely the live firing ranges that could result in release of heavy metals or other noxious materials. Analysis of incompatible land uses within a cave preserve and/or drainage basin were evaluated qualitatively using aerial imagery to assess density and severity of incompatible land uses. Concealed threats such as underground infrastructure and stockpiles were not explicitly evaluated, however, it was recommended that resource managers internally evaluate these potential sources.

Protective provisions for the preserves ensure that the local karst ecosystem is protected from radical changes in the future and can be managed for the protection of the ecosystem in perpetuity. These provisions can include a variety of conditions but are often legally binding or can be put in place as a management plan or agreement with resource managers. Camp Bullis has a series of protective provisions outlined in the JBSA's Integrated Natural Resource Management Plan (INRMP), which are considered in this evaluation (JBSA, 2020).

Case Studies: Hanging Rock Cave and Pain in the Glass Cave

We present two case studies to demonstrate the karst preserve evaluation process and to illustrate examples of preserve variability at Camp Bullis. The two case study caves are both within the largest contiguous karst preserve area (an area of overlapping KPAs) that encompasses a cumulative 268 ha (662 acres); however, the quality of preserves for these two caves fall on opposite ends of the ranking spectrum. Although they are both managed similarly and are part the largest protected area, the characteristics of each site need to be considered both holistically and independently to produce a thorough, objective evaluation.

Hanging Rock Cave

Hanging Rock Cave is a vertical cave approximately 19.5 m (64 ft) in depth, located on a hillside away from any cleared firing range facilities or areas of heavy impact. The KPA around Hanging Rock Cave extends concentrically from the cave's entrance 340 m (1,116 ft), creating a 36.4-ha (90-acre) KPA that is part of a 268-ha (662-acre) contiguous preserve (Figure 2). The vegetation consists primarily of an undisturbed native woodland-grassland community, although there is one paved road located downslope from the cave along the northwestern edge of the preserve. The 105-m (345-ft) cricket foraging radius lies within the preserve area and is not fragmented by infrastructure or other barriers. The estimated surface and subsurface drainage basins also lie within the preserve boundaries and there are no apparent potential sources for contamination that could be mobilized by erosion of soils or water.

Preserve management includes monthly to bimonthly routine inspections, vegetation monitoring, cricket exit counts, biannual RIFA control, and annual biological monitoring for karst fauna in the cave. While the cave entrance is not protected from unauthorized entry by a gate or fence, no entry is allowed without prior approval and personnel are not authorized to move within the preserve outside of existing roadways. According to the INRMP, no vegetation removal or disturbance may be conducted without approval, the use of bait or attractants is prohibited within 150 m (492 ft) of the cave entrance for any reason, and no bivouacs or other static positions (campsites) may be established within the 105-m (345-ft) cricket foraging radius around the cave (JBSA, 2020). There are no incompatible land uses within the preserve aside from the previous mentioned paved road located downslope, which is outside of the estimated drainage basins at the edge of the preserve boundary.

Evaluating the karst ecosystem preserve components and management regime surrounding Hanging Rock Cave according to the preserve design considerations and quality definitions outlined in the Preserve Design Recommendations (USFWS, 2012), the preserve surrounding this cave has been ranked as a high quality preserve.

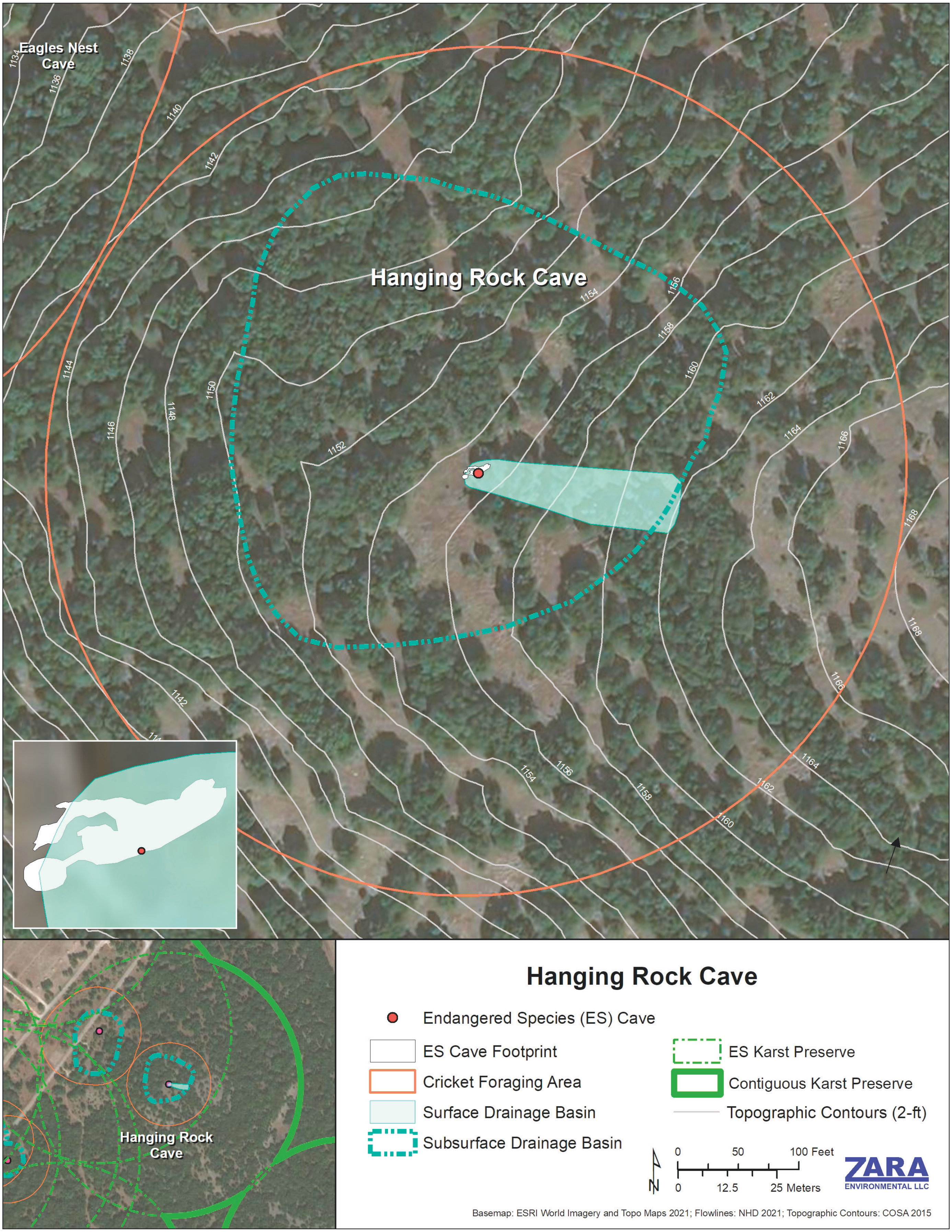

Figure 2. Preserve components surrounding Hanging Rock Cave.

Pain in the Glass Cave

Pain in the Glass Cave is a vertical cave approximately 30 m (98.5 ft) in depth with a sinkhole encompassing the entrance pit. The KPA around Pain in the Glass Cave extends concentrically from the cave's entrance 340 m (1,116 ft), creating a 36.4-ha (90-acre) KPA that is part of a 268-ha (662-acre) contiguous preserve (Figure 3). Pain in the Glass Cave is located near the center of an open firing range training facility that contains paved access roads. The native vegetation has been cleared and only grassland exists with a few sparse trees in the vicinity of the cave and along the edges of the preserve. The firing range is regularly mowed to maintain line of sight with targets; however, a 10-m (33-ft) no-mow zone is maintained around the cave entrance. The 105-m (345-ft) cricket foraging radius lies within the KPA, but the foraging grounds are the aforementioned highly modified grassland and lack the undisturbed woodland and grassland mosaic. The estimated surface and subsurface drainage basins also lie within the preserve boundaries, but there is potential for heavy metal or other contamination commonly associated with firing ranges that could be transported into the cave physically or as trace metals when mobilized by infiltrating water and eroding soils.

The preserve management regime is much the same as at Hanging Rock Cave and includes monthly to bimonthly routine inspections, vegetation monitoring, cricket exit counts, biannual RIFA control, and annual biological monitoring for karst fauna in the cave. This cave is in a restricted area of the base due to the presence of the active firing range, and the cave has been gated to preclude unauthorized entry. Personnel are not authorized to move within the preserve or within the firing range outside of existing roadways. According to the INRMP, no additional vegetation removal or disturbance other than regular mowing and maintenance may be conducted within the preserve without approval, the use of bait or attractants is prohibited within 150 m (492 ft) of the cave entrance for any reason, and no bivouacs or other static positions may be established within the cricket foraging radius. Many of these activities were already prohibited or highly unlikely to occur within this KPA due to the live firing range coinciding with the preserve.

While the karst ecosystem components are largely contained within the preserve and the overall size of the contiguous karst preserve surrounding Pain in the Glass Cave would indicate a high quality preserve, the incompatible land uses that occur on the preserve, potential for heavy metal contamination, and degradation to the natural vegetative conditions are quite severe. Thus, evaluation of the Pain in the Glass Cave preserve per the Preserve Design Recommendations (USFWS, 2012) has led to a low to medium quality preserve ranking.

Results and Discussion

Systematic qualitative analysis of KPAs was completed for 34 study caves, 32 of which are documented to contain federally listed endangered karst invertebrate species. Of the endangered species KPAs, two ranked low to medium quality, nine ranked medium quality, seven ranked medium to high quality, and 14 ranked high quality (Figure 4). Due to the density of endangered species caves on Camp Bullis, overlapping preserve boundaries created six contiguous karst preserve areas that contain all but two of the study cave preserves. The contiguous preserves range from a 39.7-ha (98-acre) preserve containing two endangered species caves to a 268-ha (662-acre) preserve containing 15 caves. In total, there are approximately 831 ha (2,054 acres) of karst preserve areas protecting endangered species caves on the base.

Camp Bullis is able to provide large contiguous karst preserve areas that exceed USFWS standards for karst preserve size due to the combination of density of cave and karst resources on the base, the unique geologic and biologic setting of the area, and the mission of this facility to function as a large area for training maneuvers. Military installations such as Camp Bullis have an exclusive opportunity to preserve and manage endangered species habitat for a number of reasons: 1) their missions often dictate the need for high-acreage, undeveloped land to complete training exercises, 2) they generally consist of one to a few land tracts that are many hundreds to thousands of acres, allowing conservation decisions to be made and implemented on a landscape scale, 3) there is a department of educated natural resource managers dedicated to land management and conservation, and 4) there is no monetary incentive to sell or subdivide the land into smaller, less controllable residential or commercial tracts, so they do not face the pressures that a rural ranch owner, for example, may experience. Thus, these military installations have an unparalleled ability to fulfill a land management regime that can assist with species recovery, which would otherwise be unobtainable in the sprawling urban landscape that has encroached on these vulnerable, isolated populations of karst invertebrate species.

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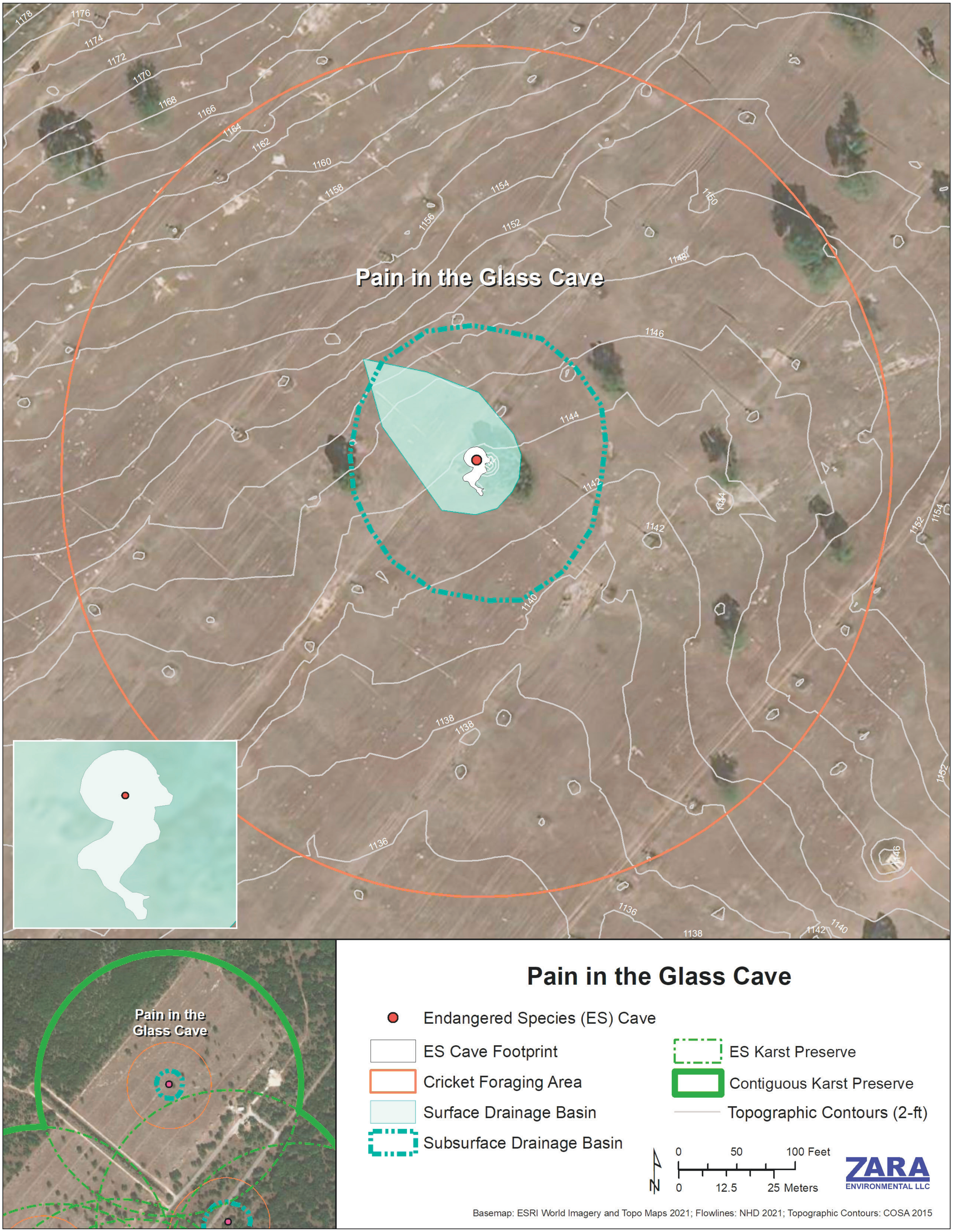

Figure 3. Preserve components surrounding Pain in the Glass Cave.

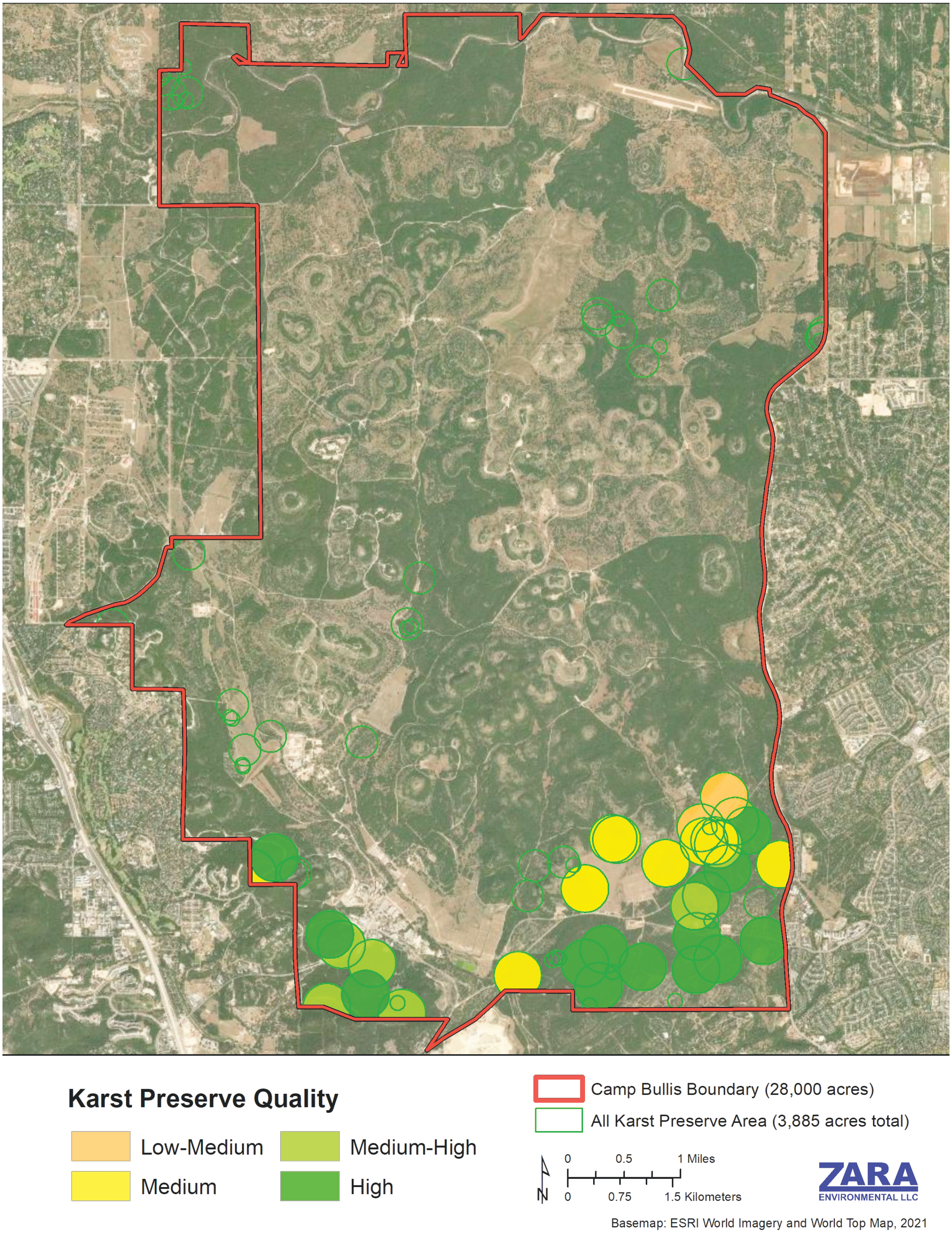

Figure 4. Quality rankings of preserves surrounding 32 endangered species caves. Two preserves ranked as low-medium quality, nine preserves ranked as medium quality, seven preserves ranked as medium-high quality, and 14 preserves ranked as high quality.

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Monitoring Microbial Communities for Cave Conservation

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Abstract

Fort Stanton Cave in Lincoln County, New Mexico is the 10th longest cave in the United States. With the discovery of the Snowy River passage in 2001, it has emerged as one of the most scientifically significant caves in the West. We used 16s rRNA and genomic DNA sequencing to analyze the composition of microbial communities present in Crystal Lake, the terminal sump located at the downstream end of the Snowy River passage. Compared to the low concentration of microbial cells expected in an oligotrophic cave environment, Crystal Lake had a high concentration of microbial cells. We suspected that some of the microbes in Crystal Lake may not be cave resident microbes, and sought the possible surface origins of these microbes. Specifically, we took samples at the resurgence, further downstream in the cave, and from nearby surface water sources which are known or suspected to flow into Fort Stanton Cave, including the suspected insurgence at Eagle's Mouth. This study established a robust baseline for both the resident microbial community in Crystal Lake and its expected relationship with nearby surface water. We present this case study as a proof-of-concept for the feasibility and cost-effectiveness of microbial monitoring for cave conservation. Microbial monitoring through sequencing has become increasingly accessible through the advent, evolution, and commercialization of next-generation sequencing (NGS) technologies. We discuss practical applications and limitations for monitoring microbial communities in caves.

Central Texas Cave Life

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Abstract

Starting at the cave entrance, and traveling deeper, I will show the amazingly diverse faunal community found in Central Texas caves. Through macrophotography and videography, I shed light on these seldom seen subterranean organisms. The cave-loving troglophiles feel right at home in the moist, stable underground ecosystem. And even though they could survive on the surface, they prefer the conditions below. Some of these include frogs, toads, salamanders, spiders, and snails. The ecologically important trogloxenes are the main source of nutrients entering many Central Texas caves. These part-time cave dwellers include mammals such as raccoons, opossums, bats, and the biggest contributor, though smallest in body size, are cave crickets. Large groups of roosting cave crickets provide abundant nutrients from their eggs, their bodies, and from their droppings which grow fungus and bacteria that feed other cave organisms such as springtails, snails, and millipedes. The cave obligate troglobites have become so adapted to the stable, near 100 percent humidity environment, that they can no longer survive on the surface. Some of their adaptations include slower metabolism and longer lifespans than their surface relatives. Other adaptations are loss of eyes and pigmentation, elongation of legs and antennae, and increased vibratory and olfactory senses. These include troglobitic harvestmen, millipedes, pseudoscorpions, and spiders. In cave streams, pools, and the aquifer live the stygobites, the obligate ground water fauna.

Collaboration in Karst Knowledge Session

Chair: Devra Heyer

Cavers and Karst Scientists: The Bridge to the Underground

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Abstract
Several centuries of karst research support the idea that appropriate management, protection, and research of karst landscapes require a holistic, karst-specific approach. It is also widely understood that karst-specific scientific knowledge is not necessarily attained by common geological or hydrological studies. Nonetheless, karst-related positions within the public and private sectors are often occupied by scientists with very limited knowledge, training, or experience in karst science. Such individuals are often willing to learn from and collaborate with the cave and karst community. However, if the willingness to learn is absent or the network of karst specialists is unknown or inaccessible, then a significant knowledge gap may persist, reducing our understanding of karst resources and hampering efforts to protect them. Such issues can be mitigated by proactively cultivating a practice and culture of collaboration between the karst community and various stakeholders.

Two cases illustrate the effective inclusion of cavers and karst scientists into decision-making and evaluation of karst resources on public lands. Cavers and karst scientists are collaborating with the United States Forest Service to survey caves and karst in the Bridger-Teton National Forest. Beneath Virginia's Jefferson National Forest, cavers are working with paleontologists from state, federal, and private sectors to extract an intact Pleistocene cat skeleton from a remote vertical cave. In both cases, effective communication between collaborators helped prevent the alienation of project partners that could have resulted in detrimental impacts to both the research projects and the already vulnerable cave and karst resources.

Introduction
Karst terrains constantly amaze us with their complex and unpredictable behavior (White, 1988; Ford and Williams, 2007; Palmer and Palmer, 2009; Stevanović, 2015). After over 200 years of studies (Gams, 1974; Shaw, 1992; Krešić and Stevanović, 2021), we still cannot generalize most gained knowledge to be broadly applicable on various karst terrains and landscapes (Urich, 2002; van Beynen and Townsend, 2005; Ravbar, 2007; van Beynen, 2011; Goldscheider, 2012; van Beynen et al., 2012; Kosič Ficco and Sasowsky, 2018; Jiménez-Madrid et al., 2019; Kosič Ficco, 2019; Younos et al., 2019) There are two main groups of people that unceasingly focus on karst and improve our understanding of its peculiarities. The first one is project cavers. In this study, the term caver is used to describe a group of people that are experienced in cave exploration, surveying, and mapping. Most project cavers understand how to use geological and hydrological data to predict where caves might be located. They are knowledgeable in aerial imagery and LiDAR analysis to identify potential cave entrances, springs, and sinking streams. They are skilled in evaluations to locate these features in the field and use technical exploration methods such as the Single Rope Technique (SRT). The other group is the karst scientists. The term karst scientist, in this instance, refers to a person who is skilled in karst-specific scientific techniques. In addition to the classic type of studies about karst, karst scientists increase their understanding of karst

phenomena through scientific investigations on karst terrains. They continuously contribute to the knowledge about karst hydrology, geology, geomorphology, biology, and other branches of karst science, including caving and resource management.

It could be perceived that all cavers are karst scientists and vice versa. However, many cavers have a limited understanding of karst geology, hydrology, biology, and karst phenomena. Similarly, in some instances, karst scientists do not have extensive technical caving skills and rely on partnerships with cavers for safe access to caves, one of the best karst laboratories that a scientist can find.

To properly evaluate karst in a particular area or landscape, we need to understand the general characteristics and functioning of karst and, among other things, the local geology and hydrology. Additionally, anthropogenic elements, such as land use, ownership, and management of the area in focus, need to be considered and included in the evaluations (Ravbar, 2007; van Beynen, 2011; Kosič Ficco, 2019; Kosič Ficco et al., 2019). Hence, appropriate knowledge of karst functioning and its interactions with other terrains is fundamental. The geologic and hydrologic peculiarities of karst terrains make it difficult for the typical geologist or hydrologist untrained in karst processes to properly evaluate and manage these areas. Yet, karst-related positions at federal, state, and local governmental levels and in public and private practice are often occupied by scientists with very limited knowledge, training, or experience in karst science. These limitations can result in the person in charge placing too little or too much emphasis on the importance of specific karst features or failing to prioritize the relative importance of multiple karst features. Such behavior can result in some karst terrains and phenomena being overly protected or emphasized, while others of equal or greater significance are entirely ignored. Although excessive protection can be seen as a positive approach, it can have severe shortcomings in the long-term management of the karst features and landscapes. For example, suppose all caves, even shelter caves with no significant hydrological, geological, or other important aspects, are deemed significant and/or protected. In this case, the public and other stakeholders might not differentiate between those caves that do include critical resources and those that do not, and as a result, underestimate the value of those that are demonstratively significant. This scenario might also result in misunderstanding the importance of systematic survey and exploration of such caves. Additionally, designating all karst terrains as uniquely and entirely vulnerable and attempting to prevent development on such landscapes can have significant economic and social implications, leading to the dissatisfaction of the communities and intentional non-abidance of implemented protection (Kosič Ficco, 2019).

On the other hand, if we are not aware of the karst surrounding us, we cannot correctly assess and protect the resources karst offers. In such situations, people might exploit karst resources, especially karst aquifers, with little to no knowledge of recharge areas and processes, with correspondingly few and ineffective protective measures.

There are multiple examples, provided by karst scientists and cavers, of how different approaches to karst management are impacting the environmental, economic, and social aspects of communities worldwide. In many cases, karst protection and economic development can be compatible (Knez et al., 2011, 2012, 2015; van Beynen, 2011; Krešić, 2013). While some land managers choose to ignore such important lessons, and the knowledge that can be provided by the karst scientists and cavers, many are willing to learn from and work with the karst science and caving communities. By looking at successful examples of such cooperation, we can understand the benefits of these collaborations, and the shortcomings from the lack of such actions.

The two examples in this paper present different aspects of interdisciplinary teamwork on U.S. Forest Service (USFS) lands. The first is a project performed in the Bridger-Teton National Forest, where local USFS employees sought knowledge from the caving community to help them systematically survey and explore karst of the Bridger-Teton area. The second example is a collaborative project among karst scientists of the Virginia Department of Conservation and Recreation's Natural Heritage Program, members of the Cave Conservancy of the Virginias, paleontologists from the Virginia Museum of Natural History and Science Museum of Minnesota, and local project cavers, which enabled the extraction of a fully preserved Pleistocene cat skeleton from a remote and challenging technical cave.

I. Bridger-Teton National Forest Karst Surveys

Study Area

The Bridger-Teton National Forest (BTNF) extends over 13,700 km^2 in the Wind River, Gros Ventre, Wyoming, Salt River, Teton, and Absaroka mountain ranges. Karstified rocks underlie 1,275 km^2 of the BTNF (Thomas et al., 2021). Currently, karst evaluations and surveys are being performed in the Gros Ventre Wilderness Area and the Wyoming Mountain Range (Figure 1). Both areas consist of alpine karst, where cave-forming limestones are exposed at an elevation of 2,000 - 3,000 m (Medville et al., 1979).

The predominant cave-forming bedrock units in the study areas are limestones of the Mississippian Madison Group (Palmer and Palmer, 2009), followed by the Cambrian Death Canyon Limestone (Hill et al., 1976). Other cave-forming units in the region are the Mississippian Lodgepole Limestone and the Ordovician Bighorn Dolomite. All of these formations are part of an over 1,000 m thick sequence of carbonate rocks. For detailed stratigraphy of the area, see Medville et al. (1979) and Blanchard et al. (1991).

The area is characterized by extensive limestone pavements, karren, sinkholes, sinking streams, swallow holes, and caves (Keefer, 1963; Medville et al., 1979; Thomas et al., 2021). There are several significant caves and karst features known in Wyoming, including Great Expectations Cave in the Big Horn Mountain Range and Columbine Crawl in the Teton Range. These are challenging alpine caves and two of the deepest caves in the U.S. Many notable springs have been identified, such as the large periodic karst spring near Afton, which is the primary water source for the town of Afton situated in the foothills of the Salt River Range (Figure 1). There are also several documented sulphuric and ice caves in the state.

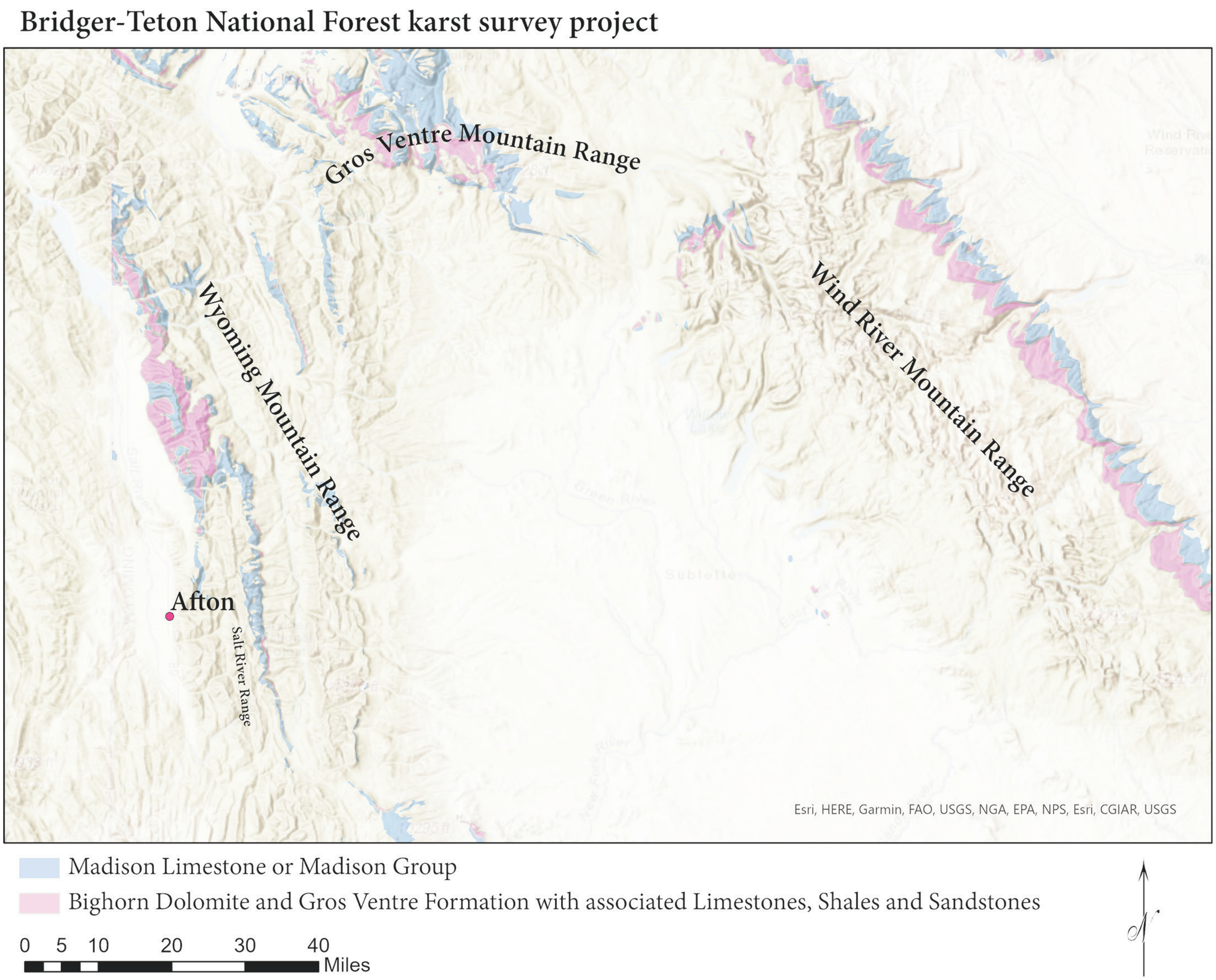

Figure 1. Approximate extent of the exploration areas in the Bridger-Teton National Forest with simplified geology.

Very few hydrological and karst studies have been performed in the BTNF (Medville et al., 1979; Blanchard et al., 1991). Previous authors describe the Gros Ventre karst as primarily characterized by karst fissures, sinkholes, sinking streams, sub-surface water flow, and dead bottom pits, with no apparent access to more extensive caves (Keefer, 1963; Werner, 1974; Palmer and Palmer, 2009). Even less is known about the karst of the Wyoming Range. Caves and karst from the Gros Ventre and Wyoming ranges were initially explored and described by Charlie Plantz and Doug Medville in the 1970s (Hill et al., 1976; Medville et al., 1979).

The hydrology in both exploration areas is characterized by surface streams, swallow holes, sinking streams, and extensive groundwater systems. The sites are characterized by autogenic and allogenic recharge, impacting karst development on different surfaces (Medville et al., 1979). The extent of groundwater systems can only be based on the field observations and cave explorations performed during the project. Existing tracer tests are very limited in the area and are mostly connected with the periodic spring in Afton (Blanchard et al., 1991).

Systematical Karst Surveys in the Bridger-Teton National Forest

In 2017, a seasonal employee for the BTNF-Pinedale Ranger District, Robin Thomas, with a geology degree, became interested in the karst of BTNF and realized that the vast karst terrains have had minimal karst exploration. To assure systematic and appropriate karst-specific evaluations, she contacted the National Speleological Society to find experienced cavers willing to assist and consult on the project. Two skilled cavers, Philip Schuchardt and Pete Johnson, with experience in karst science, volunteered to join the team, and the project was underway.

The first step was to perform geological and hydrogeological analysis using existing publications about the area, followed by aerial and LiDAR imagery analysis. These studies helped determine a few areas in Gros Ventre and the Wyoming Range where preliminary field evaluations were performed. Once these areas were identified, the team recruited volunteer cavers and karst scientists from various U.S. states to help with the project.

The team performed field evaluations included ridge walking and drone studies. All significant karst features observed, including caves, springs, and sinking streams, were recorded and described during field evaluations. If a cave were discovered, a team would enter the cave and start surveying and mapping. Survey trips included rigging the cave's vertical component, measuring the cave, and drawing a cave map while continuing exploration, meaning the explorers needed to be skilled in all these caving techniques.

The USFS employees associated with the project had limited previous caving or surveying experience. (Figure 2). However, they could provide extensive knowledge about the geology and hydrology in the area. Since karst terrains vary greatly depending on the location (Ford and Williams, 2007; Kosič Ficco, 2019; Stevanović, 2019), knowledge about local hydrogeological characteristics is extremely important. On the other hand, the volunteer cavers and karst scientists taught and explained alpine-style SRT and rigging, cave surveying and mapping, and the basics of karst science to the rest of the team (Figure 3). Additionally, they helped shape a management plan for the significant caves and karst resources.

Karst scientists encouraged subterranean biology inventories, taught biological sampling techniques,

Figure 2. Mike Ficco, a Virginian caver and karst scientist, teaching Brad Ellis, a USFS intern, cave mapping techniques (photo: Katarina Kosič Ficco).

processed biological samples, helped identify taxonomists to examine specimens, and assisted in groundwater tracer tests.

Both project areas are at high altitudes and characterized by strenuous and challenging alpine terrains that require considerable mountaineering and caving skills and solid physical preparation. Additionally, such a project requires an extensive amount of equipment. Some of the gear and volunteers' expense reimbursement were provided by the USFS. Volunteers, who took time off work or worked remotely while exploring during the weekends, contributed a significant amount of personal gear in addition to their time.

The project could never be successful without cooperation among cavers, karst scientists, and the BTNF staff. While the cavers and karst scientists enabled appropriate and safe karst evaluations by providing their expertise, the USFS involvement was crucial. Not only did they give permission to perform exploration on USFS land, but they also ensured that gathered data are appropriately processed and conservation-minded management of the caves and karst is ultimately implemented. In addition, Forest Service staff continue to work with other departments to ensure exploration and inventories can continue and are performed consistently and safely. A great example is surveying in the Gros Ventre Wilderness.

In the Gros Ventre Wilderness, no permanent structures or mechanical devices are allowed. Therefore, cavers have had to use traditional removable climbing gear (e.g., cams and chocks) to rig and assess the potential of found caves (Thomas et al., 2021). This prohibition of fixed rigging hardware significantly limited the safe access to the caves for inventory and exploration. The majority of cave entrances in the area are vertical shafts in loose, often frost-shattered rock, thus requiring complicated anchor-building techniques to gain initial access. In addition, exploration beyond the entrances shafts was often prevented because

Figure 3. Mike Ficco assessing a sinking stream disappearing into glacial deposits (Photo: Katarina Kosič Ficco).

such climbing gear could not be used deeper in the cave due to a lack of fissures for anchoring the gear. In 2021, the continued exploration and inventory of the caves was made possible through the persistent involvement of the USFS employees who worked with Wilderness managers and caver volunteers to obtain a bolting permit for the area. This permit established a suitable set of guidelines for limited, removable bolting activities so that exploration can continue safely while the spirit and regulations of the Wilderness Act are still respected.

Five years of systematic surveys in the Gros Ventre and Wyoming mountain ranges, and successful cooperation among numerous stakeholders, have revealed over 54 caves and multiple large springs. Among them, three caves are still going, and some have already proven to be highly significant.

II. Paleontological Project in Lee County, Virginia

Background and Study Area

Southwestern Virginia is home to numerous significant karst resources. Examples include the Omega Cave System, the longest cave system in Virginia and the deepest cave system in the Eastern U.S. (Schwartz, 2019), and The Cedars State Natural Area Preserve. The preserve encompasses all documented caves and springs from which the federally endangered Lee County cave isopod (*Lirceus usdagalun*) is known. Significant caves and karst in southwestern Virginia are developed in Cambrian, Ordovician, Silurian, and Mississippian carbonate rocks.

The Omega Cave System occurs in the Mississippian-aged Greenbrier (aka Newman) Limestone. The Greenbrier Limestone is approximately 150 m thick and mainly crops out on the steep scarp slope faces of Powell, Cliff, Stone, and Cumberland mountains, which collectively rim the Powell Valley (Schwartz and Orndorff, 2009; Schwartz, 2019) (Figure 4). Hydrologically, the area is characterized by surface streams, karst springs, and losing streams.

Since discovering the Omega Cave System, cavers have been searching for other, similar caves as many of the surrounding mountains share the same geology and potential for another long and deep cave. In 2016, Mike Ficco and Katarina Kosič Ficco discovered a cave entrance with the potential to lead to such a cave. The cave, also located in the Greenbrier Limestone, was named Burja Cave (Figure 4), after a Mediterranean wind, due to extensive air movement through the cave's passages. Burja Cave proved to be highly challenging due to its vertical extent and vast mud accumulation. Nevertheless, it also presented several important resources, including a new species of cave beetle (*Pseudanophthalmus sp.*) and the nearly fully preserved skeleton of a large feline found on the third exploration trip in the cave. The skeleton was mostly buried in the mud and only evident from specific angles (Figure 5). This cave is located in the George Washington and Jefferson National Forests.

Cavers established a good relationship with the District Ranger and Wildlife Biologist of the USFS Clinch Ranger District during the exploration of the Omega Cave System. This relationship has enabled the Clinch Ranger District to inventory and characterize karst resources on their land and ensure that appropriate karst and cave exploration and management approaches are implemented. Cavers have provided the labor and expertise for identifying and exploring caves in the National Forest, continuously informing the District of their discoveries, and educating the local community about the importance of caves and karst resources. This relationship between the USFS and the cavers was an essential factor in the success of the ongoing study of the feline skeleton.

Petra Project

Cavers discovered the skeleton on their third cave survey trip in Burja Cave. After observing the bones, the cavers appropriately delineated the skeleton with rocks and flagging tape. On their next trip, they took numerous photos, and Dr. Joe Myre developed a 3D model of the skeleton to share with paleontologists and USFS personnel. The team developed a strong attachment to the fascinating finding and decided to name it Petra. The name was chosen in honor of Petra Domajnko, a dear friend of Katarina and Mike Ficco, and because the name is derived from the Greek word "πέτρα" (pronounced Petra), meaning stone or rock.

Then the search for a paleontologist began. The skeleton was located approximately 400 m into the cave and 30 m below the elevation of the entrance. Despite the shallow depth, the approach is highly technical due to the cave's character, and whoever wanted to access the skeleton had to have extensive SRT experience. After realizing that paleontologists with appropriate SRT knowledge are rare in the U.S., the cavers decided to find a paleontologist that would be willing and strong enough to learn appropriate caving skills to evaluate and potentially excavate the skeleton.

During a separate cave paleontological project in another area of Virginia, Katarina Kosič Ficco met Dr. Alex Hastings of the Virginia Museum of Natural History.

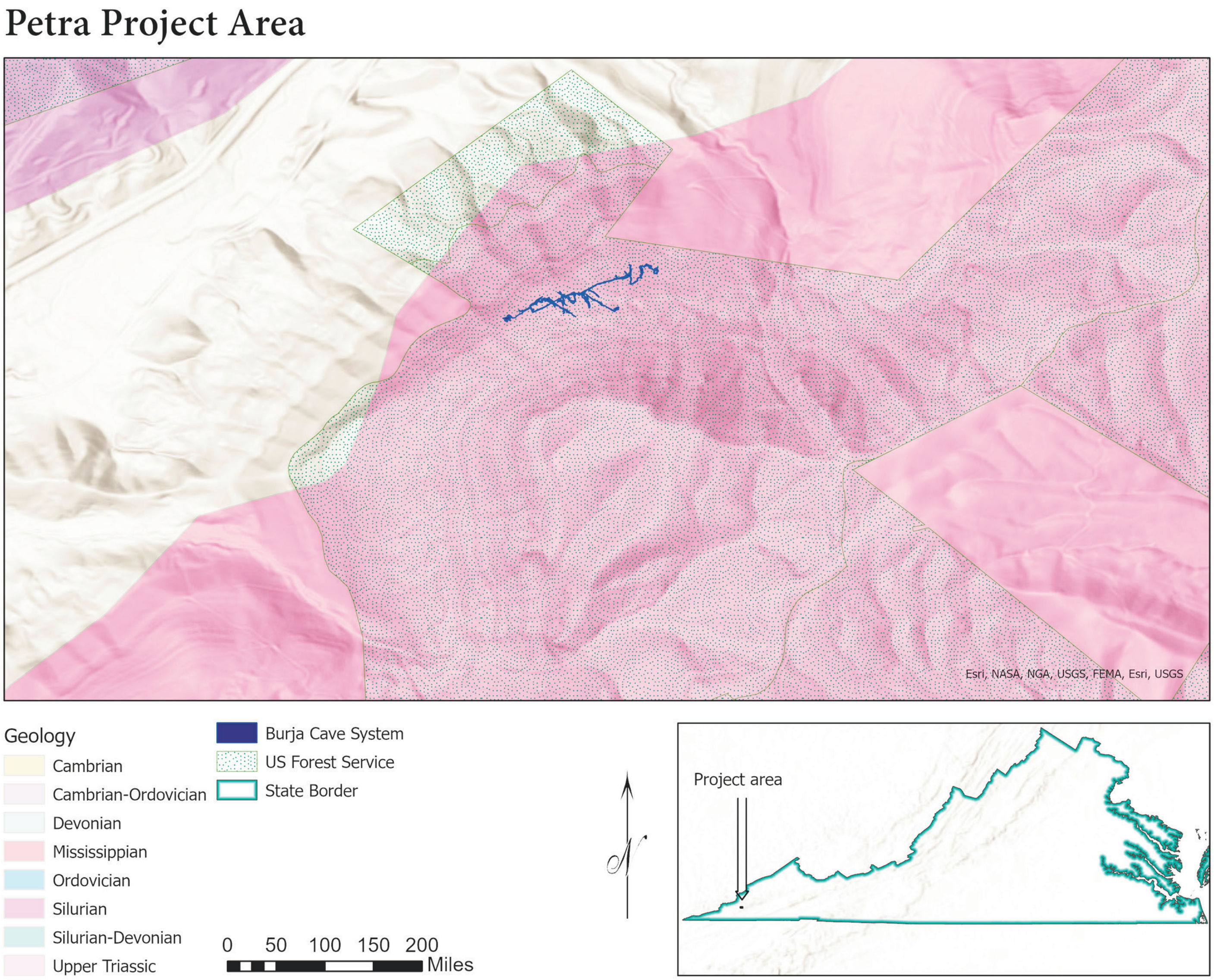

Figure 4. Paleontological project area with the Burja Cave footprint and simplified geology.

Based on photographs, Dr. Hastings was intrigued by the discovery and determined that even without a positive species identification, this finding was significant enough to warrant excavation and preservation/study. He immediately began intense and extensive caving training, performed by Mike Ficco (chairman of the Cave Conservancy of the Virginias) and Katarina Kosič Ficco. Training included learning SRT basics on a tree and in a local quarry, followed by visiting several complex vertical caves, including the Omega Cave System. High motivation and an appropriate mindset enabled them to conclude with the necessary training after visiting 5 caves.

In the meantime, the Cave Conservancy of the Virginias (CCV) began the process of obtaining the necessary permits and permissions to proceed with the project. The permitting process involved state and federal agencies, including the Virginia Department of Conservation and Recreation, Division of Natural Heritage (VDCR-DNH), and the USFS. Upon receiving the USFS paleontological permit, funding and support from various organizations were secured. The CCV allocated a grant to finance the materials and a portion of the transportation costs. Dave Socky, a CCV board member, agreed to provide videography for the project. VDCR-DNH provided lodging at nearby Natural Tunnel State Park as well as the labor for the entire Karst Program and helped to identify caver volunteers. The Virginia Museum of Natural History agreed to be the curator for the bones, and Dr. Hastings' current employer, the Science Museum of Minnesota, supported his continued participation in the project.

After postponing the excavation several times due to the COVID-19 pandemic, in the early fall of 2021, a team of 11 cavers, including paleontologist Alex Hastings, finally entered the cave and extracted the skeleton. Since cavers

Figure 5. Dr. Alex Hasting climbing into the room with the skeleton. Can you find the cat? (photo: Katarina Kosič Ficco).

did not have enough experience to assess the quality of the bones, Alex had to develop several alternative plans to address all potential scenarios. As it usually happens with such projects, none of the prepared scenarios worked completely as planned, and the team had to improvise with the excavation techniques and packaging of the fossil material (Figure 6).

Nevertheless, the team successfully excavated and extracted the skeleton in two intense days in the cave (Figure 7). The cavers and karst scientists also learned basic principles of fossil excavation techniques and how to assess bone stability (Figure 6). The gained knowledge will help them assess any potential future findings, making it easier for a paleontologist to prepare for and perform excavations.

Cooperation and the Importance of Cave Communities and Karst Scientists

By looking at successful cooperative projects in the field of caves and karst, we can see how specific entities can bring a vital element into karst and cave management and protection. In the cases presented above, the government agencies contributed:

- Knowledge about the area's geology and hydrology,
- Understanding and managing the administrative aspects of exploration and field surveys performed on governmental lands,
- Access to the lands,
- Personnel for field activities,
- Financial and in-kind resources for exploration and scientific studies,
- Long-term management and protection of the resources.

On the other hand, the caving community and karst scientists:

- Performed background studies of the areas of interest,
- Defined the previous extent of the karst exploration,
- Defined the areas that should be evaluated,
- Performed karst-specific geological, hydrological, and biological studies,
- Informed land managers of habitats in the caves and made suggestions for their protection,
- Systematically surveyed these areas and inventoried karst features,
- Surveyed and explored newly discovered caves,
- Taught governmental employees the necessary caving skills and scientific methodologies, enabling them to perform cave and karst studies independently in the future,
- Provided necessary gear or advised on gear procurement,
- Transported necessary gear to the location,
- Engaged other stakeholders that might contribute to the project,
- Assisted in the development of management plans for discovered resources,
- Developed GIS maps, cave maps, and reports of their findings and shared them with the involved entities,
- Cooperated with other stakeholders to ensure successful completion of the project,
- Most commonly assisted as volunteers.

There are some challenges for successful collaboration between the caver/scientist community, governmental institutions, and land managers. One example would be the often complicated issue of data sharing and differing

Figure 6. Dr. Alex Hastings, a paleontologist, and Dr. Zenah Orndorff, a Virginian caver, excavating the skeleton (photo: Katarina Kosič Ficco).

Figure 7. The successfully excavated skeleton (Photo: Katarina Kosič Ficco).

philosophies and mandates for what data should be public versus private. However, this and other challenges can typically be overcome through thoughtful discussion and problem solving among the participants, and the benefits of collaboration greatly outweigh the effort needed to reach an agreement on these issues.

Conclusion

It is commonly known that karst requires a holistic approach for proper study, protection, and management (Goldscheider, 2012; Kosič Ficco, 2019). Now it is time to extend the holistic approach beyond the scientific methods. The more examples one looks at, the more it is evident that only through cooperation and inclusion can karst be adequately protected and managed (Kosič Ficco and Sasowsky, 2018). Each entity contributes significantly to the final goal, but the fact is that cavers and karst scientists are the core of the process. They are the ones who have dedicated their lives to studying, exploring, and learning from the caves and karst, and they are often the ones with the most knowledge of the local karst. They are generally eager to share their knowledge with everyone interested in karst, and they spend endless hours documenting it through various organizations, presentations, and publications. Plus, they often do this voluntarily, making their inclusion in the process both time and financially efficient.

Agencies such as the VDCR-DNH Karst Program, who are aware of this resource and do not hesitate to use it, are the ones that can confirm that without the inclusion of these entities, not only the karst resources would not be protected; but also the public, environmental, and economic development interests would suffer. So let's start accounting for them and their knowledge, and by including them, ensure that the protection and management measures we develop are based on the latest knowledge and information the karst scientists and caving community can provide for us.

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Optimizing Cave and Karst Management Through Collaborative Outreach

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Abstract
What can organizations do to optimize cave and karst management and outreach efforts? Synergistic collaborations provide opportunities to leverage resources to enhance and expand community engagement. We will explore the opportunities and challenges which exist when nonprofits and government agencies work together, share best practices that we have developed, and highlight examples of how partnerships offer a model for others to more effectively manage karst resources and engage the public in conservation. We will provide an overview of our Cave Collaboration Committee, which consists of representatives from multiple City departments, state agencies, caving organizations, and local cave managers. Members from each of these stakeholder groups met to address their concerns and operational needs; first forming a simple agreement about training requirements for guides and total numbers of visitors to each cave per year to minimize the impact on caves with endangered species as we increase the number of educational tours. The collaboration quickly evolved into a way of organizing annual training for interpretive guides and teachers in cave biology, geology, and safety. The partnership continued to yield more collaboration, including the reintroduction of large-scale public education efforts like the Austin Cave Festival (with over 3,000 participants), art projects, cave rescue training, and shared educational resources. In just a few years, previously unconnected cavers and land managers from across the city developed much closer relationships and coordination, resulting in improved protection of endangered species habitat, more meaningful and informative cave visits for the public, and stronger emergency action plans.

Introduction
What can organizations do to optimize cave and karst management and outreach efforts? Synergistic collaborations provide opportunities to leverage resources to enhance and expand community engagement. We will explore the opportunities and challenges which exist when nonprofits and government agencies work together, share best practices that we have developed, and highlight examples of how partnerships offer a model for others to more effectively manage karst resources and engage the public in conservation.

One major way that we engage the public is through youth education programs that focus on caves, springs, water quality, and our local endangered karst-dwelling species. The City of Austin Watershed Protection Department offers several youth education programs, including Earth Camp and Earth School (for fifth graders), Watershed Detectives (for middle school), and Hydrofiles (for high school). Earth School provides hands-on presentations on school campuses that involve the students in conducting experiments with aquifer and watershed models to see how water and pollution can travel across the watershed and through the aquifer. Earth Camp, Watershed Detectives, and Hydrofiles give students the opportunity to explore caves (Figure 1), discover local cave critters, and see firsthand how water enters the aquifer as they directly observe a droplet of water on a stalactite. The students follow the journey of water through the Edwards Aquifer to Barton Springs, where they learn about Austin's endangered and endemic Barton Springs Salamander (*Eurycea sosorum*) and Austin Blind Salamander (*Eurycea waterlooensis*), how our actions on the land affect water quality, and what they can do to be good environmental stewards (Figure 2).

Collaboration has been key to the success of these youth education programs. Partnering organizations, including the Texas Cave Management Association, the University of Texas at Austin Lady Bird Johnson Wildflower Center, and the City of Austin Parks and Recreation Department, provide access to caves that enable students the opportunity to go underground and foster their appreciation of the fragile karst ecosystems that we live upon. These and other collaborating organizations have also made it possible to provide engaging field experiences to large numbers of students. Many of the caves in Austin that are used for education are small and only accommodate 15 participants at a time, but middle school groups often request a field experience for an entire grade level, which might be a hundred students or more (Figure 3). Through working with collaborating organizations, we are able to divvy the students up into groups (around 15 students per group)

Figure 1. Watershed Detectives middle school students exploring a cave.

and rotate the groups through stations that include cave exploration as well as surface stations that focus on topics related to the recharge zone, cave habitat, and groundwater issues (Figure 4). For more information about the City of Austin Watershed Protection Department's Youth Education programs and resources, see www.austintexas.gov/watershed/YouthEd.

Figure 2. Watershed Detectives middle school students learning about endangered salamanders at Barton Springs.

Other departments included karst environments in summer camps, and with so much use of local cave resources, cave biologists expressed worry that camp and recreational use might be damaging habitat for endangered cave invertebrates. Educators argued that if you want the public to care about caves, to feel connected to these habitats, people had to be able to experience them. This challenge emerged in Austin over ten years ago and, with input and effort from many different stakeholders, resulted in multi-agency collaborations to more effectively manage karst resources and engage the public in conservation. Specifically, we'll discuss the Cave Collaboration Committee that was formed: its stakeholders, primary concerns and needs, and outcomes such as the Austin Cave Festival, art projects, trainings, and shared educational resources.

Figure 3. Middle school students on a Watershed Detectives field trip at the Lady Bird Johnson Wildflower Center.

Figure 4. Middle school students conducting water quality tests with a hydrogeologist to compare surface water and groundwater.

Faced with the question, "How can we engage people in protecting cave resources without damaging them?" this is our answer! What began as a scheduling conflict and concern over messaging quickly became a robust partnership. Members of the Cave Collaboration Committee include City of Austin staff from many departments, a state agency, a university, and key nonprofits that protect and study caves. Departments from the City of Austin, including Parks and Recreation (involving the Austin Nature and Science Center, Camacho Activity Center, and Park Rangers), Austin Water Wildland Conservation, and Watershed Protection, collaborated with the Barton Springs Edwards Aquifer Conservation District, the University of Texas at Austin Lady Bird Johnson Wildflower Center, the Texas Cave Management Association, and the Underground Texas Grotto (Figure 5).

The Cave Collaboration Committee's goals are to both educate the public AND protect caves through agreeing on access to caves, standard operating procedures and safety protocols, fact sheets for commonly visited caves, and shared goals for outreach events. We collaborated about how to increase educational tours while minimizing impact on caves with endangered species through the adoption of standardized cave guide training with an emphasis on cave biology, hydrogeology of the Edwards Aquifer, and cave safety taught in a blended classroom/ cave environment (Figure 6). The Cave Collaboration Committee formed agreements about the number of visitors that each cave could sustainably welcome as well as training requirements for guides and annual training for educators and camp counselors in temporary roles.

One major outreach outcome from this successful collaboration was the renewal and expansion of the Austin Cave Festival. This free, family-friendly event welcomed Austinites to learn more about the world beneath their feet and engaged over twenty community organizations to help tell stories of biodiversity, geologic history, and cave heritage. From the local chapter of the Sierra Club, to the crawl-through educational CaveSim (www.cavesim.com), and from environmental consulting companies to the US Fish and Wildlife Service, the organizations brought an incredible breadth and depth of knowledge to share. Participants were able to see bats and endangered salamanders up close (see Figure 7), use a virtual reality (VR) headset to tour a cave (Figure 8), hike to a sinkhole, or don a helmet and go underground in small groups (Figures 9a and 9b). The wide spectrum of activities lent to the inclusivity of the event with talks geared towards adults, a kids' art cave to decorate with hand-drawn cave bugs, a climbing tower to try vertical skills (Figure 10), and live music for all to enjoy. Local experts gave talks on wastewater management over the aquifer, karst invertebrates, the National Speleological Society, surface-groundwater interactions, and more. Science and art intermingled with murals of cave scenes and paintings of local cave dwellers decorating the exhibit hall walls.

The introduction of virtual caving using VR headsets (Figure 11) and a 3D aquifer tours (Figure 12) was a great way to inclusively connect a diverse community with the underground world. These technologies helped increase access to cave exploration by providing those who were not able to (or did not want to) go into a cave for various reasons (e.g., they were nervous about being underground in a small space, they had small children with them, or they had mobility issues) an opportunity to explore the cave ecosystem while remaining on the surface. If you would like to go on a virtual tour of one of Austin's caves, check out http://www.atxwatersheds.com/VR-CaveTours/ - /. Another cool example of a technological innovation we used to engage the public was an augmented reality bat that flew out of the Austin Cave Festival stickers when viewed with a phone app (Figure 13), which also linked to the event map and website.

The height of the fun was experiencing a cave habitat alongside biologists, geologists, and educators. Participants signed up to cave and received a sticker to show their tour time and specific cave. Before going in, volunteers helped them with helmets as staff shared background information about hydrogeology and biology with the captive audience (Figure 14). For an exceptionally fun, activity-filled day that reached several thousand community members, the lasting impact of this effort was on the caving community. Several visitors joined the local grotto and others even began to work in cave restoration projects on conservation lands nearby.

A big festival isn't the only way to do this. Apart from the festival, we work with the caving community to host trainings for teachers and rangers, organize guided hikes and online resources, partner with artists and filmmakers, and occasionally break in a new volunteer digger. Here are a few examples of how inviting new audiences into the caving community yielded more collaboration:

- Volunteers not only helped to make the 3,000-person Austin Cave Festival happen, but the festival also introduced new volunteers to opportunities to lead guided hikes, participate in ecological restoration, and support research and monitoring on cave conservation lands.

Figure 5. Many of the members of the Cave Collaboration Committee celebrating Education Cave Restoration Day.

Figure 6. Cave guides from several City of Austin departments learning about cave habitat and the hydrogeology of the Edwards Aquifer from experts.

Figure 7. A salamander biologist shows Austin Cave Festival participants Austin's three endangered salamanders.

Figure 8. A child becomes immersed in a Virtual Reality Cave Tour.

Figure 9a. Families and friends enjoyed caving together at Austin Cave Festival.

Figure 9b. Austin Cave Festival participants exploring the underground world.

Figure 10. Children climbing to new heights on CaveSim's vertical tower.

Figure 11. Virtual Reality Cave Tours increase access to cave exploration.

- We work together to offer other opportunities for the public to go caving and learn about cave habitat, the aquifer, and springs at other free, family-friendly events such as Nature Nights at the Lady Bird Johnson Wildflower Center (Figure 15).

- We host an annual cave rescue training for 120 firefighters across 27 distinct units of the local fire department. The first responders get access to caves to conduct mock rescues and receive a brief overview of karst habitat from cave biologists.

- Another outlet for community engagement is through online resources. We can't take everyone caving…and not everyone is keen on getting into a cave. Online resources like this storymap (www.austintexas.gov/caves) help provide information to a wider audience. The storymap has links to videos of karst invertebrates, online lessons, and interviews and webinars with experts.

- Nerd Nite Austin, a local nonprofit that hosts monthly talks on nerdy topics asked us to curate

Figure 12. A 3D Tour of the Edwards Aquifer is fun for all ages.

Figure 13. Augmented Reality bat flying out of Austin Cave Festival sticker

speakers for an Austin Cave Festival edition of their event each year. This reaches a new audience that is eager for reports on scientific research, but usually new to environmental topics in Austin.

- In 2018, Alamo Drafthouse owner Tim League suggested that we schedule the Austin Cave Festival talks at his Slaughter Lane location, which happens to have a cave beneath it. This created opportunities for other Austin Water Wildland documentary screenings at Drafthouse theaters, again reaching new audiences with stories of karst landscapes.

- An artist who came to the cave festival was excited to see a Western Slimy Salamander (*Plethodon albagula*) and some "neato" cave crickets for the first time - to even think about cave habitat - which inspired him to include cave species in his next children's book.

The outreach to the public starts to be exponential when we invite in new people and new ways of telling a story. In our story, previously unconnected cavers and land managers from across the city developed much closer relationships and coordination, resulting in improved protection of endangered species habitat, more meaningful and informative cave visits for the public, and stronger emergency action plans. Over the years, this group of stakeholders has enjoyed the fruits of many collaborations. We've developed best practices for working together across agencies to engage people without damaging cave resources. The major tools of this longstanding collaboration include agency/organization agreements, public education events, training, and the creation and use of online resources.

Figure 14. A hydrogeologist provides an introduction to Austin's cave heritage before participants explore the underground world.

Figure 15. Young explorers enjoyed a wonderful caving adventure during Nature Nights at the Lady Bird Johnson Wildflower Center.

Shake, Rattle & Roll: Instigating a Cultural Shift in NPS Cave and Karst Management

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Abstract
Cave management has been and still is an evolving field across the country and worldwide. The same is very true within the National Park Service. Each new NPS National Cave and Karst Program Coordinator (NCKPC) adds their personal spin, while keeping true to the original purpose of protecting, conserving, and promoting our cave and karst national treasures.

I'll discuss the challenges I face on a weekly basis addressing the lack of knowledge, missing information, and the need to reach out to the caving community to find out about NPS cave and karst resources. These challenges forced me to reevaluate my thinking about how cave and karst resource data is managed as well as recognizing the need for a massive cultural change in the thinking of the NPS cave and karst community. A conceptual framework has been developed and is in the process of being implemented. As the NCKRI Director of Cave and Karst Management Sciences, I see the beginnings of a new chapter in how the "Feds" manage cave and karst resources data.

The Federal Cave Resources Protection Act of 1988 stipulated that cave locations may not be made available to the public. In addition, the National Parks Omnibus Management Act of 1998 authorized the NPS to withhold information from the public regarding a FOIA request that could reveal "the nature and specific location" of caves and objects within caves. This information includes, but is not limited to, survey data, surface and subsurface maps, and names of geographic features.

Researchers who are granted permits to conduct work within an NPS cave often sign a confidentiality agreement or it is spelled out within the permit that cave information is not to be shared outside of the scope of the research project. This includes not putting cave locations and names in publications. In most cases, researchers are asked to use the park's cave identification number instead of the name. Researchers include volunteers such as cavers who help with mapping, inventory, monitoring, restoration, and other cave related activities.

Every NPS Unit that has major cave resources keeps its own database of cave information: location, resources within caves, sketches, notes, maps, etc. – or they have an MOU with an outside organization to assist with data organization. This information is not shared with other divisions within the park (unless necessary for a management activity), nor with the region and certainly not at the national level within the park service. It's interesting to note that cave resource offices (CROs) have no problem with volunteers holding sensitive cave information, but don't trust the NPS on a national level to protect that same information. NOTE: The last also applied to myself when I was a Cave Resource Specialist at Lava Beds National Monument.

I was asked, "What about creating a national cave base?" during both the interview and the onboarding processes. Each time I politely commented, "That's an interesting concept, perhaps something to look into in a few years." Mentally, I was thinking, "Not happening, not ever."

Then in the space of two weeks I got four requests for help with cave-related information:

1. Potential cave locations for a paleontological resources inventory at two NPS units without cave resources staff.
2. Request for a potential cave location associated with a spring next to a historic cabin restoration.
3. Request for cave resources information from a park with a cave resources office, but the Cave Resources Specialist had retired, the position hadn't been filled, and no one else at the park was able to provide that information.
4. Request from a Cave Resources Specialist hoping that we had a copy of a valuable research report that

had been misplaced at their office. Unfortunately, we were unable to find a copy of the report.

In the first three cases, I had to reach out to the caving community (thank you CRF and NSS cavers) for the needed information. Since then, I have had several more requests for information in which I had to reach out to the caving community for information.

For NPS units founded for reasons other than caves, and in which caves are not a focus, there is no central location to manage cave data and often little interest in doing so. When the Cave Resource Specialists leave the park service and their position is not filled, there becomes a vacuum in accessing cave resource data. Older cave research reports, data, and maps that are not backed up disappear. All these problems make it difficult to provide adequate help in a reasonable amount of time. Suddenly, the idea of a national NPS cave database wasn't looking so bad after all.

After thinking about the implications of such a database, I met with Jack Wood, NPS cave and karst teammate, and Lima Soto, USFS National Cave and Karst Program Coordinator. We first started with Jack playing devil's advocate to the idea of a central database, and once sure that I could answer all his concerns, we moved forward to review the Forest Service's national cave database. Lima walked us through the database and talked with us about what worked well and what needed improvement. I then presented the idea to my NPS supervisor and from there we have been meeting with a database design team.

Some basic requirements for a national NPS cave database include:

- Only the Cave Resource Specialist and their appointees will have full access to their NPS unit's data.
- The NCKPC (or appointee) will have full access to an NPS unit's data if NO Cave Resource Specialist exists.
- Annual approval and signing of confidentiality agreement by all who access the database.
- Seasonals will have term-limited accessibility – automatic termination of access, unless extended by the CRO.
- The CRO will receive email notification when their unit's data has been accessed.
- WASO will have roll up data by park, state and region for specific information.
- The number of caves, cave types, usage, monitored, Pseudogymnoascus destructans (Pd) https://www.google.com/

Creating a Brighter Future: Teaching Conservation with CaveSim

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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 students to consider careers in science and conservation, and inspires young people to take a stand for conservation. Since 2010, the authors have traveled around the United States with a mobile conservation education program. The authors and their team of staff and volunteers teach K-12 students about conservation of caves, groundwater, and a variety of species including bats and invertebrates. The program has educated approximately 40,000 children in 19 states, and the authors often collaborate with local, state, and federal agencies to bring the program to under-served and rural populations. The authors will share numerous examples of collaboration between government agencies and their organization (CaveSim) with the aim of inspiring future collaborative initiatives. The authors will also illustrate how they have aligned the CaveSim program with state education standards to make it easier to bring conservation education into public schools.

The *Agency Guide to Cave and Mine Gates*, a 12-year History

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Abstract
Before White Nose Syndrome siphoned away all cave conservation funding, a small group of experts was focusing on protecting the most critical bat roost habitats in the United States. Utilizing state-of-the-art cave gate designs and placement based on bat ecology and the study of cave microclimates, this information rapidly became the "industry standard", adopted by the National Park Service, US Forest Service, US Fish and Wildlife Service, The Nature Conservancy, and many state land management agencies. In order to convey those concepts and practices in simple language to the agency folks making the decisions and providing the funding (and writing the RFPs), the most active "gaters" developed the *Agency Guide to Cave and Mine Gates*. New modifications and innovations meant that the *Agency Guide* has been periodically revised, with the latest revision occurring in time to be released at this Symposium.

Introduction

Bat gates have been evolving for many decades, having changed from simple barriers designed to prevent human access to caves and mines, to ecologically-transparent structures that do not impede the movement of air, water, nutrients, and small animals into and out of the cave ecosystem (Dalton, 2004; Elliott, 1996; Hathorn and Thornton, 1987, 1993; Hunt and Stitt, 1975, 1981; Kennedy, 2006; Kennedy and Powers, 2005; Powers, 1985, 1993, 2004; Tuttle, 1977; White and Seginak, 1987). Many materials have been used, in varying shapes and compositions before finally settling on 4″x⅜″ angle iron for accessibility, ease of use, strength, and lack of flight restriction (Dalton, 2004; Kennedy, 2012; Powers, 2004; Vittetoe, 2002; Werker, 2004; White and Seginak, 1987). There have been ample case studies documenting successful protection efforts using these materials and designs (e.g., Anonymous, 1985, 1993a, 1993b, 1995, 1997; Bobo and Greene, 2000). And there have been many studies of bat acceptance (Altenbach and Milford, 1995; Butchkoski, 2010; Currie, 2002; Herder, 2004; Kurta, 2002; Ludlow and Gore, 2000; MacGregor, 1993; Pugh and Altringham, 2005; Sherwin et al*.*, 2004; Spanjer, 2004a, 2004b).

But not all "bat gates" were created equal. It was unfair to compare the success (or lack of) poorly designed and poorly situated gates with those having optimum characteristics. In fact many "bad" gates were eventually replaced with better ones. Around the same time these modern gate designs were being implemented, more attention was devoted to the cave and mine roost characteristics being selected most by the bats, including microclimate (Brown and Berry, 2004; Elliott and Clawson, 2001; Ingersoll et al*.*, 2010; Kennedy, 2004b; King, 2005; Raesly and Gates, 1986; Tuttle and Kennedy, 2002; Tuttle and Stevenson, 1978).

Conservationists also noted that many sites had been already modified by human activities such as saltpeter mining or commercialization attempts, and that pre-existing conditions must somehow be returned for successful bat use (Kennedy, 2004a; Kennedy and Whitney, 2004; Martin et al*.*, 2006; Murphy, 1993; Olson, 1996; Toomey et al*.*, 2002. Parallel efforts were being made in modifying abandoned mines to improve microclimates (Carter and Steffen, 2010; Grol and Voûte, 2010).

The explosion of studies and articles and internet accessibility of the last several decades has resulted in some confusion for the field biologist or land manager not entrenched in the history of cave gate development. General guidelines have been published for local use (Altenbach et al*.*, 2000; Dansby, 1995; Elliott, 2001; Gobla, 1994; Navo, 2001; Olson, 2004; Sherwin et al*.*, 2009; Tuttle and Taylor, 1998; Wilhide and Ash, 2002), but no comprehensive guide was widely available.

Because of this confusion and due to the desire to "train up" additional contactors and land managers, a small cadre of the top bat gate builders in the United States collaborated to plan and teach the first National Bat Gate Workshop. Held near Yakima, Washington for two consecutive weeks in 1997, the workshop focused on classroom lectures in the evenings and hands-on gate construction at Boulder Cave on the Wenatchee National Forest during the day, setting the format for successive workshops. Instructors were the late Jim Nieland, Cave Specialist for the U. S. Forest Service; Bob Currie, Endangered Species Biologist for the U.S. Fish and Wildlife Service; the late Roy Powers, the "Mastergater" and former President of the American Cave Conservation Association; and Jim Kennedy, Cave Resources Specialist with Bat Conservation International (BCI). This workshop was quickly followed-up with similar ones at Gregory Cave in Great Smoky Mountains National Park, and the privately owned Sinnett-Thorn Mountain Cave System in West Virginia. To date, eight such workshops have been held, with the last being in 2011 at Gorman Cave in Colorado Bend State Park, Texas. The retirement of one of the four principal instructors, and the deaths of two of the others, has placed a temporary halt to the series. However, there continues to be a great need for these workshops, and the remaining instructor, Jim Kennedy, plans to restart them once again in the coming years by recruiting additional experts.

The materials used for handouts at these workshops consisted of a variety of reprints, data sheets, and other pertinent material. However, they were only distributed to participants and instructors of the workshops. But another very important and useful publication soon became available, and much more widely distributed. *Bat Gate Design: a Technical Interactive Forum* (Vories et al., 2004) is a 452-page tome that is the result of a discussion group of invited cave and mine gate specialists from across the U. S. who were assigned topics based on their areas of expertise. The free download is no longer available on the internet, but a PDF is available from this author. The *Bat Gate Design* book did not become the bat-gating handbook that was originally envisioned, but it did set a new precedent in consensus standards for bat gates, planning, design, construction, monitoring, alternate designs for special circumstances, and many other gems of information that had never before been published outside of the gray literature.

Two other important cave-gating resources also deserve to be mentioned here. The *Proceedings* of the National Cave and Karst Management Symposia and related meetings have many useful papers and are freely available on the Karst Information Portal. And in 2006, the National Speleological Society published *Cave Conservation and Restoration,* a great resource with many related chapters, including one specifically on cave gates by this author (Kennedy, 2006).

The need for a simple decision-making guide still existed. Kennedy and Jerry Fant, a welder who worked closely with Kennedy on many gating projects, wanted to put together a user-friendly guide for persons with no prior gating knowledge. Building off of William Elliott's *Cave Gating Criteria* (2001) and other sources, they outlined a rough draft and sent it off to Elliott and Roy Powers for comment. The final result was the *Agency Guide to Cave and Mine Gating* (Fant et al., 2009, 2021) and originally released on BCI's website. Since that time, numerous refinements and additions have been incorporated, first in 2012, then 2017, and most recently in 2021 in time for the National Cave and Karst Management Symposium in San Marcos, Texas.

The *Agency Guide* tackles questions such as whether or not to gate, what style of gate is appropriate, where the gate is optimally located, when the gate should be built, and who is the best choice to design and construct the gate. There is a nice decision tree right up front, scaled schematics of gate design details, many photos of completed gates, and good tips on follow-up monitoring and maintenance. There is also a much longer gating bibliography than is included with this paper.

The standard bat gate styles remain from the 2009 edition, including the Basic Gate (a standard vertical angle-iron gate with horizontal bars placed in a horizontal opening), the Half Gate (a Basic Gate open at the top but protected by an overhanging shield, for large gray bat maternity colonies and big cave entrances) the Chute Gate (a Basic Gate with an angled tube extending outward and upward, for maternity colonies with much smaller entrance dimensions), and the Cupola Gate (a box-type gate over a vertical entrance). Later editions added gate variations such as the Window Gate (a three-sided Chute Gate built under an overhanging roof and therefore not projecting upwards from the gate), the Semi-Cupola Gate (built into a hillside or sinkhole, and therefore lacking one or two sides), the Folded Gate (one side and a top, built into a sinkhole), and the Flat Gate (just the top, built over a vertical entrance that is not used by bats but is important for maintaining airflow). Newer illustrations of each gate style were included, mostly from more recent projects. The publication can be obtained for free from the author.

There may never be an all-inclusive Bat Gating Manual. The individual nuances of each cave entrance, management directives, bat usage, access, and so on are just too diverse to cover each eventuality. The best information comes from working with an experienced gate builder on multiple projects. But for those agency folks tasked with making management decisions about a resource they may have little time, money, or experience to deal with, the *Agency Guide to Cave and Mine Gating* can help answer many questions. We have included a copy of the latest revision as an appendix to this paper (Appendix A). Please feel free to copy and distribute it widely.

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The "Agency Guide to Cave and Mine Gates" is included as Appendix A on p. 137 of these Proceedings.

Geotechnical Solutions in Karst Session

Chair: George Veni

Mechanical Ventilation of Caves That Have High Levels of Carbon Dioxide

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Abstract

Many caves in the Austin area have high CO_2 levels during the summer and early fall (Cowan et al., 2009), making access for management difficult if not impossible, especially for tasks that require long exposure times such as cave excavation work. Ventilating caves with portable air blowers has been a relatively cheap and effective tool to allow such access. The staff was able to determine how effective ventilating was at reducing CO_2 levels, and how long these levels remained low; so therefore, how frequent was ventilation needed for various CO_2 caves of various depths and sizes.

Introduction

The study was conducted in five caves that were known to have high levels of CO_2. All the caves are located in Travis County, Texas (Figure 1). Ireland's, Lost Oasis, and Midnight Cave are located in southern Travis County in the Kainer Formation of the Edwards Group, and within the Barton Springs segment of the Edwards Aquifer. No Rent Cave is located in northern Travis County in the Kirschberg member of the Kainer Formation, and Collaboration Cave is located in northwest Travis County in the Edwards Group.

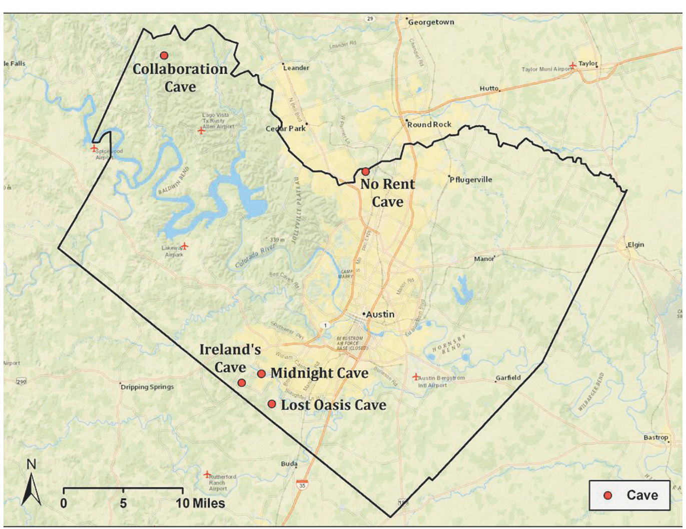

Figure 1. Map showing location of study caves, Travis County, Texas.

Materials and Methods

All caves were mechanically ventilated in mid-October, 2021. Prior to mechanical ventilation, staff entered each cave to take CO_2 readings with the Vaisala Data Logging CARBOCAP GM70 Handheld CO_2 meter and the Telaire 7001 CO_2 sensor to record the initial reading, and then ventilation would commence. For the line graphs, we used the Vaisala CO_2 meter readings instead of the Telaire 7001. The primary reason was that the Vaisala Data Logging CO_2 meter could take multiple readings without staff present. The Vaisala data logger was set to take measurements at one-minute intervals.

Figure 2. Photos of materials used in study and cost.

Staff utilized a portable 2.5 HP, 1500 CFM air blower powered by a portable gasoline powered generator to pipe surface air into the cave. A flexible four-inch diameter duct hose was attached to the blower to pipe fresh air to the desired section of the cave. Tubing length varied from 50 to several hundred feet. The cost of materials used in the study is shown in Figure 2. We ventilated each cave for various lengths of time; the idea was to see how long it took to get CO_2 levels down to humanly safe levels.

Results

Ireland's Cave had an initial CO_2 reading of 2.9%; CO_2 levels dropped to 1.8% after 112 minutes of ventilation. Once mechanical ventilation ceased, CO_2 levels rose to 2.3% in 18 minutes. The Telaire CO2 sensors read much higher levels than the Vaisala meter (Figures 3 & 4). All other graphs show just Vaisala meter readings.

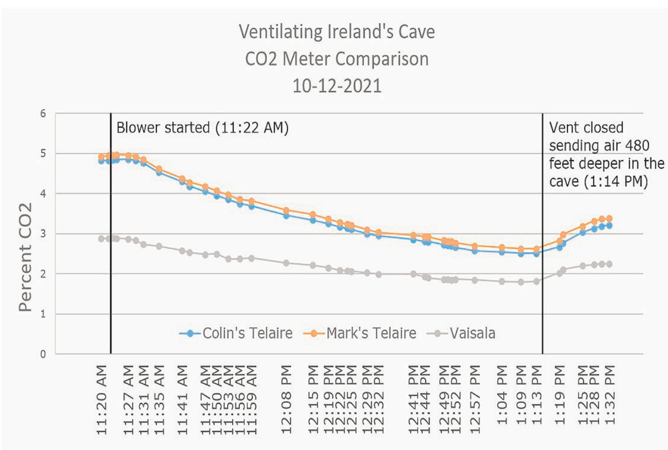

Figure 3. Time series of CO_2 levels in Ireland's Cave.

Lost Oasis Cave had an initial CO_2 reading of 2.2%; CO_2 levels dropped to 0.3% after 32 minutes of ventilation, at which point, levels began to rise while we continued to ventilate. This was most likely due to diurnal barometric pressure change (Truebe and Webster, 2019), drawing higher CO_2 levels from deep within the cave. It should also be noted that this cave has very strong airflow, so in combination with the barometric change, the portable air blower was not strong enough to outpace this sudden increase in CO_2 (Figures 5 & 6).

Midnight Cave had an initial CO_2 reading of 2.0%; CO_2 levels dropped to 1.6% after 98 minutes of ventilation. We continued to monitor CO_2 levels for one hour, and CO_2 levels subsequently slowly rose to 1.7% (Figures 7 & 8).

No Rent Cave had an initial CO_2 reading of 2.7%; CO_2 levels dropped to 0.95% after 112 minutes of ventilation. Once ventilation ceased, CO_2 levels rapidly rose to 1.75% in just 10 minutes and continued to rise to 2.5% after an additional 90 minutes (Figures 9 & 10).

Collaboration Cave had an initial CO_2 reading of 3.2%; CO_2 levels dropped to 0.3% after 27 minutes, and once ventilation ceased, slowly rose to 1.75% within 85 minutes (Figures 11 & 12).

Conclusions

Staff was able to determine how effective mechanical ventilation was at reducing CO_2 levels, and for how long these levels remained low; so therefore, how frequent was ventilation needed for various CO_2 caves of various depths and sizes. This method was quite successful at lowering

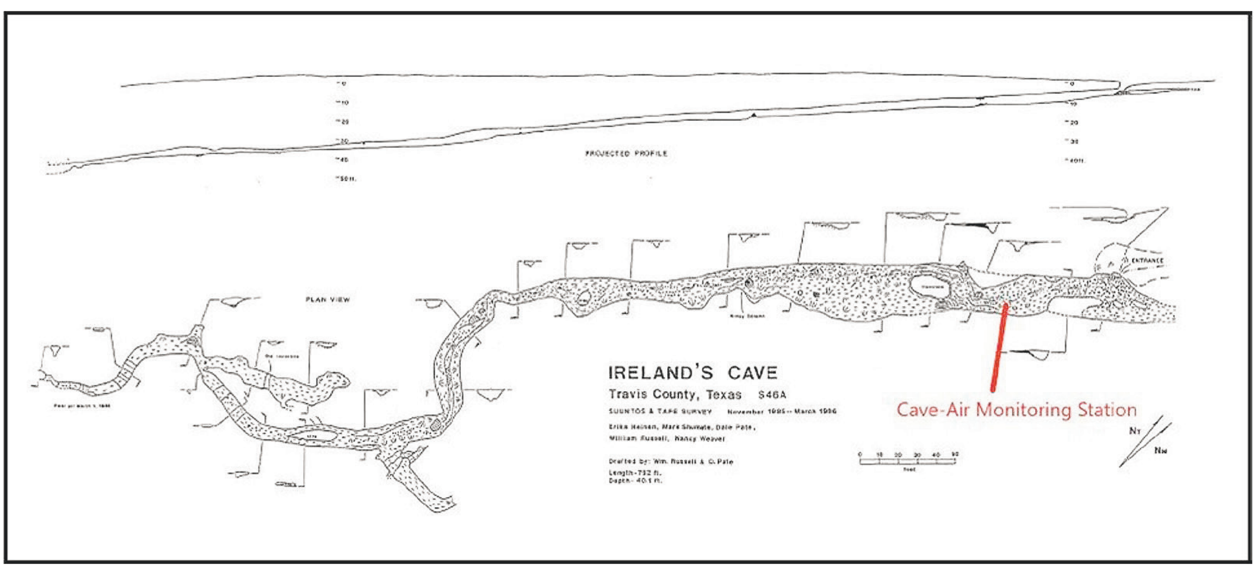

Figure 4. Map of Ireland's Cave.

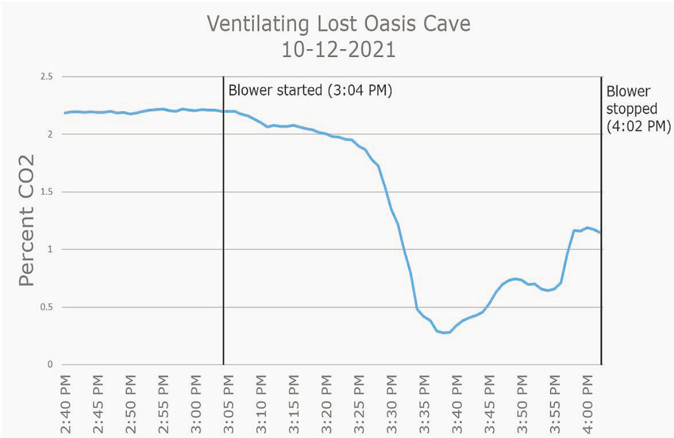

Figure 5. Time series of CO_2 levels in Lost Oasis Cave.

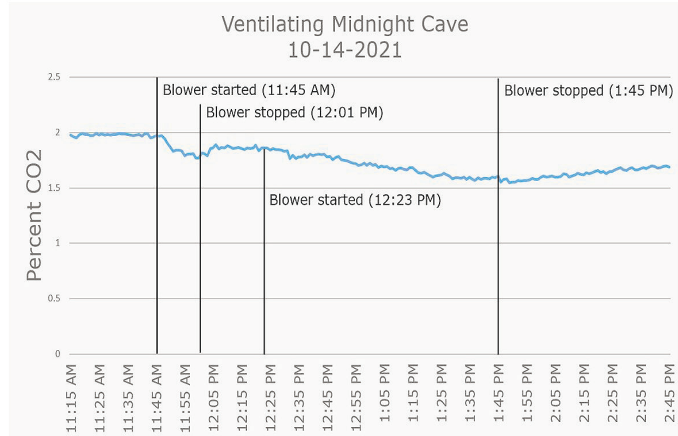

Figure 7. Time series of CO_2 levels in Midnight Cave.

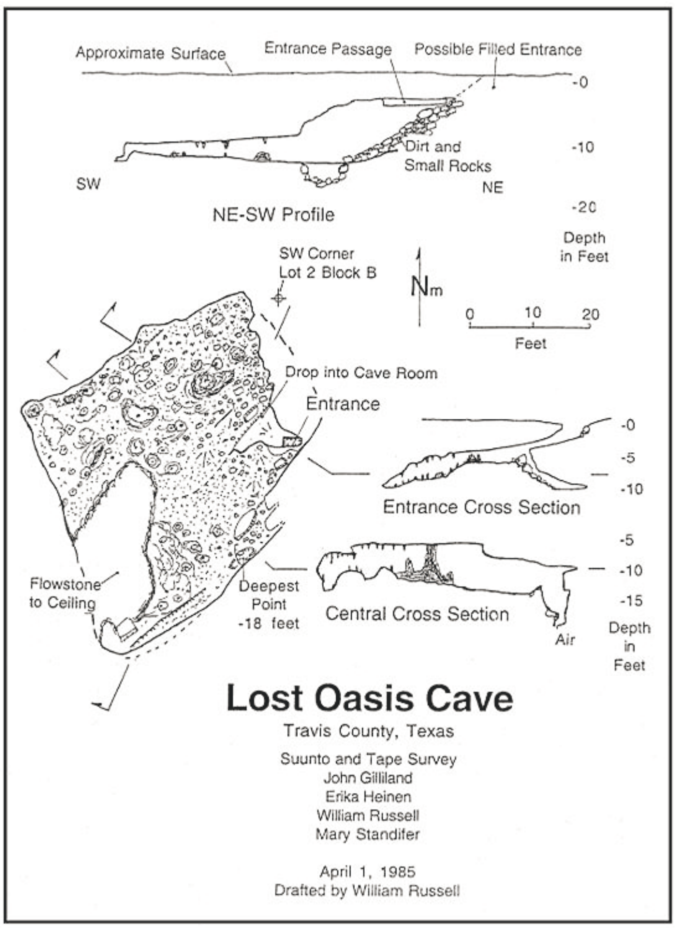

Figure 6. Map of Lost Oasis Cave.

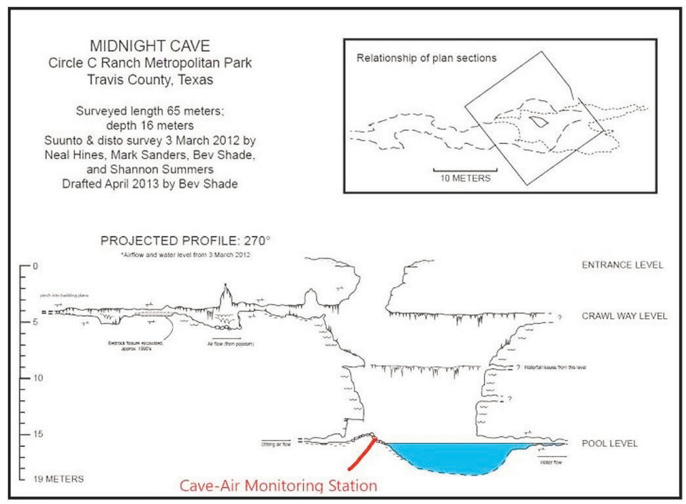

Figure 8. Map of Midnight Cave.

CO_2 levels to safe levels in some of the caves, so in our opinion, anyone working in caves with high CO_2 levels should seriously consider using this method.

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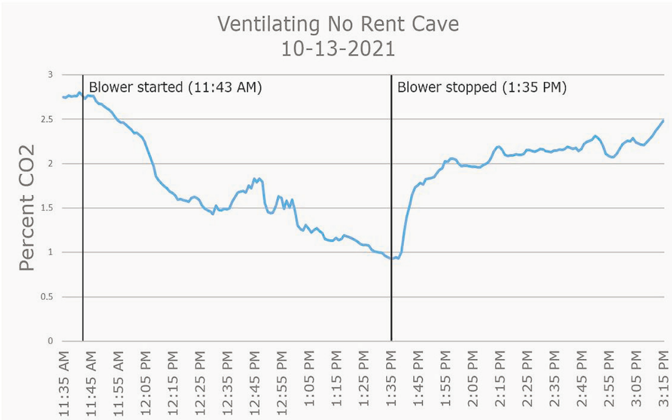

Figure 9. Time series of CO_2 levels in No Rent Cave.

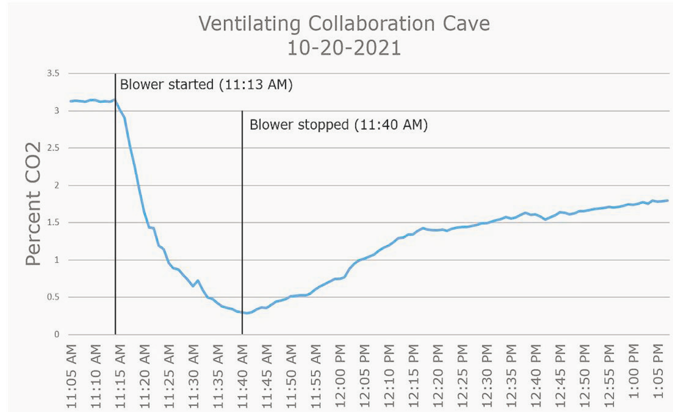

Figure 11. Time series of CO_2 levels in Collaboration Cave.

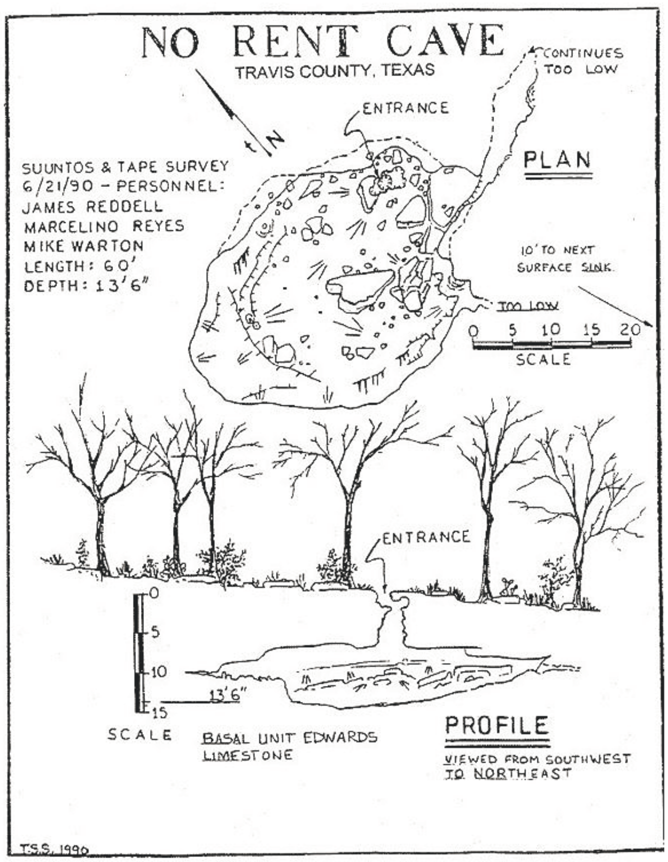

Figure 10. Map of No Rent Cave.

Figure 12. Photo of Collaboration Cave.

The Sinkhole Stabilization of the Blowing Sink Research Management Area

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Abstract

In 2013, Dr. Nico Hauwert of the City of Austin's Watershed Protection Department, along with a team of City cave specialists and Zara Environmental, LLC personnel, proceeded to implement a plan to stabilize five of the major karst features on the Blowing Sink Research Management Area in south Austin. With the decades-old shoring becoming greatly distressed, we found ourselves with no other options other than watch the entrances to these caves collapse in on themselves over time or to excavate to bedrock and erect a permanent and more ecofriendly solution to these threatened karst features. Despite confronting many obstacles and restrictions, many departments of the city came together along with contractors and volunteers to help make this vision become a reality and a cave restoration success story.

The Use of Morphologic Character Analysis to Determine Sinkhole Risk for Solar Site Development

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Abstract

Construction in karst terrains can present a challenge to development, and the solar energy industry has become increasingly aware of the potential impact to both site infrastructure, human health, and the environment that may result from the mismanagement of construction activities at solar sites. These impacts include development of new karst features or accelerated growth of existing features, damage to water supply wells and springs, and potential negative impacts to the habitat of stygobiont taxa.

Prior site studies have often depended on the subjective evaluation of individual features by a karst specialist. However, at large sites (>1000 acres) with high concentrations of dolines and ponors, the analysis of the risk these features present is time-consuming and often inaccurate. To address this, we have been developing a method using morphologic character analysis in an attempt to reduce subjectivity in karst feature evaluation. The process involves an initial desktop review to identify suspect karst features, followed by a field survey during which feature risk is determined based on the systematic coding of documented characters including: 1) the presence of an open throat, 2) parapet characteristics, 3) degree of soil raveling, 4) drainage leading to the karst feature, and 5) presence and quality of vegetation. Each karst feature is assigned a risk category where the recommendations detail approaches for each karst risk level. We then work with project engineers to assist in designing appropriate measures intended to minimize the impact to planned infrastructure and the karst resource.

Introduction

Over the last few decades there have been several methods utilizing morphometric analysis of karst features to model potential sinkhole development risk (Bondesan et al., 1992; Siska et al., 2016; Todd and Burden, 2016). Methods for geomorphologic modeling of karst impact affecting human health and the environment have also been proposed and described (Veni, 1999). Nevertheless, these methods have not addressed the potential impact of karst features on solar site development in areas of high karst feature density.

Solar sites are somewhat unique in that the greatest chance of sinkhole development, reactivation or enlargement, occurs during the site construction phase. Stripping, grubbing, and grading of a site under development removes the vegetation root mass, which can result in sudden formation of cover collapse sinkholes. Poorly planned erosion and sediment control measures can result in sediment- or contaminant-laden water plunging into existing open-throat sinkholes and swallets, and/or result in the expansion and deepening of these sinkholes as soils are transported from the surrounding drainage areas. Transported sediment also poses a significant threat to the karst aquifer, as it can carry residual-phase contaminants adsorbed to the particle surfaces.

Figure 1. Solar sites during construction present the greatest risk to the site development and the karst resource, especially if sediment and erosion control is not properly planned and managed.

In the past, most of the survey and geohazard assessments conducted for construction in karst terrains, including solar sites, have been conducted by a combination of desktop survey and field observation (Denton, 2013). At sites of less than 1,000 acres, with a limited number of surface karst features, these assessments are based on direct observation of existing features by a geologist or engineer experienced in karst feature evaluation. However, the level of risk the features may present to the developer, and the means of dealing with these features to mitigate impact to the karst resource is totally dependent on the investigator's ability, and can be highly subjective. In addition, on large sites (>1,000 acres) with a high density of karst features (e.g., ≥1 per acre) the assessment can often be cursory, and thus inaccurate or incomplete due to time and budgetary constraints, especially if each feature must be described in individual narratives.

In this article we describe a method of assessing risk based on a set series of characteristics (i.e. characters) established for each feature. Karst risk is assessed for each feature through the compilation of a data matrix comprising five karst feature variables (i.e., "character states"). These variables are assessed per karst feature by analyzing the field notes, observing photographs, and considering the overall context and resources from the desktop data review.

It is of note that this type of data analysis and reduction (i.e., character state analysis) is intended to assist in minimizing subjectivity in assessment of existing karst features for overall risk; however, it is not designed to predict where new features might develop. Finally, this method is most applicable for karst terrains located east of the North American "dry line" as indicated on the U. S. Geological Survey (Weary and Doctor, 2014), or in areas where there are carbonate rocks exposed or near the surface in a humid climate.

Data Collection Methods and Procedure

Desktop Data Review - Potential karst features are identified remotely, prior to being located and characterized in the field. This process is intended to significantly reduce the amount of time spent in actual field observation and survey tasks. The review of the existing feature locations within the subject site area of interest (AOI) is accomplished by examining data from among the following sources:

1. The Cave Database of the state speleological surveys;
2. Maps of selected karst features available from the United States Geological Survey (USGS) and the state geological surveys (if available);
3. Digital elevation models (DEMs) and LiDAR data;
4. LiDAR derived 2-foot contour interval maps for the AOI and surrounding area to within 0.25 miles, in order to determine the presence of surface features not included in the above listed databases based on the presence of closed, descending contours or other suspect karst "fingerprint" features;
5. Aerial photographs (both recent and historical); and
6. USGS 7.5-minute topographic quadrangles

In addition, readily available geological literature is reviewed for bedrock and structural characteristics, relying upon the closest resolution geological mapping that exists for the AOI. Each feature identified in the data review is then assigned a unique identifier, and considered a "suspect karst feature" until verified in the field phase.

Field Survey - Upon completion of the data review, the field reconnaissance and survey activities are undertaken. Specifically, the field reconnaissance entails:

1. Location and verification of potential surface features previously identified in the desktop review; and
2. Location of uncatalogued or previously unidentified surface features, specifically sinkholes, cave entrances, dry runs, and sinking streams

Each survey area is delineated and then examined for features (both catalogued and previously unidentified during the desktop review) in the field. This entails walking over the survey area in a systematic manner, to observe features that fit the criteria. The locations and outlines of all relevant features are recorded using a sub-meter accuracy GPS device. For this phase, the outline (parapet) of a closed depression (sinkhole) is defined as either the last closed descending contour at a 2-foot mapping interval or by the presence of a visible parapet. Cave entrances are identified as single points, unless the entrance is located within a larger sinkhole structure, in which case the cave entrance is indicated as a point within the sinkhole's parapet. Sinking streams are located as points of entry into the subsurface; however, losing streams are identified as linear features. Springs are also identified as points.

Each feature is then assigned a unique identifier using the same protocol as the data review. Features verified from the data review retain their original identifiers; however, any feature that cannot be verified in the field is removed from the final data set. Any new features are assigned the next number after the last one assigned.

Character Analysis

Karst risk for the field survey is assessed per karst feature through the compilation of a data matrix comprising five karst feature variables. These variables (character states) are assessed per karst feature by analyzing the field notes, observing the photographs, and considering the overall context and resources from the desktop data review, and then coded accordingly. It is of note that this type of data analysis and reduction is designed to assist in minimizing subjectivity in assessment of karst features for overall risk. This method is an adaptation of character state analysis used in phylogenetic modeling (Bock, 1973; Freudenstein, 2005).

The variables (characters) embodied in creating the risk data matrix and resulting risk assessment summary are:

1. Parapet characteristics
2. Presence of an open throat
3. Degree of soil raveling
4. Drainage leading to the karst feature
5. Presence and quality of vegetation

Explanation of the Characters - Shown below are examples of each character to assist in the process of feature coding for risk analysis. This typology presents examples of each character state, and their specific coding.

Character 1 – The shape and conformation of the parapet of each karst feature is important because the smoothness of the edge indicates the degree of erosion, growth, and overall activity of the karst feature. Typically, the rougher the parapet edge, the more active the karst feature and hence higher risk for the surface to continue to change.

Stable/Circular = 0

Irregular/Unstable = 1

Character 2 – The presence of an open throat (e.g., an opening into the subsurface, usually at the base of a sinkhole, an opening within a rock outcrop, or a cave entrance) in a karst feature is important since it may allow the unimpeded flow of surface runoff into the subsurface and eventually the groundwater table. This is a serious environmental concern to the groundwater, and proper erosion and sediment control and buffering must be utilized during construction around these types of karst features.

Absent = 0

Small/Unknown = 1 (small)

Small/Unknown = 1 (unknown)

Large/Open = 2

Dye traced to spring, well or cave stream = 3

Character 3 – Coincident with parapet shape changes and erosion, soil raveling of the sinkhole walls, throat, and subsidiary channels is a good indicator for sinkhole activity and risk. We further distinguish soil raveling into “minor raveling” and “major raveling” to differentiate between levels of erosion and soil inside the karst feature.

No Raveling = 0

Minor Soil Raveling = 1

Major Soil Raveling = 2

Major Soil Raveling = 2

Character 4 – An important factor that we note when assessing karst features is evidence for surface drainage focused into the karst feature. This is typically manifested as matted down grass/vegetation in the direction of the sinkhole in the case of surface runoff (sheet flow) or distinct erosion and channel development where water commonly drains into the karst feature. If the channel leading to the karst feature exhibits signs of erosion and downcutting, then this further supports the notion that the karst feature base level is decreasing and typically growing. It should be noted that it is very difficult to differentiate between "no drainage" and "sheet flow," as only a slight downward gradient of even gentle slopes will result in sheet flow to a feature. This type of flow is often attenuated by vegetation, plow lines, or soil irregularity. Thus, if it is uncertain if a feature receives sheet flow versus no flow, it is always coded conservatively (i.e. using sheet flow). Finally, it should be noted that some features exhibit flow channels that drain towards the feature (an insurgence or "swallet"), and in some cases away from the feature (i.e. an ephemeral or "wet weather" spring). In rare cases they may receive flow during low water table conditions, and reverse their flow during a high water table (referred to as an "estavelle"). However, we code any well-developed flow channel the same (see below).


No evidence of drainage = 0


Sheet flow = 1 (washed-in plant debris)


Drainage channel = 2 (flow away from feature)


Drainage channel = 2 (flow towards feature)


Active Swallet = 3

Character 5 - The presence, type, and state of vegetative cover surrounding and within the karst feature is an indicator for sinkhole development and the existence of a natural buffer. If little to no vegetative cover is present within the sinkhole, then this indicates that it is changing fast enough to inhibit plant growth and is vulnerable to surface runoff. If the sinkhole is overgrown, then this signifies that the sinkhole is more stable and that a natural vegetated buffer is present, which functions to filter out suspended soil/contamination in surface runoff.


Fully vegetated = 0


Partially vegetated = 1


Soil/rock = 2 (failed backfill)

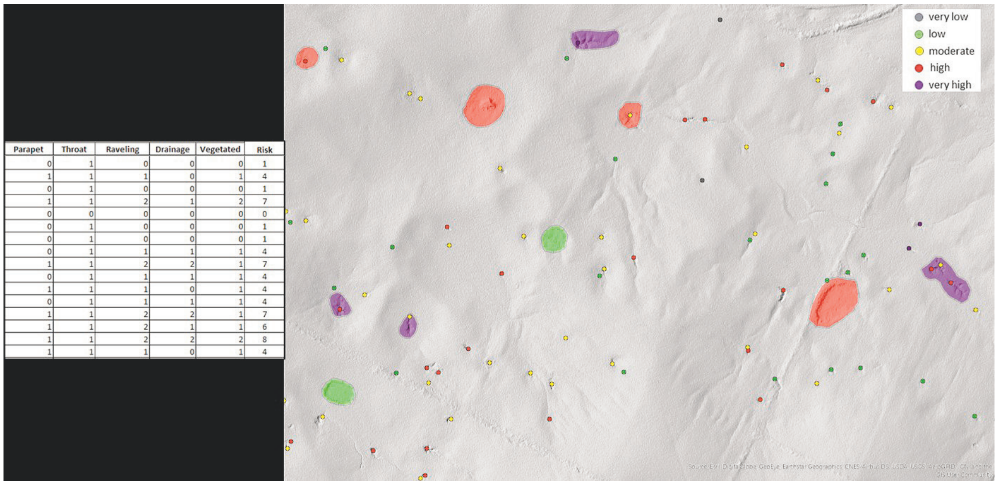

Soil/rock = 2 (plants carried by raveling soil)

Based on the character analysis, we assign a low, moderate or high-risk category to each of the confirmed karst features present, specifically to the site under study. If the defined character sum is 0, it is our interpretation that the feature is very low risk to site development. If the sum is 1-2, we believe the feature presents a low risk to site development and the karst resource. If the sum is 3-4, we believe the feature is a moderate risk. If the sum is 5-6, we believe the feature is a high risk. For features where their characters add up to 7-9, the feature is rated as very high risk for continued karstification during site development and throughout the operation of the proposed facility.

The degree of risk identified for karst features indicates the likelihood of the karst feature becoming unstable or accelerating its growth. The risk rankings are therefore used as a planning tool to aid in assessing the overall risk of developing a site. However, it should be clearly understood that even karst features designated as low risk can become unstable and negatively impact the proposed development. It is impossible to eliminate the risk of karst features, but measures can be taken to reduce the risk of karst issues.

Karst Risk Reduction and Mitigation

The reduction and mitigation of karst risk entails a suite of approaches for each karst risk level. These various solutions for karst features will depend upon the type and scope of the project, the amount of cut and fill planned for



Parapet	Throat	Raveling	Drainage	Vegetated	Risk
0	1	0	0	0	1
1	1	1	0	1	4
0	1	0	0	0	1
1	1	2	1	2	7
0	0	0	0	0	0
0	1	0	0	0	1
0	1	0	0	0	1
0	1	1	1	1	4
1	1	2	2	1	7
0	1	1	1	1	4
1	1	1	0	1	4
0	1	1	1	1	4
1	1	2	2	1	7
1	1	2	1	1	6
1	1	2	2	2	8
1	1	1	0	1	4

Figure 2. Results of the risk analysis of a 100 acre segment of a >3,000 acre solar site in the Pennyroyal Plateau area of western Kentucky.

the AOI, the presence of karst dependent, rare threatened and endangered species, and the hydrologic significance of the karst aquifer (e.g., municipal drinking water supply).

The preferred option is to avoid all karst features if possible, since every feature does bring a variable amount of risk to both the project infrastructure and the karst aquifer. In addition, avoidance preserves the vegetated buffer, especially for features which have reached equilibrium naturally.

In the case where avoidance is not possible, then the next steps may include remediation of the karst features and conducting additional studies to shed light on the extent, characteristics, and impact that the karst feature may have on the surface. Remediation will vary for each karst feature based on characterization (e.g., soil type, the architecture of the bedrock, and the local hydrology among many other factors). The type of remediation is typically determined upon subsurface exploration and excavation of the karst feature and identification and characterization of the bedrock bound throat if present at the soil/bedrock interface. Additional studies may include electrical resistivity tomography, soil borings, rock coring, air track probes, or other methods of applicable geotechnical and/or geophysical investigation.

Finally, it should be noted that solar "farm" facilities in humid environments (i.e. east of the North American "dry line") are revegetated following the installation of the solar panels and ancillary site infrastructure (cabling, substation, etc.). This is generally done by seeding with grasses suited for the specific climatic zone. Thus, the entire surface beneath and between the panels acts as a sediment "filter", as long as the vegetation is maintained properly, thus providing additional protection to the karst aquifer and subsurface habitat.

Figure 3. A well-planned solar site which has been revegetated with native plants provides the best natural filtration for stormwater and provides a high level of protection to the karst resource.

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Cambria Cavern Discovery and Mitigation: A Case Study in Urban Karst Management

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Abstract
In the early morning hours of February 8th, 2018, residents of a neighborhood north of Austin, Texas were awakened by the sound of "thunder." Hundreds of tons of the ceiling of a previously undetected cavern had collapsed taking with it portions of Cambria Drive, the adjacent sidewalk, and underground utilities. Approximately 750,000 gallons of water washed directly into the Edwards Aquifer as the nearby water tower emptied itself through the ruptured water main. By first light, commuters and school kids encountered a yawning void in the earth expelling a column of water vapor into the frosty sky. Fortunately, neither sewer nor natural gas utilities were compromised and no one was harmed. This presentation documents the aftermath and the eight-month process of protecting the cave, the aquifer, and associated habitat for threatened and endangered species, while restoring full function to the neighborhood. The exploration and mapping process is discussed, as well as the development of site protection measures, regulatory compliance strategies, occupational safety measures, and the cave closure engineering and construction plans.

Mountain Valley Pipeline: Karst Issues in Virginia 4 Years Into Construction

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Abstract
In 2018, construction of the Mountain Valley (MVP) and Atlantic Coast (ACP) 42-inch, 1400-psi natural gas pipelines began in Virginia across the Appalachian Ridge and Valley, 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 used dye traces to inform monitoring. Permitting issues delayed both projects. Dominion cancelled the ACP in July 2020, while the MVP continued construction and is over 90% completed. State agencies are working with landowners to constrain possible sources of continued turbidity at a spring hydrologically connected to sinkholes that in 2018 received sediment from a now-completed section of the MVP. Much of the remaining construction is on karst and at stream crossings where permits are pending. Delays in project completion increase environmental risk; the 6.5-km section along Sinking Creek Mountain (Giles County) is in its fourth year of construction. Monitoring for potential impacts at two springs draining this section continues. In February 2019, nine meter-scale sinkholes were discovered in an area blasted but not trenched in 2018, and where karst pinnacles had been excavated during grading. Project opponents characterized this area as an unroofed cave. Virginia Department of Conservation and Recreation (VDCR) staff considered the sinkholes to likely be the result of fines traveling into blast voids, and pipe installation here in 2021 exposed no caves. MVP is working with VDCR to protect any newly discovered karst features, and funded the purchase of the Salamander Cave Preserve by the Southeastern Cave Conservancy.

Introduction

Construction of the 42-inch diameter, 1400-psi Mountain Valley Natural Gas Pipeline was continuing into its fourth year as of November 2021. A similar and 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 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 Orndorff et al. (2017) and Orndorff et al. (2020). 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, and following the storm events in May 2018 (Orndorff et al., 2020).

This paper describes karst-related issues associated with construction of the Mountain Valley Pipeline (MVP) since October 2019. Most of these issues occurred where the MVP runs along an approximately 6.5-km long belt of karst on the northwest flank of Sinking Creek Mountain (Figure 2) in Giles County, VA. Though small reroutes were made to avoid a state designated Significant Cave and a handful of hydrologically active karst features, the entire Sinking Creek Mountain section was not avoided as recommended by VDCR and the Virginia Cave Board.

Installation of Pipeline Through Area With Sinkhole Swarm

In late winter of 2019, a swarm of eight small sinkholes appeared along an approximately 150-m section of the MVP where the surface had been graded and blasting was performed in July 2018 in preparation to excavate the ~2.5-m deep pipeline trench ("blast zone subsidence," Figure 2). Construction had been suspended prior to excavation due to unrelated permitting issues. A ninth sinkhole appeared in the same area in 2020. The sinkholes were confined to this area, and were interpreted by VDCR, the Draper Aden karst team, and the Virginia Cave Board

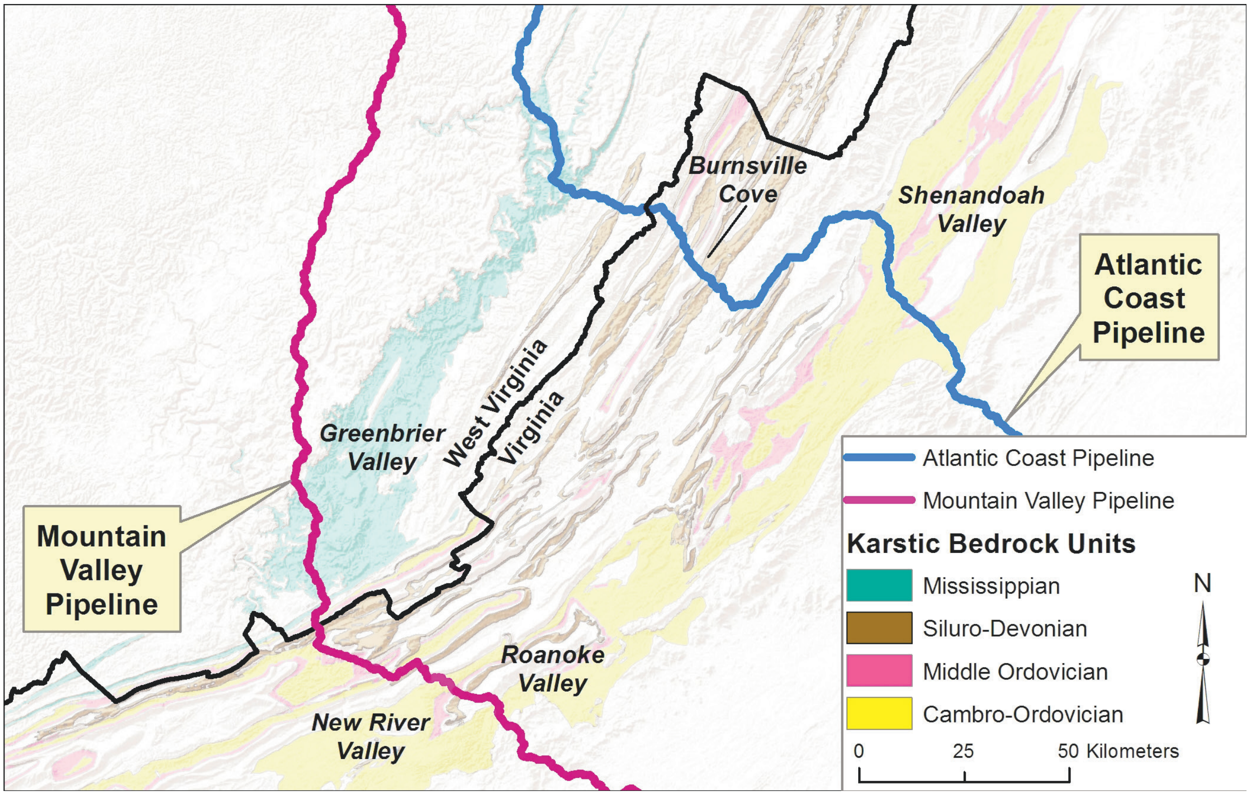

Figure 1. Proposed routes of Mountain Valley and Atlantic Coast high pressure natural gas transmission pipelines crossing the Appalachian Karst, VA and WV (Karst from Weary and Doctor, 2014).

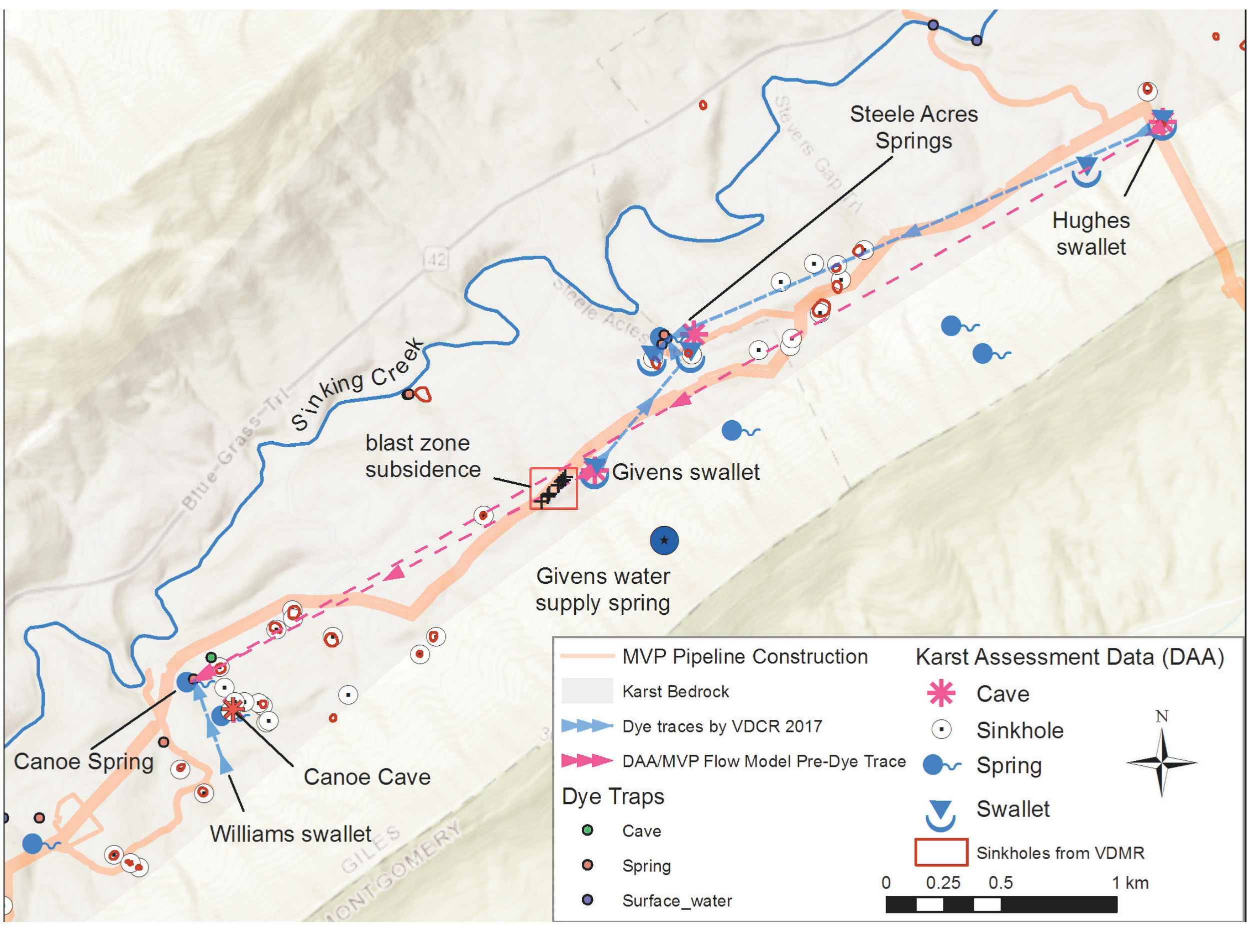

Figure 2. Sinking Creek Mountain Section of the Mountain Valley Pipeline, Giles County, VA.

Figure 3. Exposed pipe trench (June, 2021) in area of 2019 sinkhole swarm along Mountain Valley Pipeline, Sinking Creek Mountain, Giles County, VA: A) overview of the trench in the area of the sinkhole swarm looking east, B) trench at the base of karst pinnacles exposed during grading, C) pinnacles with residual clay fill, D) limestone exposed in the trench along the slope just east of the area with the sinkholes.

as most likely related to the blasting rather than karst processes. However, pipeline opponents (e.g., Bowers, 2019, 2020) in consultation with other karst experts, maintained that MVP had "unroofed" a cave in this area, citing the sinkholes and karst pinnacles exposed and/or removed during grading as evidence. The situation is described in detail in Orndorff et al. (2020).

Trenching and installation of the pipeline through this area occurred from May through July 2021. The trench was inspected by representatives from the Virginia Department of Environmental Quality (VDEQ), the Federal Energy Regulatory Commission, MVP's consultants, and the VDCR karst team; the authors of this paper. No significant voids or indication of collapsed cave passages were observed in the exposed trench. Representative photos are shown in Figure 3. The pipeline is now installed in this area, the trench filled, and the surface restored to approximate original grade. Final revegetation of this area is in progress.

Monitoring Two Springs Along Sinking Creek Mountain

The Federal Energy Regulatory Commission (FERC) did not require pre-construction monitoring of springs with watersheds crossed by the MVP, despite recommendations by VDCR, VDEQ, the Virginia Cave Board, and others that they do so. The lack of pre-construction characterization of springs along the pipeline route made issues like the one at Bottom Spring (Orndorff et al., 2020) difficult to evaluate. In an attempt to address this at least partially for the remainder of construction, VDCR implemented real-time monitoring of water quality parameters, including turbidity, at Steele Acres Spring and Canoe Spring, both of which lie at the base of the northwest slope of Sinking Creek Mountain downslope of the 6.5-km section crossed by the MVP (Figure 2). The monitoring installations consist of In-Situ brand Aqua Troll 500 multi-parameter sondes equipped with temperature, pressure, specific conductivity, pH, oxidation-reduction potential (ORP), and turbidity sensors. Note that weirs were not constructed at either site and spring discharge is not measured continuously. Each Aqua Troll 500 is connected to an In-Situ Tube 300r telemetry system, which logs readings and transmits them via the cellular phone network to an Internet server that provides real-time access to the logged data via the Hydrovu software interface. The field installation is shown in Figure 4. Instruments are calibrated every 1 to 2 months for all parameters. Readings are inspected daily by VDCR staff.

Dye tracing by VDCR in 2017 partially delineated the watersheds of each spring. Traces demonstrated that at least 3 km of the MVP corridor are likely to recharge at Steele Acres Spring, while Canoe Spring may receive recharge from the corridor 1 to 1.75 km northeast of the spring, and from 0.3 to 2 km to the southwest. A lack of injection points made more detailed estimates impractical. These relationships are illustrated in Figure 2.

Figure 4. Water quality monitoring and telemetry installation, Canoe Spring, Giles County, VA.

Construction on the Sinking Creek Mountain section of the MVP was suspended in July 2018, and as of fall 2019, was not slated to resume in the near future. With the construction ROW temporarily stabilized, we recognized an opportunity to gather monitoring data that could serve as a surrogate for background data on the springs. Without a time machine, this was the best we could hope for. Installation of the Aqua Troll 500s was completed in December 2019, and fifteen months of data was collected prior to resumption of pipeline construction in the spring of 2021.

Though the springs were very similar, there were some small, consistent differences. Water quality parameters are summarized in Table 1. A detailed description of the results is beyond the scope of this paper, but some general results merit noting. Each spring is characterized by nearly undetectable levels of turbidity under base flow conditions. The temperatures of the two springs were similar, with Canoe Spring slightly higher on average, 11.19°C versus 11.02°C at Steele Acres Spring. Both showed lowest base flow temperatures in March, ~10°C, and highest in late September, ~11.5°C. Ph values were also very similar between the springs, with values at both slightly alkaline as expect in karst groundwater systems. The pH was slightly higher and more variable at Steele Acres Spring. Specific conductivity values were moderate at both springs, with the values at Steele Acres Spring about 10% lower than at Canoe Spring.

Parameter response to precipitation events is critical for evaluation of potential impacts from construction activities, in particular the release of sediment to the recharge features for these springs. Sediment (measured as turbidity) emerged as a primary contaminant of concern in 2018 when failure of erosion control measures during MVP construction was followed by high turbidity spring discharge from Bottom Spring in Montgomery County, VA (Orndorff et al., 2020).

Figure 5 shows turbidity and temperature of the two springs over the first 21 months of monitoring, while Figure 6 displays specific conductivity and pH. Both figures include cumulative precipitation measured at gauges within or near to the respective springs' recharge areas.

Both springs exhibited short-lived turbidity responses (Figure 5) to precipitation events that generated runoff. Turbidity responses are more frequent in the winter than summer at both sites, and Steele Acres Spring exhibits turbidity responses about twice as frequently as Canoe Spring. Typically, turbidity returns to values less than 1 NTU within a week of the associated precipitation event, and turbidity peaks at each spring lag precipitation events by 1 to 2 days.

Temperatures at each spring (Figure 5) peaked during September at approximately 11.5°C, when surface water contribution to flow is generally negligible and spring

	Turbidity (NTU)			Temperature (°C)			pH			Sp. Conductivity (μS/cm)		
	Avg	Med	σ	Avg	Med	σ	Avg	Med	σ	Avg	Med	σ
Canoe	1.94	0	11	11.19	11.25	0.41	7.50	7.49	0.12	231	232	32
Steele Acres	2.75	0	15	11.02	11.06	0.43	7.57	7.57	0.18	207	213	30

Table 1. Summary of water quality parameters, Canoe and Steele Acres Springs, Giles County, VA.

water temperature only changes in response to very large events (e.g. September 21, 2021). Temperatures were at their lowest and most variable from February through April, when temperature decreases were observed in response to most precipitation events. The frequency of temperature responses was similar at the two springs, but higher in magnitude at Steele Acres Spring.

The signals for specific conductivity and pH (Figure 6) were generally similar to each other at both springs in terms of how they responded to precipitation events. Frequency of pH and conductivity responses to precipitation events was similar between the springs in winter, and the Steele Acres Spring was more responsive during the growing season, when Canoe Spring generally did not exhibit a conductivity response to precipitation. Conductivity values at each spring rose by 40 to 50 mS/cm over the growing season (May through October), reaching their highest values around October 1. During this same interval, pH values at the springs fell by 0.2 to 0.3.

In bulk, these observations suggest that the Steele Acres Spring is more closely connected to surface features than is Canoe Spring. This is consistent with VDCR's tracing of multiple sinking perennial streams to Steele Acres Spring (Orndorff et al., 2020). For purposes of monitoring, January 2020 through March 2021 functions as the reference or control period, while April through October 2021 was a period of active pipeline construction. No obvious differences were observed at the springs when comparing these two intervals. The reference period experienced more and larger turbidity events than did the construction period (Figure 5) at Steele Acres Spring, presumably due to more frequent precipitation events and more total precipitation during 2020.

The monitoring data also facilitates comparison of springs and/or events to look for evidence of construction-related impacts. The best example of this comes from the September 20-21, 2021 precipitation event, consisting of ~100 to 125 mm of rain during a 24-hour period. During this event, in the construction right-of-way just southwest of Canoe Spring, inspectors reported a sinkhole collapse in a sediment sump at the base of a water bar (see next section). There was concern that this failure might impact Canoe Spring, which became very turbid on September 22 (Figure 7). To evaluate this concern, we compared the responses of the two springs to this event, compared the response of Canoe Spring to similar previous events, and performed a dye trace (see next section) to see if water entering the failed sump flowed to Canoe Spring.

As shown in Figure 7, the responses of the two springs to the event were similar. However, it took longer for Canoe Spring (2 weeks) to return to pre-existing turbidity levels than did Steele Acres Spring (6 days). In addition, the Steele Acres Spring response was "bumpier," most likely due to the separate contributions of several surface swallets to the spring flow (Orndorff et al., 2020).

Figure 8 shows that the response of Canoe Spring to the September 2021 storm resembled responses to prior events from February 2020 and May 2020. However, neither of these events were completely analogous. Though bulk precipitation amounts were similar in both previous events, the precipitation was spread over several days. Following the February 2020 event, turbidity returned to pre-event levels within about 1 week, while for the May 2020 event, it took approximately 2 weeks, probably as a result of the multiple precipitation events documented during that interval.

Based solely on the monitoring data, it is not possible to exclude the possibility that the elevated turbidity at Canoe Cave Spring following the September 2021 storm was in part due to the failure of a nearby sump. However, dye tracing (discussed below) failed to demonstrate a connection between the failed sump and Canoe Spring. In any case, the turbidity at Canoe Spring did not persist and there is no evidence of any long-term impact.

Karst-Related Failure and Dye Tracing of Sediment Sump

During the storm event of September 21, 2021, karst inspectors from Draper Aden Associates informed VDCR of the formation of a sinkhole in the construction zone in

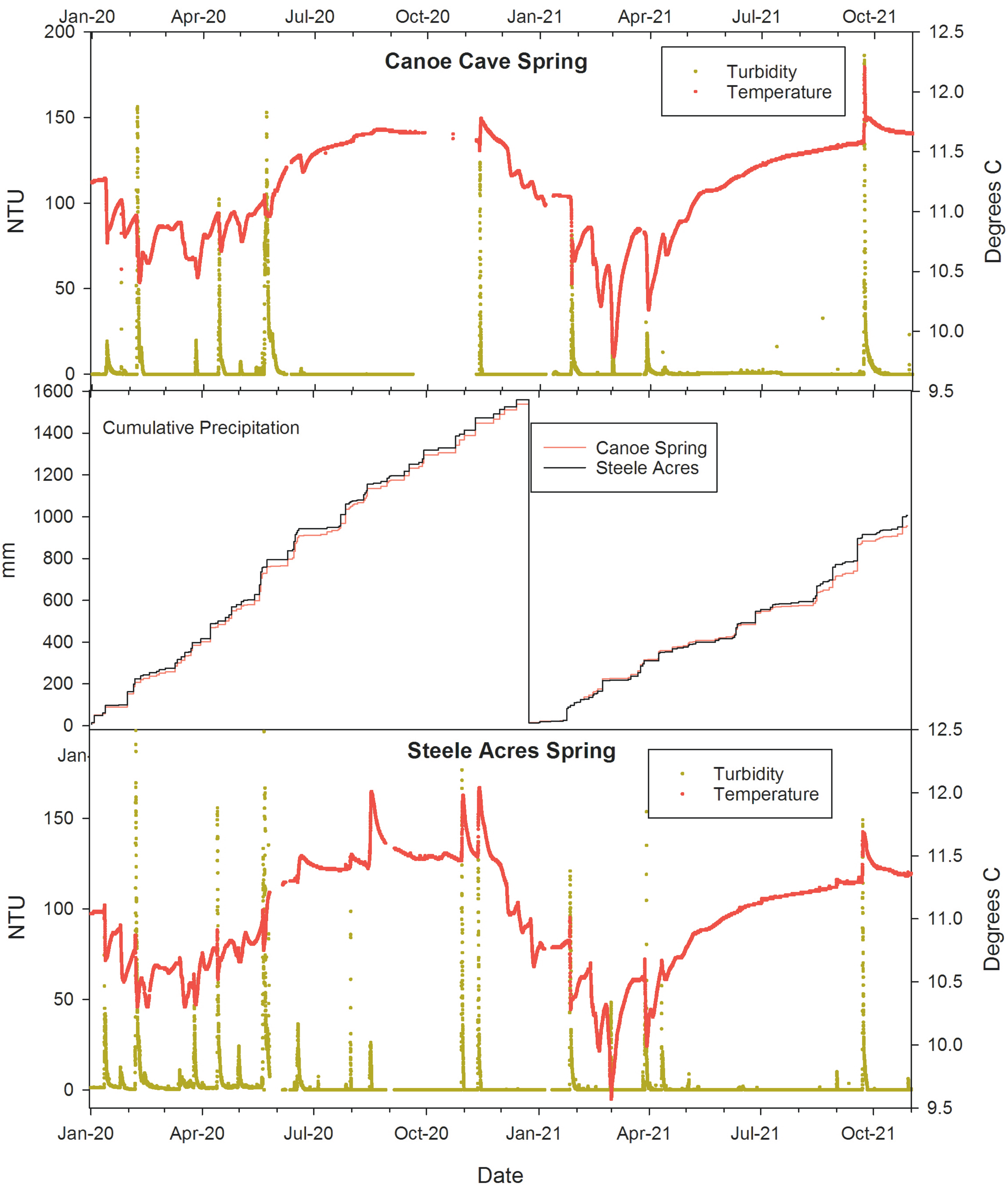

Figure 5. Turbidity and temperature values versus precipitation at Canoe and Steel Acres Springs, Giles County, VA (January, 2020 through October, 2021).

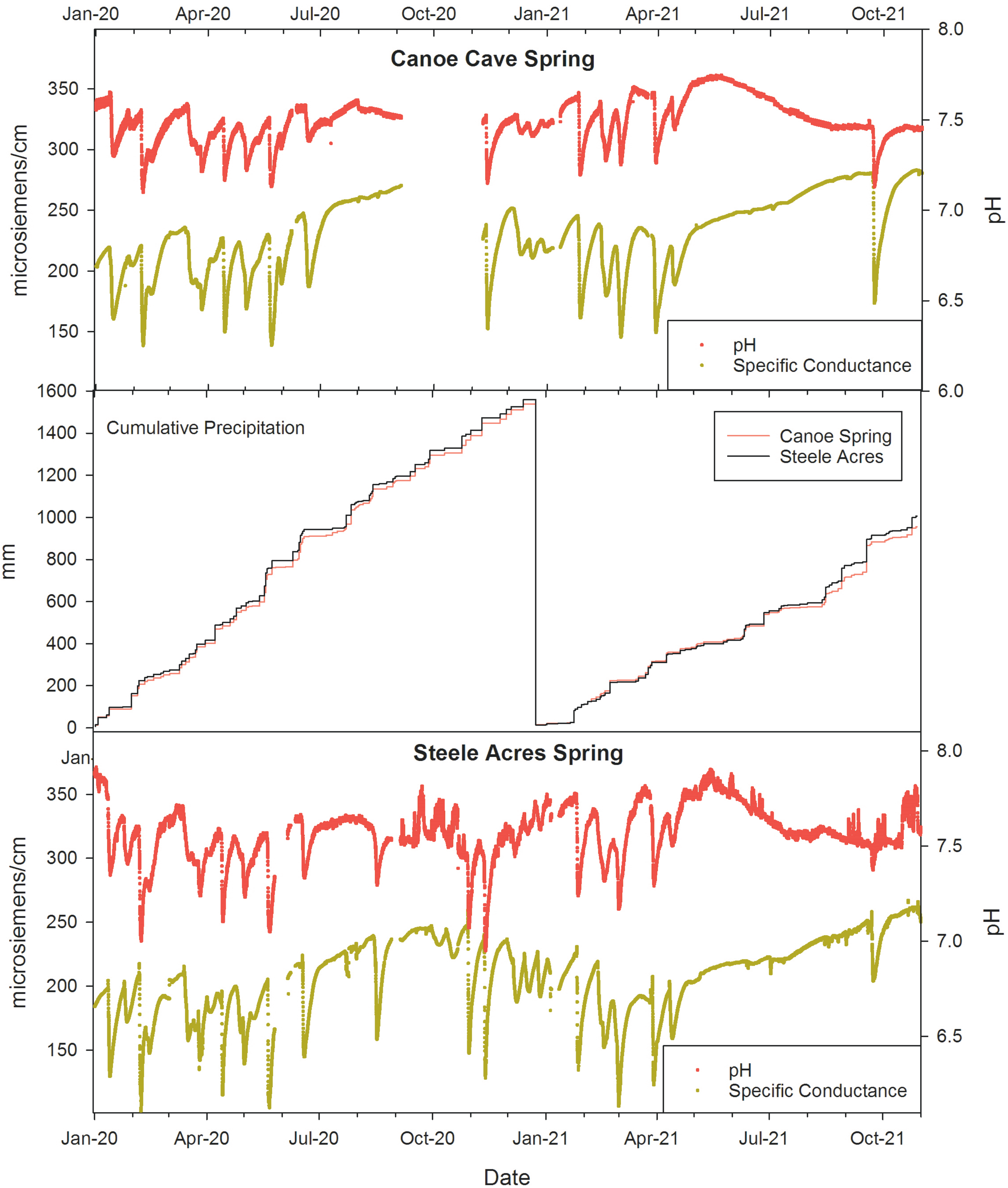

Figure 6. Specific electrical conductivity and pH values versus precipitation at Canoe and Steel Acres Springs, Giles County, VA (January, 2020 through October, 2021).

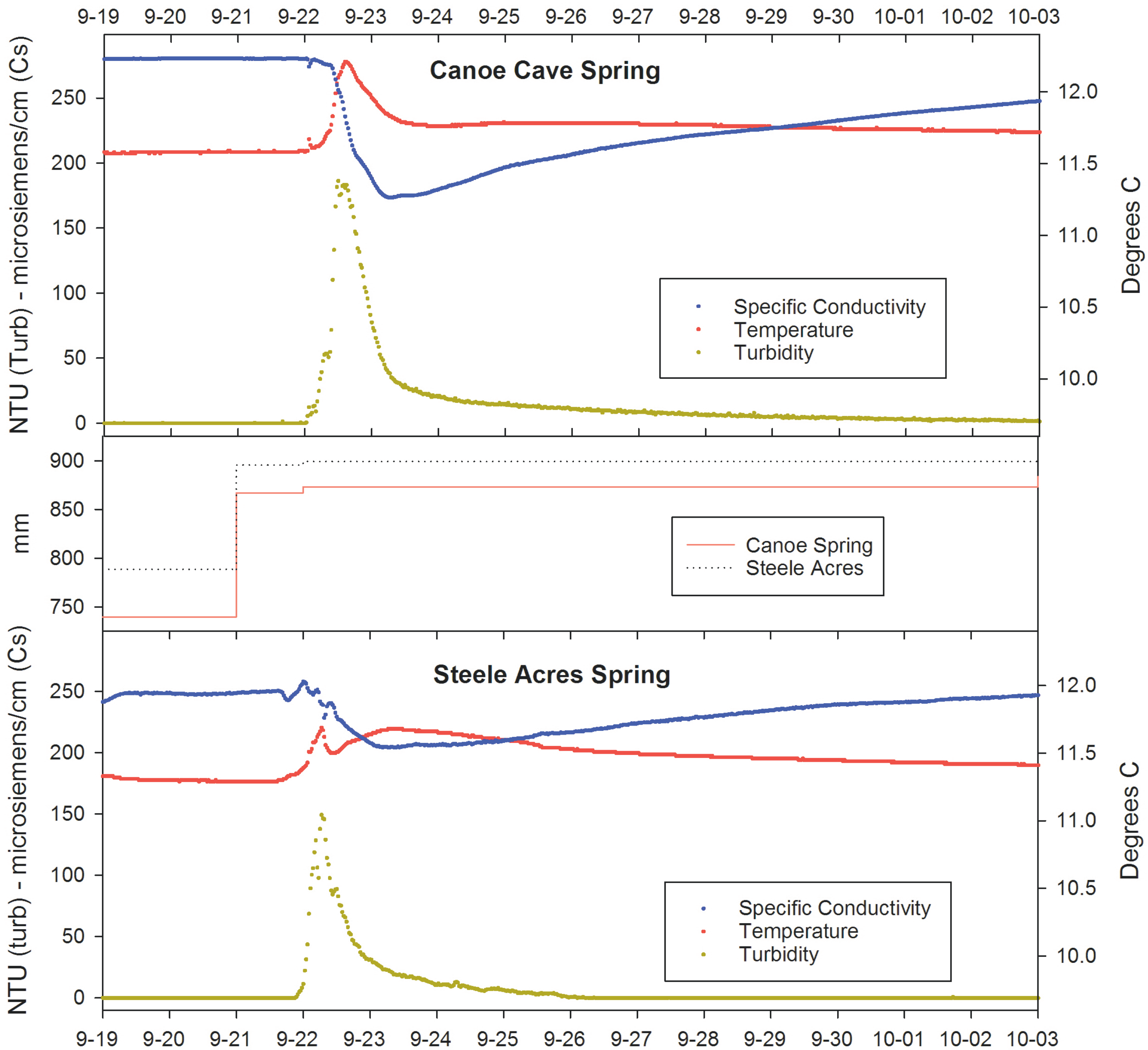

Figure 7. Responses of selected parameters to September 21-22, 2021 storms, Canoe Spring and Steele Acres Springs, Giles County, VA.

a sediment sump at the base of a water bar, approximately 400 m southwest of Canoe Spring, along geologic strike and in the same belt of limestone as the spring. This was the largest single precipitation event, 127 mm, recorded during construction in this area. VDCR staff accompanied the Draper Aden geologist to the site, where they found an open throat sinkhole receiving sediment-laden runoff from the construction right-of-way (Figure 9A). MVP environmental staff immediately began remediation work on the feature, with temporary stabilization and sediment control measures installed in less than 24 hours (Figure 9B). The feature was subsequently repaired with an intermittent filter.

Dye tracing was performed to determine what spring or springs might be impacted by this discharge of muddy surface water to the karst groundwater system. Dye samplers were established at four locations on September 21 as shown in Figure 10, including Canoe Spring, which seemed the most likely place for the water to go. Background samplers were collected on September 22, and then 250 gm of Rhodamine WT was released into the sump failure. At this time, water was not flowing into the feature, and the erosional control fabric (Figure 9B) had to be pulled back to inject the dye. Additional precipitation was forecast for September 22, but only an additional 6.15 mm was recorded after the dye was released.

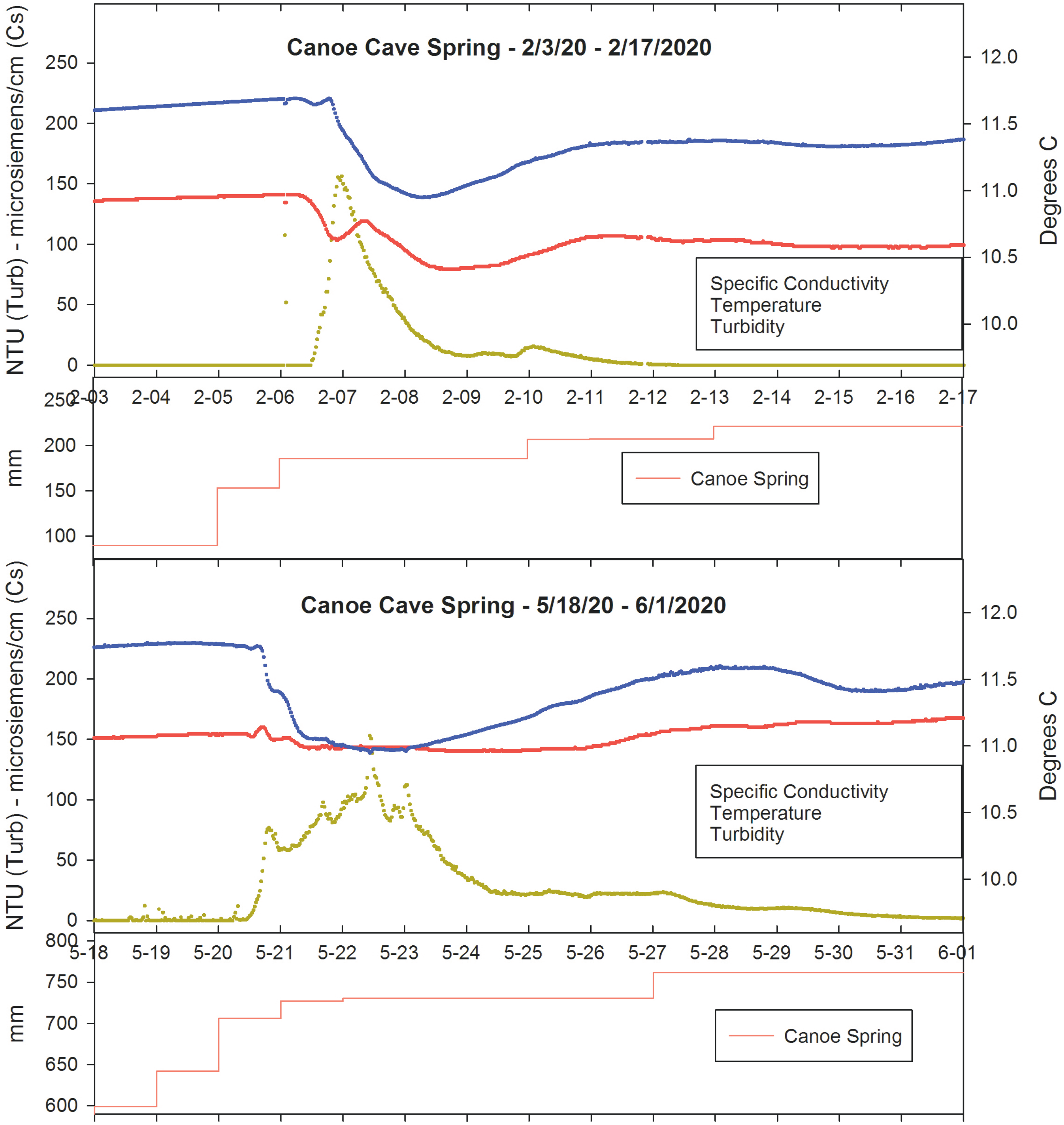

Figure 8. Responses of selected parameters to precipitation events of February 5-6, 2020 and May 19-21, 2020, Canoe Spring, Giles County, VA.

Unexpectedly, dye was not recovered at Canoe Spring, but rather at a small tributary 200 m north of the sump failure on three consecutive sampling dates (9/24, 9/28, and 10/12). Dye was present in the water samples collected on those dates as well, suggesting that the introduced dye was slowly releasing into the tributary from groundwater. Though no eosine was introduced by VDCR, fluorescent peaks corresponding to eosine were detected in the charcoal samplers collected on these dates, but was not detected in water samples. These fluorescent peaks were likely associated with discharge to the sump swallet from the pipeline construction area.

Because of the installation of temporary stabilization measures and a reduction in runoff between September 21 and dye injection on September 22, we cannot exclude the possibility that runoff entering the sump swallet during the peak of the storm may have flowed to Canoe Spring. However, the turbidity data response of Canoe Spring did not appear anomalous and it is most likely that Canoe Spring was not impacted by the sump failure.

Discovery and Protection of Cave With Entrance in the Construction Limits of Disturbance

MVP's karst consultants and biological consultants had both identified an "unenterable" portal within the construction limits of disturbance, and within or adjacent to the permanent pipeline easement, and reported this feature to the VDCR karst team and to the U.S. Fish and Wildlife Service due to its potential for bat use. To protect the cave and the landowner's privacy, the specific location of the cave cannot be shared at this time. VDCR staff visited this feature on May 20, 2021 and observed airflow and possible cave passage visible beyond a sandstone boulder blocking the entrance. We requested that MVP move the boulder to see if traversable cave passage could be reached. On May 24, MVP moved the boulder, and karst consultants from Draper Aden reported that the cave appeared enterable. Two members of the VDCR karst team entered the cave on May 28 to perform an initial assessment and survey. Due to forecast storms that afternoon that could make the construction right-of-way impassable, visitation was limited to a few hours. We were surprised to discover a

Figure 9. Intermittent swallet (A) and temporary stabilization (B), of the collapsed sump at the end of water bar, Mountain Valley Pipeline, Giles County, VA.

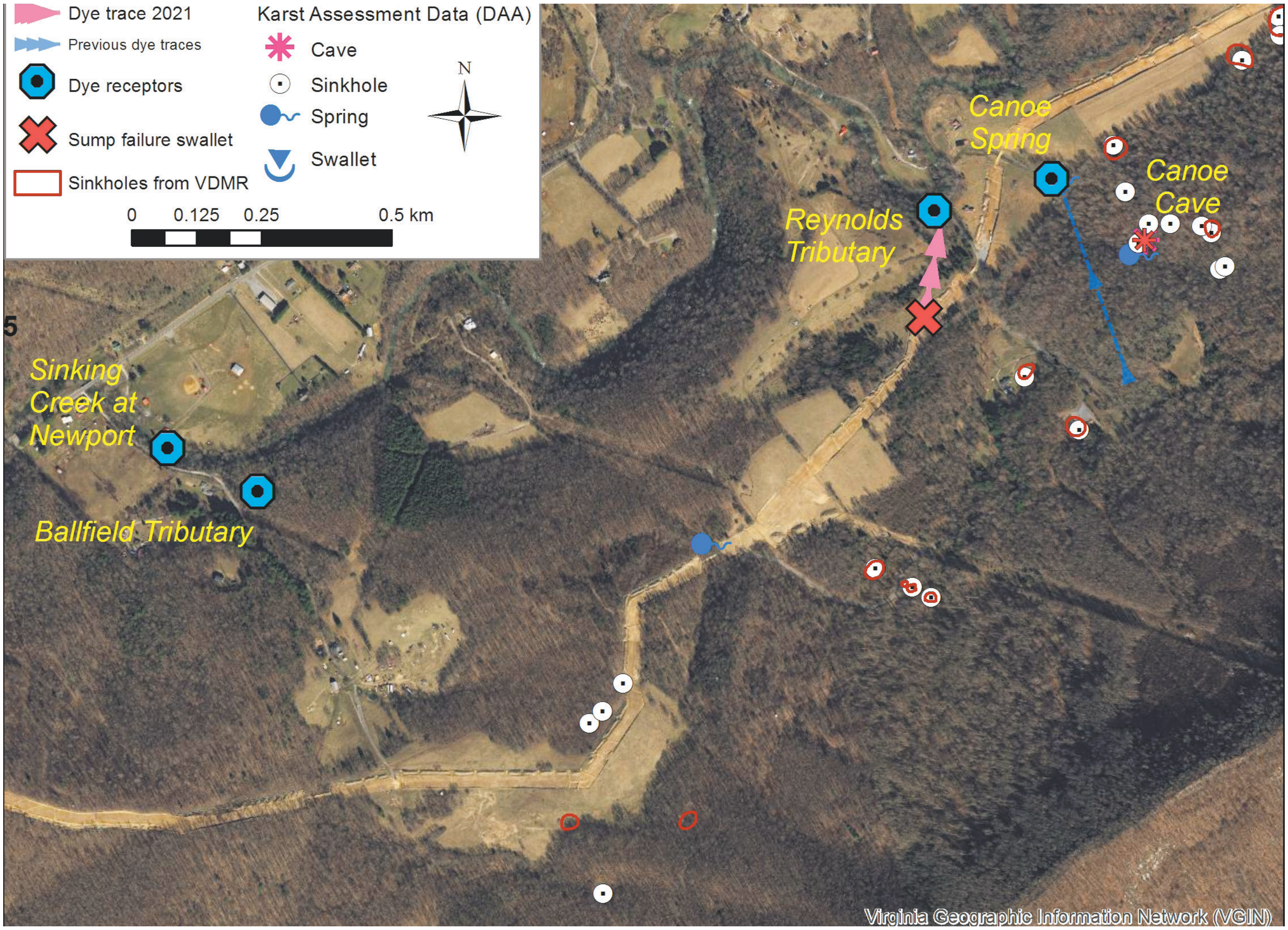

Figure 10. Results of dye trace from sinkhole in sediment sump, September 2021, Giles County, VA.

well-decorated, hydrologically active cave with ongoing passage (Figure 11). Passages are sufficient in size for use as a bat hibernaculum by some species; particularly the Big Brown Bat (*Eptesicus fuscus)* and the Tricolored Bat (*Perimyotis subflavus)*, a state endangered species. Due to the aforementioned time constraints, only 38 m of passage was surveyed. The cave descends steeply to the south, reaching a depth of 15 m approximately 9 m horizontally south of the entrance beneath the permanent pipeline easement. A narrow but traversable canyon passage continues to descend in this direction, and the canyon contains a small, calcite-saturated stream flowing to the south.

This data combined with geophysics will be used by MVP to minimize the likelihood of intersecting the cave during excavation of the pipeline trench. VDCR recommended installation of a bat-friendly gate over the entrance, to which MVP agreed pending landowner cooperation. As of December 2021, this issue has not been resolved as ownership of the land has changed since the initial exploration of the cave. VDCR staff will continue to survey and assess the cave once construction activities make it safe to do so, and when landowner permission is secured. Ideally, access to the cave will be maintained for exploration and monitoring efforts.

Establishment of Southeastern Cave Conservancy Salamander Cave Preserve

Through November 2021, MVP has spent over $8 million on land conservation for forest core regions (Forest CORE Fund) and in 2020, had committed another up to $19.2 million to the Appalachian Trail Club for conservation of lands along the trail corridor and to enhance outdoor recreation opportunities. Unfortunately, none of these funds have to date been able to support conservation of cave and karst resources like those crossed by the pipeline. Both forest core and Appalachian Trail related projects tended to occur on or adjacent to ridges, while karst areas in the region lie mostly in the valleys or the lower slopes of some ridges.

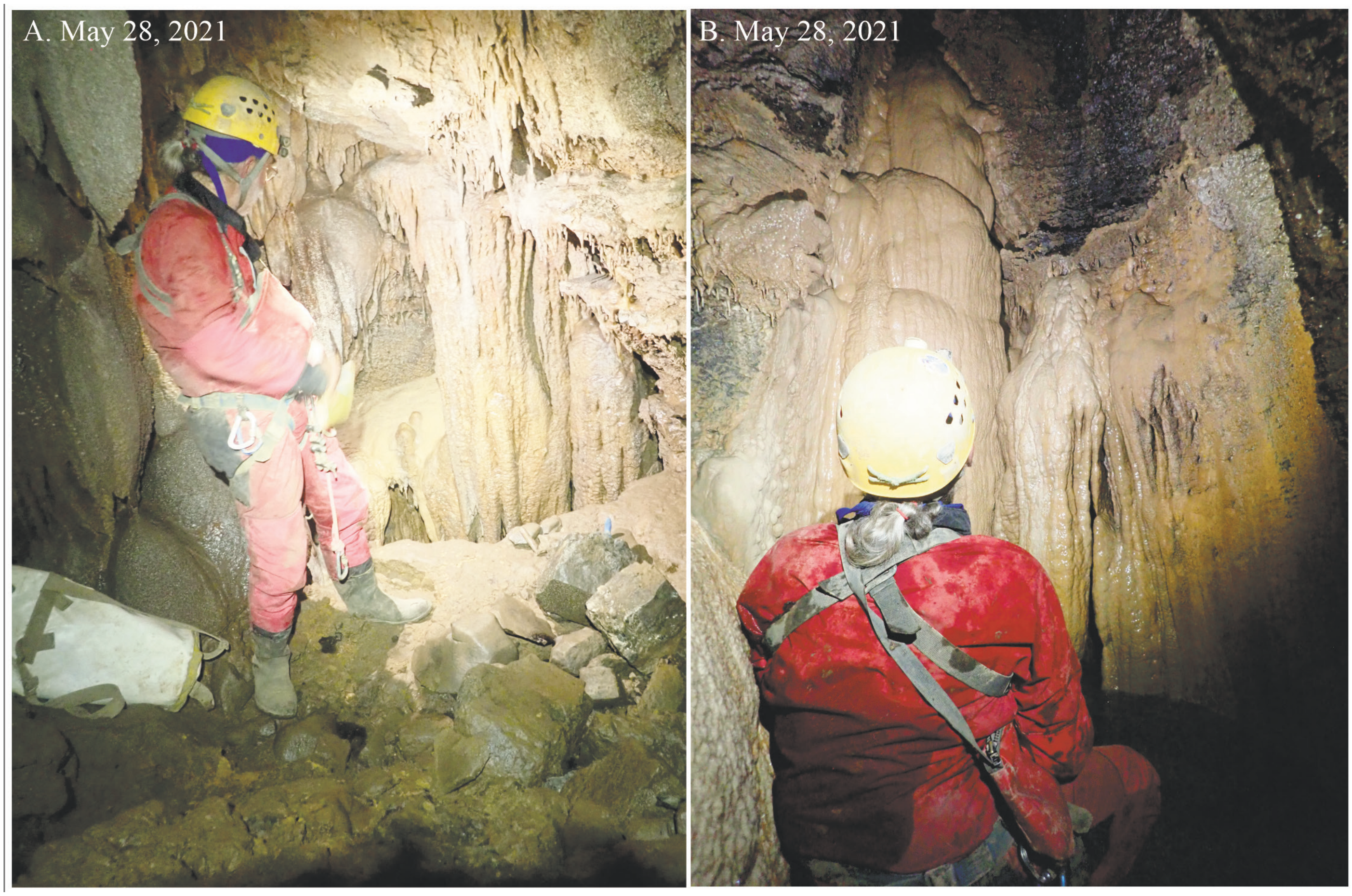

Figure 11. Well-decorated, hydrologically active cave passage in newly discovered cave beneath Mountain Valley Pipeline right-of-way, Giles County, VA.

In the fall of 2020, the property containing the entrance and much of the land overlying Salamander Cave in Giles County was offered for sale by the owner. Salamander Cave has a geological setting virtually identical to that of Canoe Cave and the Sinking Creek Mountain section of the MVP, and is located about 38 km to the southwest (Figure 12). Both caves are developed in limestones of Ordovician age exposed along the northwest flank of the sandstone ridge that comprises the Sinking Creek and Walker mountains.

Salamander Cave in a vertical maze with 4 km of surveyed passage and a depth of over 90 m. It is designated as Significant under the Virginia Cave Protection Act for length, depth, biology, paleontology, geology, and esthetic appeal (Figure 13). Several globally rare cave invertebrates are documented from the cave, and the paleontological resource includes the remains of ice age bears. Use of the cave as a hibernaculum by a small group of Indiana bats was reported in the past, but has not been observed on recent trips, possibly due to population declines due to White Nose Syndrome. Recreational visitation to the cave by responsible cavers is compatible with the cave's conservation, provided seasonal closures are implemented for hibernating bats should they be discovered using the cave.

Discussion with the landowner revealed that he was a motivated seller and unable to wait long enough to attempt to sell the property directly to a state conservation agency, which can take several months to years depending on the specific situation. VDCR approached Mountain Valley Pipeline and suggested that, since protection of cave and karst resources may not occur under the other grant programs they had funded, MVP could directly fund the long-term conservation of Salamander Cave, including the overlying land surface and upslope areas draining to the cave. Mountain Valley Pipeline agreed to consider funding this project, and VDCR karst staff approached the Southeastern Cave Conservancy (SCCi), a 501(c)(3) nonprofit organization and the largest private cave conservancy in the United States. VDCR worked with the SCCi, real estate agent Keith Gore, and several landowners to develop and submit a proposal to MVP to support the land purchase and subsequent establishment of the Salamander Cave Preserve.

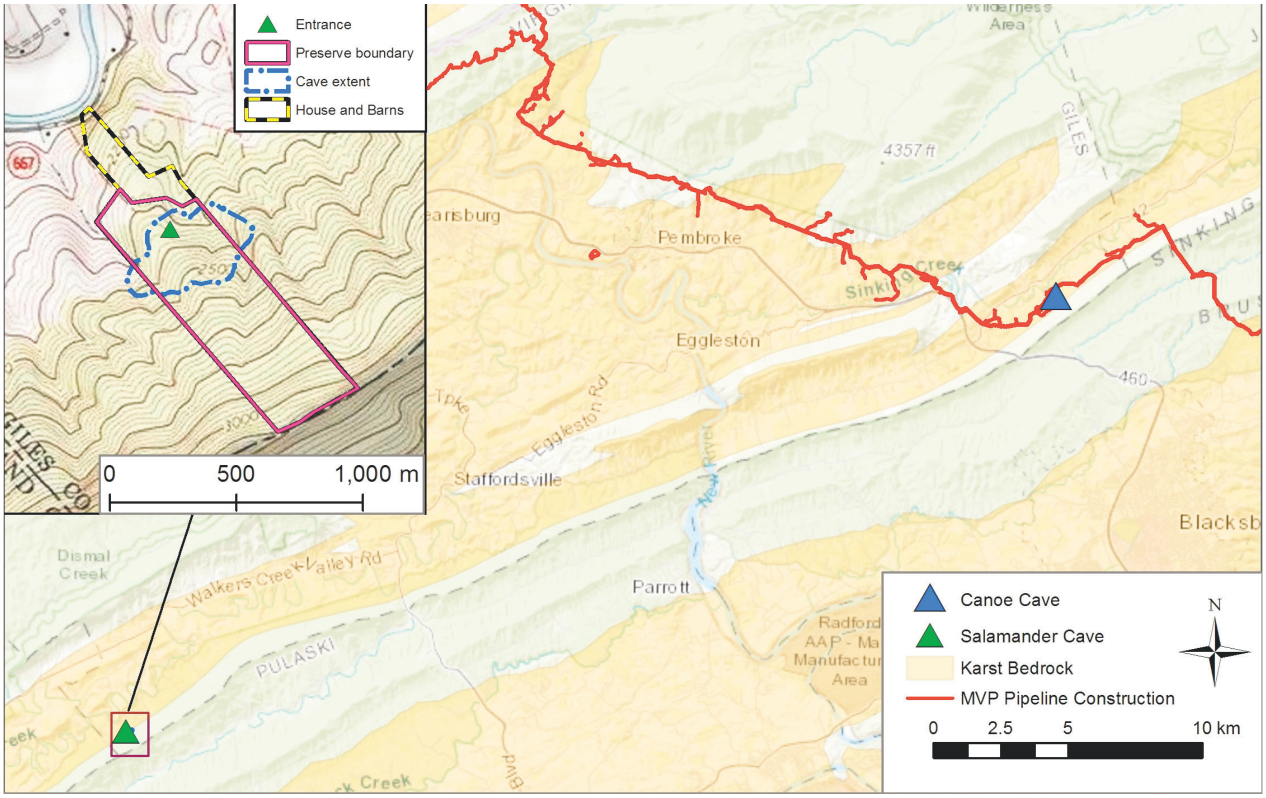

Figure 12. Location of the Salamander Cave Preserve, Southeastern Cave Conservancy.

Figure 13. Salamander Cave, Giles County, VA. Fungus room drop (left) and Hallelujah Trail (right). Photos by Sam Moore.

With the endorsement of the project by VDCR, MVP funded SCCi to purchase three parcels totaling 28 ha (69 acres) (see Figure 12) that included the cave entrance, most of the land overlying the cave, and all upslope areas. MVP provided additional funds for start-up and stewardship costs. Shortly after purchase, SCCi sold the northernmost 3.6 ha (9 acres) of the property, including a house, workshop, and several agricultural buildings. This portion of the property is downslope of the cave entrance with little potential to impact the cave. Proceeds from the sale will be used by SCCi for additional conservation acquisition and preserve management projects in Virginia.

Summary

MVP now forecasts the completion of pipeline construction for the summer of 2022. While over 90% of the pipeline is completed, remaining work is concentrated in the karst areas of Giles County, VA, and consists mainly of stream crossings and final ROW stabilization and restoration. The environmental impacts of pipeline construction have been exacerbated in many cases by the protracted construction schedule that resulted from court ordered revocation and suspension of various permits. To date, the impacts to karst resources have been minimal, reflecting the effectiveness of the karst resource inventory and mitigation plan; especially the identification and avoidance of sensitive features. The largest flaw in the project's karst protection strategy was the lack of a requirement for the pre-construction characterization of karst springs receiving recharge from the pipeline construction corridor. Mountain Valley Pipeline has cooperated with VDCR to protect newly discovered caves and karst features along the corridor, and funded the establishment of SCCi's Salamander Cave Preserve in Giles County.

Acknowledgements

VDCR thanks the Southeastern Cave Conservancy for their willingness to take on the Salamander Cave Preserve project, and acknowledges the financial support of Mountain Valley Pipeline, LLC, the Cave Conservancy of the Virginias, and the New River Land Trust.

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Protocol for Using UAV Photography for Rapid Assessment of Karst Features in Southeast New Mexico

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Abstract

Karst surveys are traditionally performed by pedestrian reconnaissance; walking transects spaced evenly across the area of interest. Small unmanned aerial vehicles (UAV) are used to augment the human portions of the karst survey by photographing the land surface at regular overlapping intervals, using photogrammetry to produce a digital surface model, which is reviewed in a 3-dimensional analysis by a qualified karst expert. SWCA Environmental Consultants have performed dozens of these reviews, producing a data recovery, analysis, and reporting system that reduces the amount of survey time, but increases the quantity and quality of data collected. The flight systems, analysis, and review steps taken by SWCA to produce a karst survey comparable to a pedestrian survey will be presented.

Introduction

Karst surveys are necessary to protect karst features and groundwater from contamination caused by accidental releases from liquid mineral installations and infrastructure, for the safety of personnel, and for the protection of equipment and infrastructure. Typically, all karst surveys have been pedestrian, employing visual observation of the landscape by a trained survey team. The present unmanned aerial vehicle (UAV) protocol was developed by a team of resource specialists to reduce the amount of time and labor needed to perform a basic karst survey, identify all suspected features, and then recommend a protection buffer around those karst features. The initial study area where this protocol was developed is on Bureau of Land Management – Carlsbad Field Office (BLM-CFO) lands, which has designated approximately 3968 km^2 with a high potential for karst features, 1018 km^2 of which are considered critically vulnerable to contamination due to the underlying geology. There are also 4400 km^2 with medium and 16,203 km^2 with low karst potential within the BLM-CFO region. Currently, there are 8368 km^2 of surface area administered by the BLM-CFO that potentially can be surveyed and continually monitored for karst features prior to project implementation. The protocol developed by SWCA and Southwest Geophysical Consulting, LLC is divided into three areas that set minimal standards and best practices for UAV karst surveys: UAV photography, data processing, and expert review and analysis.

UAV Photography

If UAV photography is to be used in lieu of a pedestrian karst survey, a set of minimal standards for documentation needs to be set to insure proper coverage, image quality, and repeatability (Table 1). These standards are intentionally

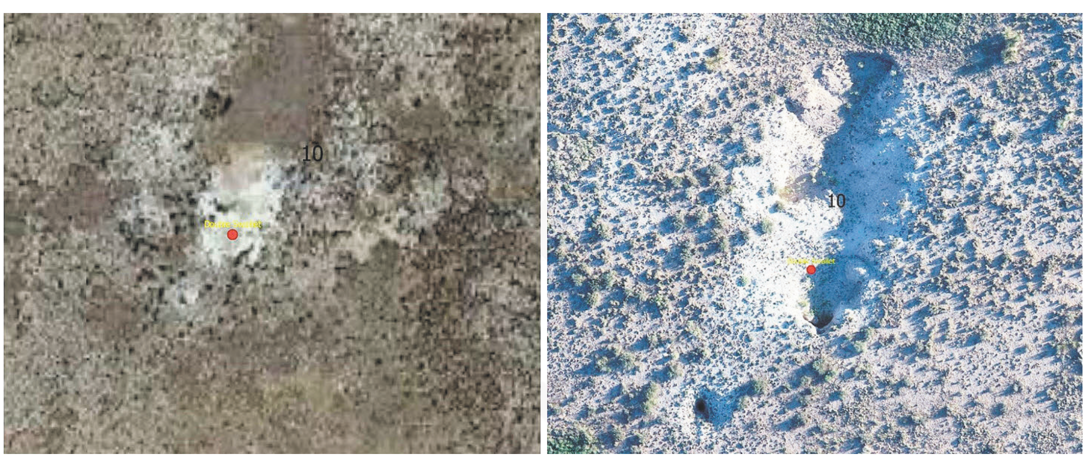

Figure 1. Google Earth image of a karst feature in southeast New Mexico versus a 1-inch per pixel UAV image of the same karst feature.

set at a level much greater than standard UAV and satellite image capture standards because the minimal target karst feature that needs to be identified is approximately 20 cm in diameter (Figure 1). In collaboration with the BLM-CFO, SWCA uses a large buffer to ensure adequate coverage around potential resources and to allow for projects siting options to avoid potential karst features. For block project areas, all data products shall cover an area extending 200 m beyond the proposed project footprint or right-of-way. For linear projects, a 400-m corridor shall be analyzed. BLM reserves the right to modify these required analysis areas on a project-specific basis.

All drone photography must conform to a basic standard of at least one square inch (6.5 cm^2) per pixel or raster cell in the raw JPG image files at ground level. Higher resolutions produced from pixel interpolation is not acceptable for image processing. Image overlap must be at least 75% on the top to bottom axis between photos, and 65% on the side-to-side axis of each photo to ensure enough overlap to perform photogrammetry as described in the next step. All images must be in RGB color, with 24-bit color depth, and can be of any standard format: JPG, PNG, TIFF, or GIF. Raw or unprocessed file formats cannot be submitted as evidence of a photographic survey due to the large image size and the need to have proprietary programs to view these images. All photographs must be georeferenced through an onboard GPS receiver that writes this information in the metadata tags incorporated into each image or using ground control points. All images must also have the camera model, exposure time, F-stop, ISO speed, focal length, 35mm equivalent focal length, and time and date information in the metadata (EXIF) headers. These minimal standards will ensure that enough coverage, quality, and processing potential are present in the raw data before data processing.

Data Processing
After acquiring qualifying UAV imagery, the images are processed in five steps that can be performed using a variety of programs and analysis techniques (Table 2).

Photogrammetry: All images are analyzed via a photogrammetry software package, such as Pix4D (www.pix4d.com) to produce at least two georeferenced data layers: an orthomosaic (in GeoTIFF format) and a 3D point cloud (in LAS format). The orthomosaic is produced by merging overlapping photos into one georeferenced image for the project area. The orthomosaic should be at least one square inch (6.5 cm^2) per pixel, and of sufficient detail to clearly visualize karst features on the surface. The point cloud should be as dense as possible, with approximately one point corresponding to each pixel in the input images, or no less than 1500 points per square meter. There are now many options for producing these data types with cloud-based and local computing options used.

Point cloud classification: The LAS formatted 3D point cloud produced from photogrammetry must be processed to produce acceptable results for expert review and analysis. The LAS point cloud is classified into ground points (terrain features), and non-ground points (vegetation and non-terrain features) using an appropriate algorithm. The Progressive Morphological Filter algorithm (Zhang et al., 2003) has proven effective in separating out these two types of points in the point cloud. An additional step of filling in holes caused by non-terrain point removal can also be completed, but care must be taken to use average elevations from around the hole to fill in these gaps.

Elevation models: A bare-earth elevation model is produced from the ground points of the classified point cloud using a gridding algorithm. This elevation model should have a raster cell size of no more than 50 cm. Elevation values from each cell will correspond to the smallest elevation value of a ground point located within that cell in order to optimize capture of negative elevation anomalies (i.e. holes). This process is slightly different than other elevation model techniques that seek to create average elevation points within a cell.

Local Relief Models (LRM): A local relief model is produced using the steps outlined by Hesse (2010) using a neighborhood size parameter of 10 m (Figure 2). The LRM has a relative index from -1.0 to 1.0 which helps to distinguish low and high elevation anomalies such as karst features. The LRM is colorized to highlight all negative values for further inspection. This step is very important to bring out height differences that would not be captured by

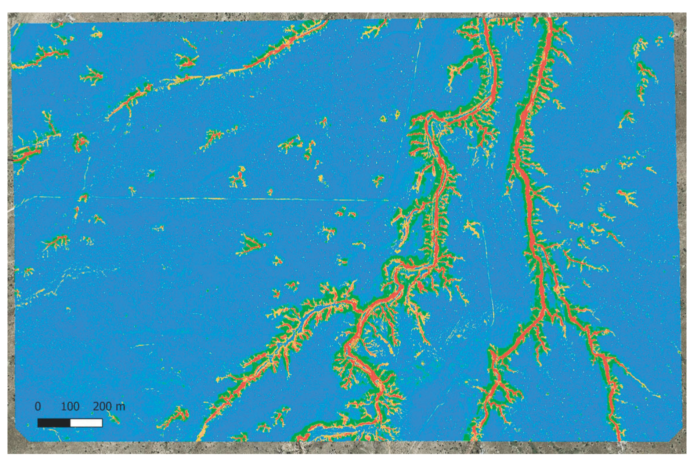

Figure 2. Karst-rich area in southeast New Mexico, showing how LRM analysis highlights areas of low relative relief (red to orange shading) in both karst features and hydrology.

looking at digital elevation models or contour maps. The LRM can be further processed to extract all groups of cells with values below -0.2 m relative elevation to generate a polygon layer of potential karst feature locations. Each polygon in this layer is considered a potential feature to be evaluated by a subject matter expert.

Expert Review and Analysis

Expert review and analysis is needed to confirm any karst features automatically identified from UAV photography and processing (Table 3). All datasets should be reviewed by no fewer than two professional karst surveyors approved by the BLM-CFO. For review, the orthomosaic, LRM, and if created, the potential feature polygon layers are imported into a GIS viewer environment such as QGIS, ArcMap, or a streaming tile service that allows for features to be added. A grid is overlaid over the area of interest above the orthomosaic and LRM to guide visual inspection; 100 m^2 cells are typical (Figure 3).

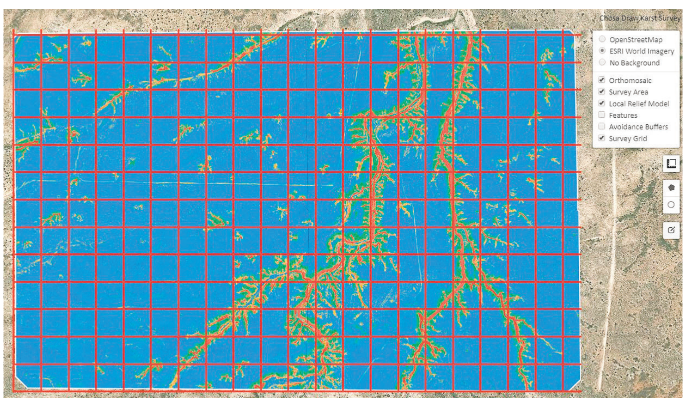

Figure 3. Karst review system showing grid and features that are used to aid in identifying and marking karst features.

SWCA produces a shapefile layer to contain information about located karst features. The attribute table associated with each feature contains the following information: feature id, date of digital evaluation, karst feature determination (yes/no/maybe – only yes and indeterminate features will potentially be associated with polygons), feature type (cave, swallet, playa, etc.), at least one sentence describing the feature, recommended buffer size, name of analyst, field visit conducted (yes/no), date of field visit, name of field surveyor, and updated field description.

The analyst begins by identifying the larger features or "hotspots" by zooming in on them and then toggling off the LRM to view the orthomosaic. A determination is then made regarding the likelihood of the "hotspot" being a karst feature. If it is determined to be a karst feature, then type, description, and a recommended buffer size are assigned. A georeferenced point is created for each potential feature location that is evaluated. If the karst feature is associated with a drainage into the feature, the drainage system must be mapped and associated with the feature. The point layers and polygons of drainages created by each analyst are combined to create a single feature layer without duplicates. If there is a discrepancy in feature determination (karst or non-karst), or a substantial difference in the description, a final determination must be made by the senior karst reviewer along with a note describing why the determination was made. An avoidance area polygon file is created by buffering each feature and the associated drainages with the recommended buffer sizes set by the karst reviewer or the BLM (Figure 4). The orthomosaic, LRM, and karst feature vector layers are made available for BLM review as a project-specific web map showing the proposed project footprint or right-of-way. The final step is to produce a pdf of the identified karst features and a KML format that can be shared with the project proponent and other agencies.

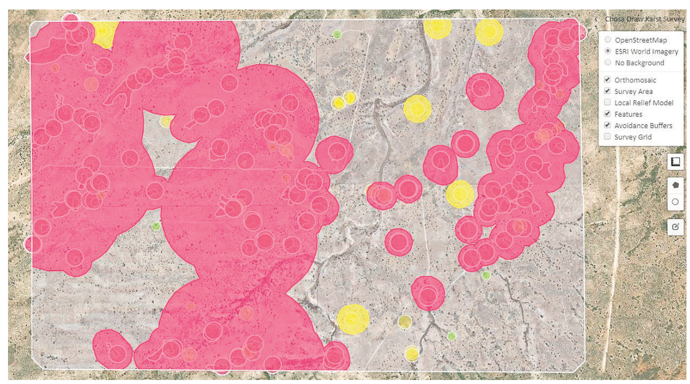

Figure 4. Avoidance buffers calculated after karst feature identification.

Conclusions

SWCA and the BLM-CFO have created a system for using UAV imagery, GIS analysis, and expert review to find karst features without the initial pedestrian survey. This technique is also quite relevant for doing large area surveys and in areas where there are potential hazards for survey crews. After the digital survey is complete, a pedestrian review and evaluation of the karst features should be conducted if the buffer zone around a specific karst feature is going to be the target of a variance. The karst feature data can be modified by field visits, in which case the avoidance polygon layers would be rectified with the review data. Projects avoiding karst features and their recommended buffer areas will ordinarily be allowed to proceed without further consideration of cave and karst resources. The BLM has the right to use these data to produce a permanent karst resource dataset and for future monitoring of karst resources.

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Table 1. Standards for UAV Survey for Karst Features in the BLM-CFO

Metric	Must meet or exceed
Ground photographic resolution for all imagery	Less than 1 inch per pixel or raster cell in the raw images at the ground level
Photographic overlap	
Side to Side overlap	65% of each image must overlap on the x axis
Top-Bottom overlap	75% of each image must overlap on the y axis
Color depth	At least 24 bit
File formats	JPG, TIFF, GIF
EXIF data	Latitude, Longitude, Altitude, camera model, exposure time, F-stop, ISO speed, focal length, and 35mm equivalent focal length, and time and date
Analysis area	Linear projects — 400-meter corridor; Block projects — project footprint or Right-of-Way plus a 200-meter buffer.

Table 2. Data Processing

File Type	Standard
Photogrammetry	
Orthomosaic (GeoTIFF format)	At least 1 inch per pixel or raster cell resolution in GeoTIFF format
Point cloud (LAS format)	Minimum point density of 1500 points/square meter. All points minimally classified as ground/non-ground
Elevation Model	Cell size no larger than 50 cm, with lowest value of all points within cell
Local Relief Model (LRM)	10-meter local neighborhood comparison, with a cell size of no more than 50 cm
Feature extraction	All features in LRM -0.2 m or more must be inspected as a potential karst feature

Table 3. Karst Feature Identification and Data Delivery Standards

Procedure	Standard
Feature identification data sets	Must use potential feature polygon layer, LRM layer, and orthomosaic layer
Karst reviewers	At least 2 BLM approved karst specialists
Feature marking	Feature ID (integer), date of digital evaluation, karst feature (yes/no/maybe — see above), feature type (cave, swallet, playa, etc.), at least one sentence describing the feature, recommended buffer size, name of analyst, field visit conducted (yes/no), date of field visit, name of field surveyor, updated field description
Drainage marking	A polygon of surface drainage flowing into the karst feature must be produced and associated with one or more karst features
Avoidance polygon	A recommended avoidance buffer of up to 200 m must be associated with each feature and drainage
Data layers	All karst feature data will be provided to the BLM for project review. LRM and orthomosaic will be delivered for BLM review as a project-specific web map

Delineation and Characterization of Gypsum Karst Geohazards in the Delaware Basin of West Texas: A Case Study Using Electrical Resistivity Tomography

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Abstract

The Delaware Basin, a major subdivision of the Permian Basin located in west Texas and southeastern New Mexico, contains abundant and diverse karst phenomena within the Permian-aged Castile Formation; a major evaporite unit within the region composed primarily of gypsum/anhydrite. The common expression of karst in the area includes sinkholes, exposed solution-enlarged fractured bedrock, solution cavities, and caves of polygenetic origin. The Castile Formation crops out across 1800 km^2 and was deposited during the Late Guadalupian to Early Ochoan epochs when carbonate reef development encircled the region forming a deep hypersaline lake ideal for evaporite deposition. Recent infrastructure development related to oil and gas activity in the Permian Basin has increased encounters with karst-related hazards. Land reconnaissance surveys conducted during the fall of 2015 and summer of 2016 documented karst features adjacent to a major thoroughfare in Culberson County, Texas.

Two-dimensional electrical resistivity surveys were conducted to characterize and delineate karst features that were not readily apparent on the surface. Preference was given to sites where subsidence or road degradation due to karst were apparent. Two sites are presented where a multi-electrode, direct current resistivity survey using a dipole-dipole array was conducted parallel to the road. Data was reduced using EarthImager-2D (Advanced Geosciences, Inc.) to create two-dimensional pseudosections of the subsurface. This non-invasive geophysical method of detecting subsurface karst was shown to be effective when coupled with standard geological investigative methods.

Introduction

The Delaware Basin of west Texas and southeastern New Mexico is a major subdivision of the Permian Basin and is commonly referred to as the Gypsum Plain (Hill, 1996). The study area lies in the northwestern edge of Culberson County, Texas, within the Delaware Basin (Figure 1). The major evaporite facies exposed is the Permian-age Castile Formation; a highly karstified unit which outcrops across 1,800 km^2 in the region (Stafford et al., 2008). Recent infrastructure development to accommodate the increase in oil and gas activity in the region has increased encounters with karst-related hazards along a major arterial thoroughfare that facilitates the transport of raw crude and gas from well sites. Sinkhole formation, road subsidence, and road base degradation and failure have been reported by state transportation officials and local residents.

Geophysical studies have been shown to be effective in various applications related to oil and gas exploration, civil engineering, and archeological investigations. These studies are often conducted in various terrains, in which the local geology constrains the quality of data collected. Electrical resistivity tomography is one method that has shown success in karst terrains where variations in local geology, both in structure and composition, i.e., anhydrite, limestone, and dolomite, are common (Zhou et al., 2002; Niederleithinger et al., 2012; Metwaly and AlFouzan, 2013; Benson and Yuhr, 2016).

Site reconnaissance of the study area during the fall of 2015 and summer of 2016 revealed several sites of probable karst-related geohazards within the right-of-way of a major thoroughfare in Culberson County, Texas. Features observed included sinkholes, solution cavities, caves, road subsidence, and leached gypsum bedrock underneath the road base. The objective of this study was to delineate the extent of subsurface karst hazards either within or proximal to the right-of-way where repeated road failures had occurred, or where karst features were observed nearby. Multi-electrode resistivity surveys were conducted at twenty separate sites using the Advanced Geosciences Inc. (AGI, Inc.) Supersting R8 earth resistivity meter. Two sites are presented in this paper as examples of the effectiveness of resistivity imaging in delineating potential shallow hazards in gypsum karst.

Geologic Setting

The Delaware Basin of west Texas and southeastern New

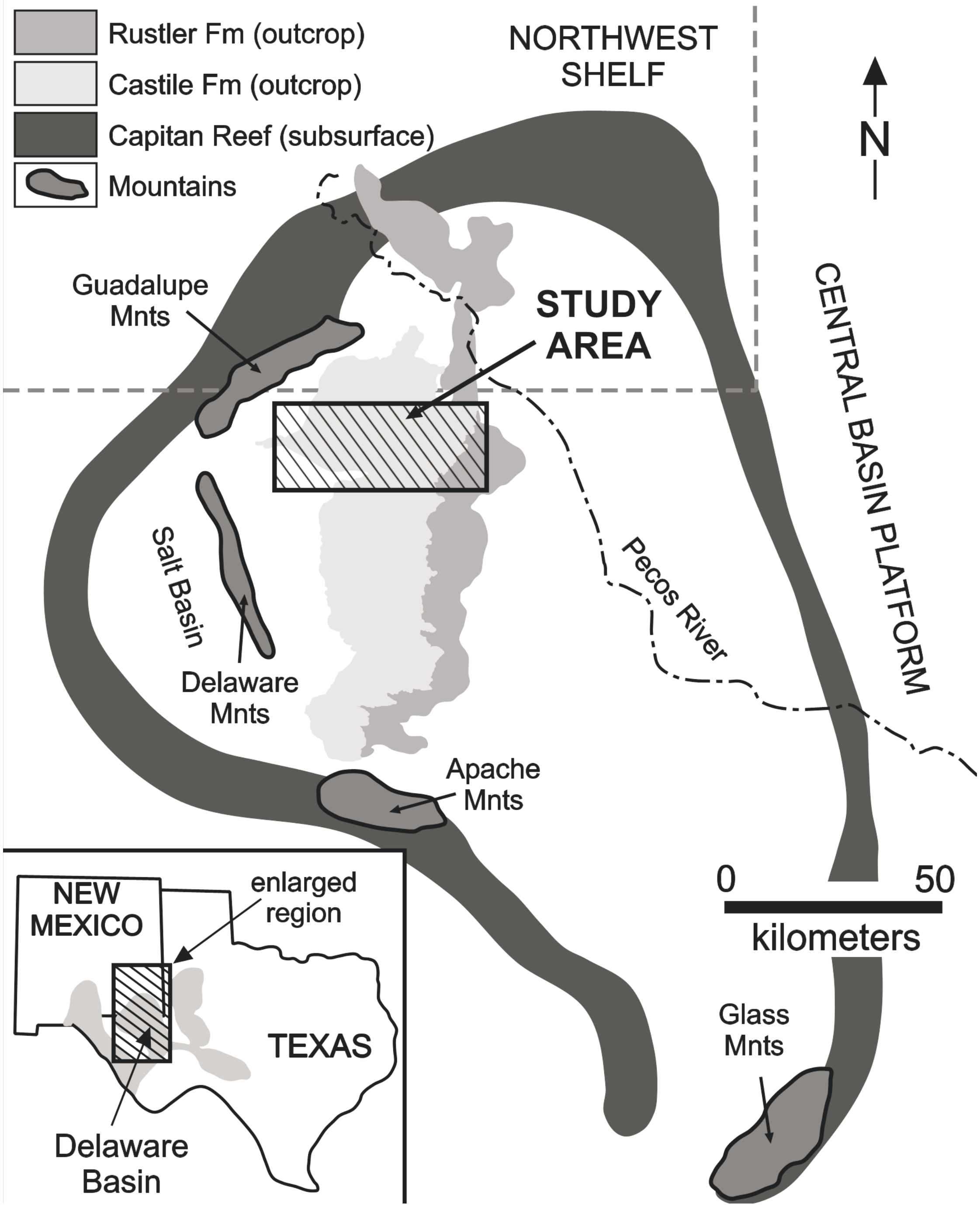

Figure 1. Map of study area showing the geographic relationship of the Delaware Basin to Texas and New Mexico with major features of geologic interest in the region. (adapted from Stafford et al., 2008).

Mexico is classified as an evaporite intracratonic basin outlined by a 600–700-km chain of Capitan Formation limestone that crops out as the Guadalupe Mountains to the northwest, and the Apache and Glass Mountains to the west and south (Hill, 1996). Assimilation of Pangea during the Early Permian resulted in faulting along Precambrian zones of weakness, creating structural separations of the Permian Basin into the Central Basin Platform, Midland Basin, and Delaware Basin (Horak, 1985). By Late Guadalupian and into Early Ochoan time, extensive reef development encircled the Delaware basin, which restricted the flow of fresh marine waters, creating a deep saline lake and conditions ideal for Castile evaporite deposition (Kirkland, 2003).

Tectonic activity associated with the Laramide Orogeny during the Late Mesozoic resulted in regional uplift and tilting of the Delaware Basin to the east/northeast. Subaerial exposure and climate fluctuations during the Pleistocene created hydrologic regimes that resulted in dissolution of the Castile Formation, which sculpted the karst landforms observed today. Within the last 10,000 years, continued climate fluctuation has transitioned the region into an arid to semiarid desert (Hill, 1996). At present, the average precipitation ranges from 15 - 40 cm with an average annual temperature of 24°C, and an average summertime high of 40°C.

Karst Development

Surficial karst manifestations within the Castile Formation crop out across 1,800 km^2 of the region as sinkholes, subsidence features, fractures, and caves: both hypogene and epigene in origin. Hypogene caves, which form by ascending fluids, are more pronounced in the western portion of the study area where hydrostatic pressures within the underlying siliciclastic Bell Canyon Formation are increased. Identification of hypogene cave types in the Castile Formation is difficult unless surface denudation has breached them. Epigene caves are more widespread in the region but are often expressed as isolated features associated with collapsed and filled sinkholes (Stafford et al., 2008).

Gypsic soil caves, or suffosion caves, are common and are often coupled with shallow epigene caves in the subsurface within the study area. Suffosion is the process by which unconsolidated clastic material is transported or washed into the subsurface leaving behind a void (Palmer, 2007). In the study area, suffosion caves form by the transport of the insoluble fraction of gypsic soils, which form a cover of variable thickness across the region. Dissolution of the soluble fraction of the soils/sediments allows for the migration of the insoluble fraction into subsurface void spaces or conduits formed by bedrock dissolution (Stafford et al., 2008).

Within the study area, karst-related hazards are directly connected to meteoric processes that occur on the surface. Land use modifications such as road design have altered the hydrologic gradients, creating abnormally high and low regions where stormwater discharge is more focused, or where ponding occurs within the road and shoulder. The solubility of gypsum is such that, depending on the environment, dissolution can occur on human rather than geologic timescales (Klimchouk and Aksem, 2005; Gutiérrez et al., 2007). Firsthand reports from local transportation officials have described the sudden opening of sinkholes along the road right-of-way during or after heavy rain events indicating the rapidity of dissolution and collapse. Additionally, dewatering shallow karst aquifers for oil and gas extraction is known to occur in the study area. Water extraction in karst terrains can exacerbate or induce subsidence by altering regional groundwater levels (Cooper and Gutiérrez, 2013); however, occurrences of subsidence in the study area can also be attributed to natural karst processes.

Electrical Resistivity Methods

Two-dimensional direct current resistivity surveys were conducted at two sites of interest using an eight-channel SuperSting (R8/IP) multi-electrode earth resistivity meter, produced by Advanced Geosciences Inc. (AGI). Both sites were selected based on observable karst processes in close proximity to the road. Surveys were conducted using 56 electrodes and a dipole-dipole array configuration (Figure 2).

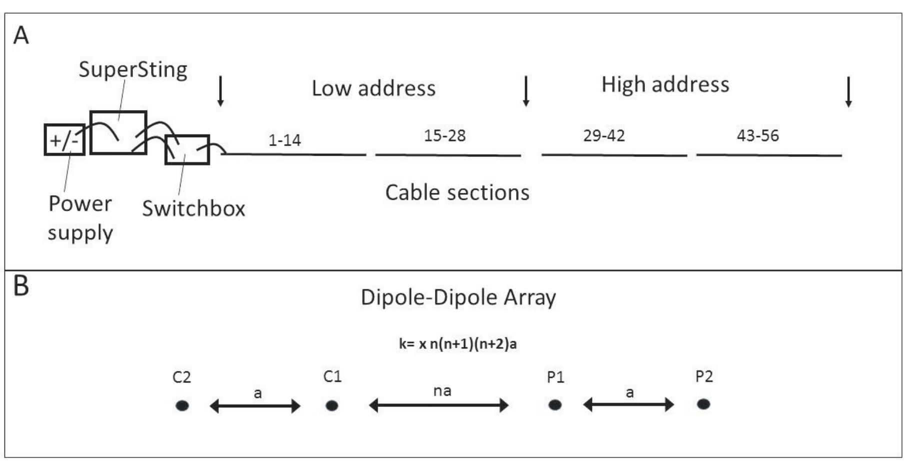

Figure 2. A) Schematic showing layout configuration of each survey conducted. Four cable sections were used with 56 electrodes at each survey site. B) Schematic showing configuration for dipole-dipole array with four electrodes. k represents the geometric factor, C1 and C2 are current electrodes, P1 and P2 are potential electrodes, and a represents the electrode spacing. From Loke (1999).

The two sites presented in this study are identified as RES 1 and RES 15. Both surveys are 110-m in length with electrodes spaced at 2-m intervals.

Prior to each measurement, electrodes were wetted with a dilute saline solution to improve electrical contact resistance with the ground. Given the arid conditions in the study area, some sites were abandoned when contact resistance could not be lowered to an acceptable level; typically less than 2000 Ω. Site-specific parameters were configured directly on the SuperSting console. This included electrode spacing, measurement units (meters), and whether a roll-along survey would be conducted or not. For all surveys, the measurement time was set to 1.2 seconds, which was cycled twice at each electrode pair. The maximum error threshold between measurement cycles was set to 2% and injected current for each measurement was set to a maximum of 2000 mA.

All data acquired were processed with EarthImager 2-D inverse modeling software produced by AGI. Pseudosections were inverted using smooth model inversion with L2 norm optimization. Noise associated with natural magnetotelluric currents was automatically removed from all data. This was accomplished by applying an estimated noise threshold of 3% prior to inversion. Additionally, misfit data were removed by utilizing a data misfit histogram after inversion was complete. This process allowed for more accurate models which represented true subsurface resistivity distribution at each site. Terrain corrections were applied to all data to better represent the topography within the survey area. This was achieved by extracting elevation values from a digital elevation model created from LiDAR (Light Detection and Ranging) data of the study area and processed in ESRI ArcGIS. LiDAR horizontal resolution was acquired at 0.3 - 0.4 m with 10-cm vertical resolution. LiDAR images were analyzed at each site for karst delineation and extent to compliment resistivity data.

Site Analyses and Interpretations

Survey Site RES 1

Survey site RES 1 was conducted in a northwest-southeast trending line with 56 electrodes at 2-m spacing and a total line length of 110 m (Figure 3). The effective depth of penetration was 23 m. This site is located in a topographically low region within the study area, making this site more susceptible to overland flow during precipitation events. Overgrowth of vegetation on the surface is localized near the center of the survey line, around the 50 to 60-m mark. The three zones of low resistivity (40 - 100 Ωm), noted by circular dashed lines at around 10 m of depth, are interpreted to be solution conduits filled with moisture-rich gypsic soils transported from the surface. A dashed line across the entire profile indicates an approximate bedrock boundary with a lower profile of leached bedrock less saturated than the upper. A continuous zone of low resistivity in the northwest end of the survey at 5 - 6 m in depth is a filled sinkhole. At depths of 15 - 20 m, a gradually increasing high resistivity zone represents fractured gypsum bedrock.

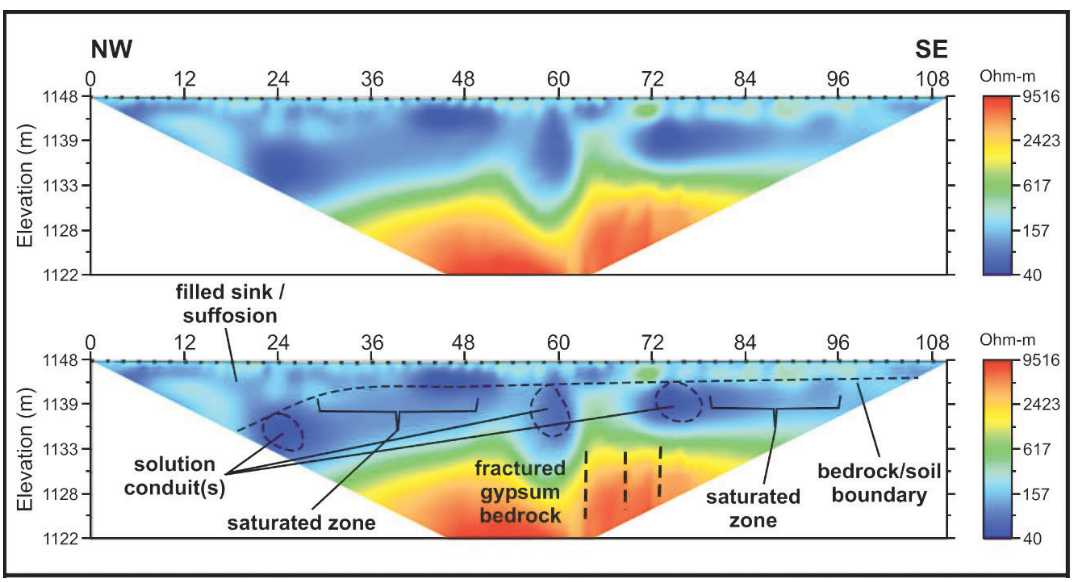

Figure 3. Site RES 1 inverted (top) and interpreted inverted (bottom) sections (dipole-dipole array, 56 electrodes at 2-m spacing with total survey length of 110 m). RMS error = 5.73%, L2 norm = 0.70, iteration = 5. Scale = 1:1.

LiDAR imagery of this site shows surficial karst features proximal to the survey site (Figure 5A). Most notable is the cave entrance directly opposite the survey site that was discovered during site reconnaissance prior to this study. Observations of this feature showed a sediment-filled solutional conduit that trends underneath the road towards the filled sinkhole on the opposite side and underneath a small collapse structure in the road. Other karst features delineated from LiDAR and site reconnaissance include a collapse feature and cave entrance northeast of the survey site; however, due to private land restrictions, this feature was not surveyed.

Survey Site RES 15

The survey of RES 15 was conducted in a northwest-southeast trending line with 56 electrodes at 2-m spacing with an effective depth penetration of 26.5 m, and a total survey length of 110 m (Figure 4). A low resistivity anomaly located between the 34-m mark and the 42-m mark and at 7 - 15 m in depth is interpreted to be a solution conduit filled with soil located on the edge of a ridge of near-surface bedrock. Thicker gypsic soil occurs to the northwest, where increased shallow suffosion is common. Stratal leaching associated with gypsum dissolution is attributed to the contrasting low and high resistivity, and represents variable moisture content in the subsurface within solutionally-widened fractures and gypsum laminae. A high resistivity anomaly at depth is interpreted to be highly fractured gypsum (dashed vertical lines). An entrenched arroyo located to the southeast and down gradient of the survey site, likely promotes increased transport of soils over the surface and through the subsurface as suffosion (Figure 5B).

Karst Processes Delineated by Resistivity Analyses

The occurrence of karst-related geohazards in Culberson County can be naturally occurring or anthropogenically enhanced. The triple permeability of soluble rocks (matrix, fracture, and conduit porosities) creates unpredictable hydrologic systems in karst terrains, while the high solubility of gypsum adds to these complexities within the study area. In general, the anthropogenic effect in karst-related geohazards is often associated with increased runoff and ponding related to road construction and road drainage, or dewatering of karst aquifers for agricultural or industrial use (Klimchouk and Andrejchuk, 1996). Within the study area, anthropogenic effects are mainly attributed to infrastructure development (roadway drainage); however, natural effects also exist. Visual surveys conducted prior to resistivity surveying identified several road degradation features such as potholes, subsidence, road base exposure, and fractures, which could be correlated to the resistivity data as zones of induced suffosion (RES 15), solutional conduits (RES 1), and fractured or leached bedrock.

Geohazards attributed to karst in the region appear to be dominated by suffosion processes that are coupled with shallow karst phenomena, both solutional conduits and solutionally enhanced leached zones. Caves, fractures, and sinkholes are areas of high permeability that facilitate

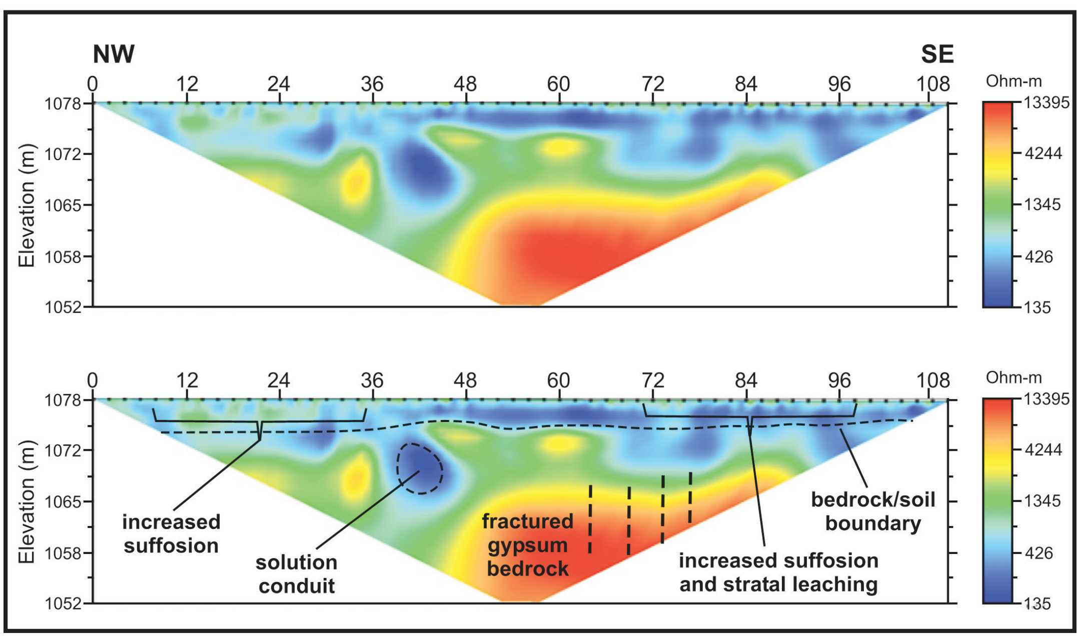

Figure 4. Site RES 15 inverted (top) and interpreted inverted (bottom) sections (dipole-dipole array, 56 electrodes at 2-m spacing with total survey length of 110 m). RMS error= 4.63%, L2 norm= 0.76, iteration= 4. Scale=1:1.

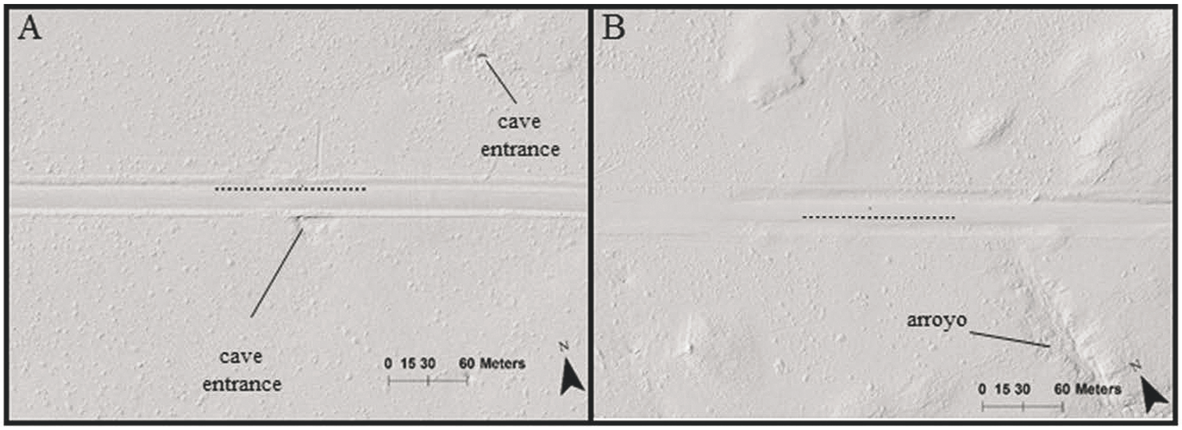

Figure 5. A) Site RES 1 LiDAR imagery showing the location of cave entrances proximal to survey site. B) Site RES 15 LiDAR imagery showing nearby entrenched arroyo. Dashed lines represent the approximate location of electrical resistivity surveys.

suffosion during heavy precipitation events, which subsequently induce piping and void creation beneath road bases resulting in subsidence of the road.

Surveys conducted at RES 1 showed thicker soil horizons in the resistivity profile section that are interpreted to be caused by suffosion where soil is 'piped' into open cavities from the surface. Discontinuities in the gypsum bedrock observed after excavation show that a zone of thicker gypsic soil fill at RES 1 is partly related to preferential dissolution or 'leaching' of bedrock at shallow depths where collapse and subsequent soil infilling have occurred. A cave passage that extends directly underneath the road at RES 1 may act as a recharge zone where overland flow transports soil into the subsurface, while also adding solutionally aggressive waters to the conduit system.

Fractures identified in the resistivity profile analyses are inferred mainly from surficial expressions at RES 1 and RES 15, where solutional widening of these fractures has occurred by gravitationally driven fluid migration, which creates near-vertical, planar features that are ubiquitous in the area. Ascension of moisture-laden air through density convection from the water table also contributes to solutional widening in these zones, which is more common in the hypogene karst regions of the study area (Stafford et al., 2008). In both instances, these fractures act as secondary pathways for soil transport associated with suffosion processes. Like fractured zones, leached zones of gypsum were identified in the profile section of RES 15, where leaching occurs in regions of sustained water ponding over fractured gypsum rock or fractured, indurated gypsic soil. Leaching subsequently results in differential dissolution both laterally and vertically, which promotes compaction and differential subsidence. Excavations conducted during this study at survey sites that are not reported in this paper showed leached zones at relatively shallow depths of 2 - 5 m where heavily fractured gypsum rock was solutionally widened and partially infilled with soil.

Conclusions

The application of electrical resistivity surveying in this study proved essential to characterize potential failures that were not directly connected to the surface as exposed karst features. Both sites RES 1 and RES 15 showed direct evidence of karst-induced road failures on the surface; however, prior knowledge of the proximal hydrologic system was required to properly identify resistivity anomalies observed, which included suffosion, subsidence, fractures, and solutional conduits.

The heterogeneous nature of karst, specifically gypsum karst, creates less than favorable conditions for electrical resistivity surveying, especially in locations in arid climates where the contact resistance is increased and electrical coupling between electrodes is difficult to achieve. In this study, sites where the surface was more homogenous or contained indurated gypsic soils were more suitable for data acquisition. Other limitations to consider are the three-dimensional effects of the features identified in two-dimensional inverted sections. A common yet more time-consuming approach to this problem would be to conduct three-dimensional electrical resistivity surveys to characterize the size and extent of shallow cavities more accurately.

Non-invasive, spatial delineation of karst geohazards is critical for infrastructure development within anthropogenically impacted karst regions. The ability to detect and characterize karst phenomena within the shallow subsurface can enable improved construction design and hazard mitigation, reducing the probability of catastrophic failure. Traditional resistivity methodologies, like this study, are time intensive, but they provide high-resolution characterization for regions of known or suspected geohazards. Furthermore, it is essential that geophysical studies be correlated with traditional geologic and hydrologic studies in karst regions for proper identification and delineation of remotely sensed hazards.

Acknowledgements
This research was partially funded by the Texas Department of Transportation with support from the Geology Department at Stephen F. Austin State University (SFASU). The author would like to thank Dr. Kevin Stafford and Dr. Wesley Brown of the Geology Department at SFASU for their guidance on this research. In addition, the author is grateful for the generous fieldwork assistance by Aaron Eaves, Niko Welch, and Jonathan Woodard. Furthermore, the author would like to thank the National Cave and Karst Research Institute (NCKRI) for the geophysical equipment provided, and the team at Advanced Geosciences Inc., in Austin, Texas, for their technical assistance during this study. Finally, the author is thankful to Brian Cowan P.G and J.A. Rummler P.G. for their review, comments, and suggestions during the preparation of this paper.

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Management and Monitoring in Karst Session

Chair: John Hickman

Widespread Cave Filling in Austin

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Abstract

The filling of caves has been a widespread practice in Texas over the last 200 years. The reasons given include keeping water at the surface for mills, stock ponds and other surface water supplies, eliminating fall hazards for livestock and people, disposing of ranch trash, mitigating perceived poor air quality, disease and habitat for undesired animals, increasing marketability for development, creating water-quality ponds, eliminating surface disturbance associated with restoration, and protecting the groundwater from surface contamination. While numerous studies equate "increasing yield" of a landscape to increasing runoff to streams, in Central Texas it is advantageous to infiltrate runoff for groundwater recharge, reduced flooding, and sustained spring flows. The effect of historic widespread filling of caves and sinkholes has contributed to increasing flooding risk and reduced habitat for cave species including rare and endangered invertebrates and bats. Cave restoration also can provide important educational and historical resources to the local community.

The majority of the known caves in Travis County required excavation and documentation by cave volunteers that were associated with the local branches of the National Speleological Society and the Texas Speleological Survey since the 1950s. Since 2013, the City of Austin has hired and contracted cavers to conduct cave excavation and restoration. Because the scope of restoring caves can be a large effort, (the number of trained cave excavators and annual investment are limited, and filled caves can be challenging to detect), the discovery of new caves occurs at a slow pace. Caves, some of which are very extensive and/or biologically significant, continue to be discovered each year in the Austin area.

Karst Impact Management Scheme for Cave Sites in the Cayo District, Belize, C.A.

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Abstract
Twenty percent of the world's total surface area consists of karst terrain, which provides 20 to 25 % of the drinking water to the world's population. As a result, it is important to protect these fragile sites such as sinkholes and caves. These karst sites serve as sensitive indicators to the overall health of an ecosystem. However, they are often exploited as natural parks and show caves where humans cause intentional and unintentional destruction. In Belize, while there are numerous cave features throughout the landscape, only a few are available for tourism purposes. The results of this study indicate that there is the need for proper development of policies and guidelines that will protect the integrity of the few cave sites open to the public. In Central America and the Caribbean, cave monitoring is very unusual and considered a low priority. The objective of this paper is to use the quantified human impacts on show caves in Belize using a karst disturbance index, and provide proper regulations that need to be implemented based on these results. A convenient sample method was used to select the Barton Creek, Actun Tunichil Muknal, and Nohoch Che'en caves as study sites. The degree of impact to cave formations (speleothems) and erosion was collected through an observation process by physically visiting the three cave sites. The karst disturbance index was applied with moderate confidence levels to assess the impacts caused by human activity at the selected caves. This research is vital for understanding the state and condition of the cave sites in Belize and institute policies that will provide protection for these karst environments in Belize.

Comparing Cave Climate During COVID Closures vs Open Times at Lehman Caves

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Abstract
In March 2020, Lehman Caves in Great Basin National Park, Nevada closed to tours and stayed closed until May 2021, a total of over 400 days. During this time, the cave lights were primarily left off except during some staff work in the cave (approximately 30 days). Visitation decreased from about 33,000 to about 50 people. Before, during, and after this closure, hourly temperature and humidity data loggers collected data at several locations in the 3-km long cave. Periodic carbon dioxide levels were recorded as well. At the site of the Doghouse relay station in the cave, the average temperature was 51.1°F during the closure and 54.0°F with limited tours. Humidity changed from an average of 100% during the closure to 94.4% with limited tours. Carbon dioxide levels near the main transformer by the Lodge Room showed a daily increase of 300 to 400 ppm in late July and early August 2021, with 6 daily tours. The maximum usually occurred in mid-afternoon, with a minimum at about 0800. Temperature at this nearby location showed an increase of 4-6°F during each day in early August with tours, with a minimum temperature at 0700 or 0800. A remote part of the cave showed no temperature or humidity change during this time period. This unexpected cave closure allowed for cave baseline climate conditions to be documented, as well as giving the Park a better understanding of how tours impact parts of the cave environment.

Introduction
A baseline of cave climate is difficult to obtain in show caves that have been visited continuously by tourists for over the past 100 years. Basic questions emerge such as: How have humans impacted the cave climate? What are the natural cave readings?

Cave temperatures are generally the average annual outside temperature of that area. Temperature and carbon dioxide (CO_2) have been found to rise in show caves when visitors are present (Dragovich and Grose, 1990; Cigna, 1993; Linan et al., 2008; Lario and Soler, 2010; Fernandez-Cortes et al., 2011).

While increased CO_2 may increase the number of troglobites (Howarth and Stone, 1990), carbon dioxide levels above 2400 ppm can deteriorate speleothems (Lario and Soler, 2010). Borsato et al. (2015) found that lower elevation caves generally have higher CO_2 levels and more speleothems, while higher elevation caves tend to have lower carbon dioxide levels and fewer speleothems. However, too much CO_2 means no speleothem growth, or speleothem growth only in the winter.

Generally, there are five inputs of carbon dioxide into the cave: 1) external atmosphere (generally about 450 ppm outside Lehman Caves); 2) soil overlying caves; 3) bacteria oxidizing organic matter in carbonated rocks or cave deposits; 4) deep gas diffusion or transport; and 5) human activity (Linan et al., 2008).

Previous study of temperature in Lehman Caves found that two monitoring locations off the tour route stayed constant year-round, while four locations along the tour route showed both daily and annual temperature variations (Sebela et al., 2019).

In March 2020, Lehman Caves in Great Basin National Park was closed to tours due to COVID-19. It stayed closed until 23 May 2021, a total of 427 days. This may have been the longest closure since the cave was opened for tours in 1885. (In 1944, during World War II, there were only 872 visitors for the year, so the cave was likely closed for a few months.) During the recent closure, the electrical lights largely remained off, except for a few work trips by park staff. Instead of 33,000 people visiting the cave, only about 50 people visited during this time period. This hiatus in normal cave operations allowed for a study of what impact cave visitation has on cave climatic conditions.

Study Area
Lehman Caves is a 3-km long cave located in the Pole

Canyon Limestone, which locally has been metamorphosed to marble. The cave has been open to the public since 1885 and is known for its beautiful cave shield speleothems (Figure 1). The cave is located in Great Basin National Park in east-central Nevada, USA (Figure 2). The cave has one natural entrance, which is gated, an entrance tunnel opened in 1939, and an exit tunnel opened in 1970. The tour route covers about 1 km of the cave along a concrete

Figure 1. Cave shields in the Grand Palace, Lehman Caves, Nevada.

path (Figure 4). An electrical lighting system, installed in 1977, uses a main transformer to step down 480V to 240V power and four additional transformers to step down to 120V power to send to the 230 lights along the path. About 180 of these lights use LED light bulbs, while the remainder use incandescent wall fixtures.

Figure 2. Location map of Lehman Caves, located in Great Basin National Park in east-central Nevada, USA.

Methods

Onset HOBO Pro v2 data loggers had been installed at various locations in the cave prior to the shutdown for other cave climate studies. They were programmed to record hourly data. Carbon dioxide was measured with a CM-501 carbon dioxide meter from CO2meter.com. Data was analyzed in Excel.

Figure 3. Electrical relay panel in the Doghouse, Lehman Caves, site for the data logger recordings in this article.

Results

Cave Visitation

Cave visitation showed a highly seasonal trend, with over 7,000 visitors per month in June 2018 and June 2019 (Figure 5). That seasonal trend is absent in 2020 and resumes to a smaller degree in 2021, with a peak of about 4,000 visitors in June.

Relay Station Temperature and Relative Humidity

In 2019, pre-closure and under normal conditions, a HOBO Pro v2 data logger recording hourly temperature and relative humidity data showed daily fluctuations (Figure 6). The temperature next to the doghouse relay station ranged from about 52°F to 60°F every day, with an average of 53.9°F. Relative humidity dropped from near

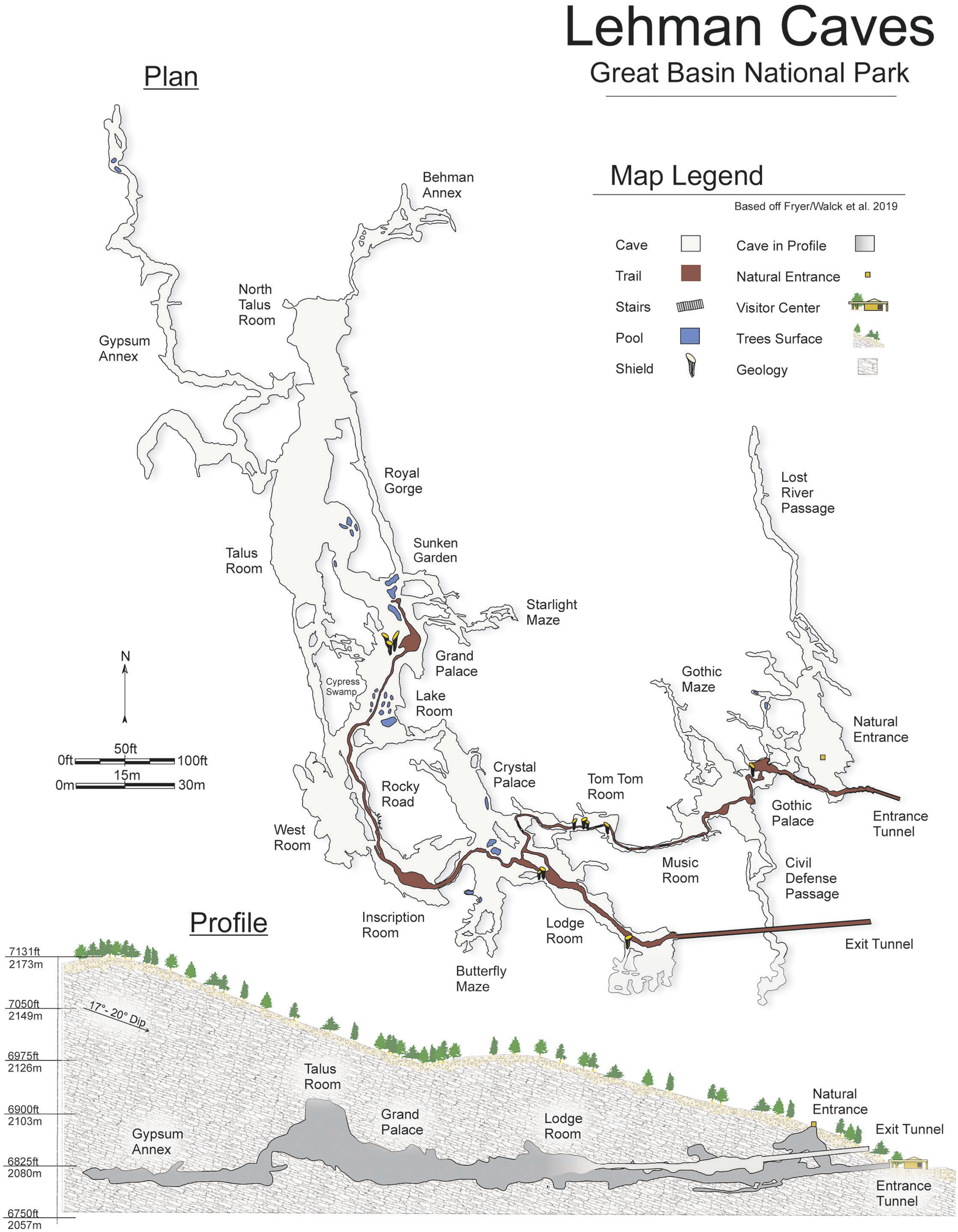

Figure 4. Plan and profile maps of Lehman Caves, Nevada. The tour route is shown in red.

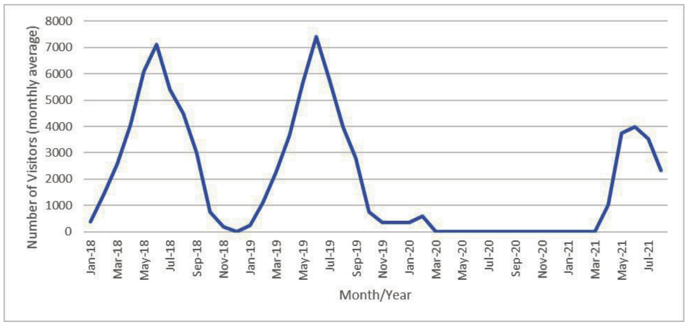

Figure 5. Lehman Caves visitation from January 2018 to August 2021. Notice the summer peaks in 2018, 2019, and 2021 (albeit reduced), and the absence of visitors in 2020.

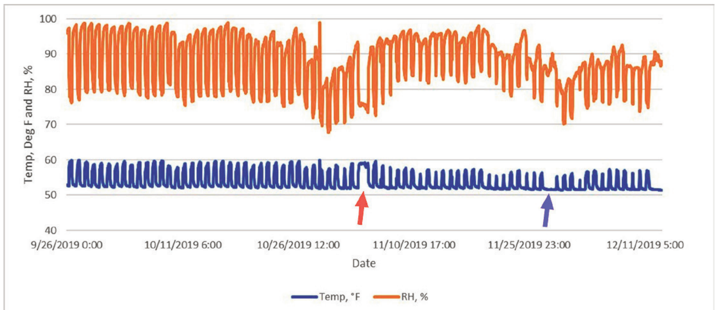

Figure 6. Temperature and humidity in Lehman Caves during "normal" conditions, from September 2019 to December 2019.

100% to less than 80% (and sometimes less than 70%) every day, with an average of 87%.

Fluctuations in both temperature and relative humidity were larger in September and October than November and December due to a reduction in tour frequency on November 1 from 4 tours a day to 1 to 2 tours a day. The data also showed when the cave lights were left on overnight on 4 November 2019, and when the lights stayed off for Thanksgiving on 28 November 2019.

On 20 March 2020, the cave closed to public tours. The average daily cave temperature on that day was 51.2°F and stayed within 0.3°F until lights were turned on sporadically in November for park staff work (Figure 7). Relative humidity remained at 100% for a few months.

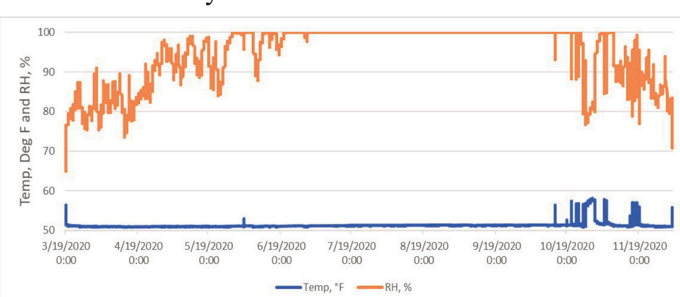

Figure 7. Lehman Caves temperature and humidity during cave closure from March to December 2020.

The cave reopened on 23 May 2021 to limited tours. Before the reopening, the cave temperature was stable at 51.1°F, except for days when lights were turned on for staff work (Figure 8). The average temperature during the period was 51.1°F, and the minimum temperature ranged from 50.6°F to 50.9°F. Once limited tours started at the end of May, we saw the same pattern as before the cave closure, with huge daily fluctuations of both temperature and humidity. Average temperature rose to 54.0°F. In addition, the minimum temperatures trended higher after regular tours started, starting at 51.0°F on 23 May 2021 and rising to 52.9°F on 4 August 2021.

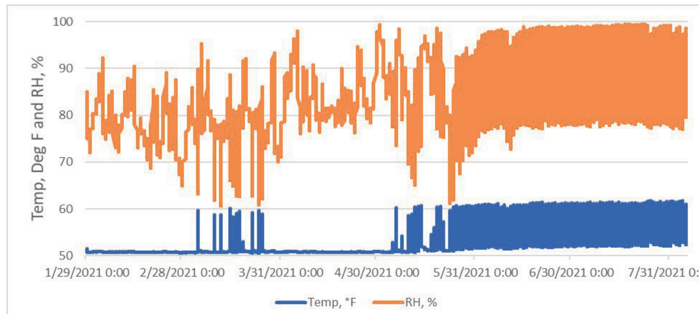

Figure 8. Temperate and humidity at the Doghouse, Lehman Caves from January 2021 to July 2021.

Overall Cave Temperatures

In the Talus Room, located off the tour route, the cave does not show the diurnal fluctuations seen next to the paved trail and electrical system (Figure 9). The cave temperature stayed a steady 52.1 to 52.3°F from January 2018 to September 2021. During the cave closure, no change was seen. The biggest change was in April 2019, when the HOBO Tidbit data logger was switched out with a HOBO Onset Pro v2 and the temperature increased 0.2°F.

This steady temperature was not observed in an off trail location closer to the entrance (Station BB near Rose Trellis Room (Figure 10). In that location, the 2019 overall cave temperature was highest, in 2020 it was lowest, and 2021 was between the two.

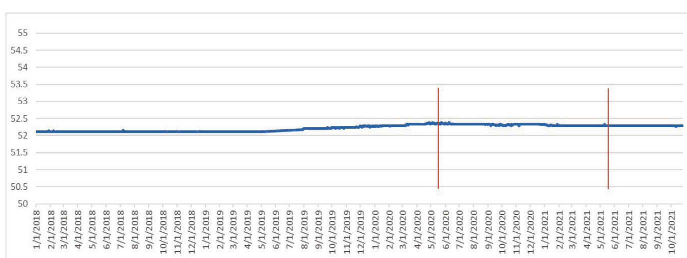

Figure 10. Temperature at off-trail station near the Rose Trellis Room, Lehman Caves, from 2019-2021.

Carbon Dioxide Levels

Due to the nature of the carbon dioxide meter used in the study, we have recordings of just a few days at a time, and then the meter had to be removed from the cave for charging.

From 9-18 December 2020, the CO_2 levels in the Lodge Room varied from about 500 to 1500 ppm (Figure 11). From 7-16 January 2020, the CO_2 varied from 560 to 870 ppm (Figure 12). No tours were conducted during this time.

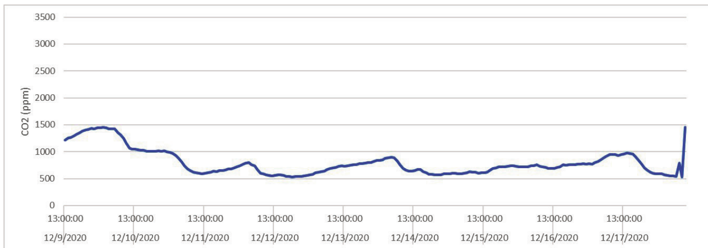

Figure 11. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 9-18 December 2020.

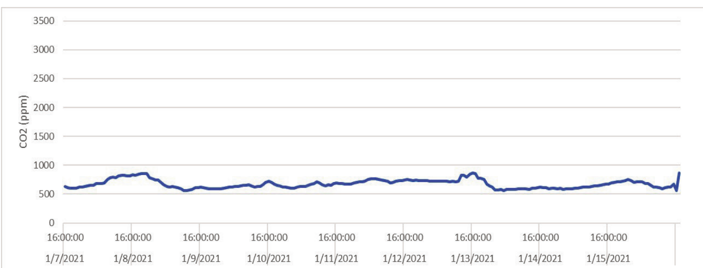

Figure 12. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 7-16 January 2021.

In June 2021, six tours a day with 20 people per tour were given. CO_2 levels exceeded 2000 ppm, with a noticeable daily fluctuation (Figure 13). This daily trend continued in

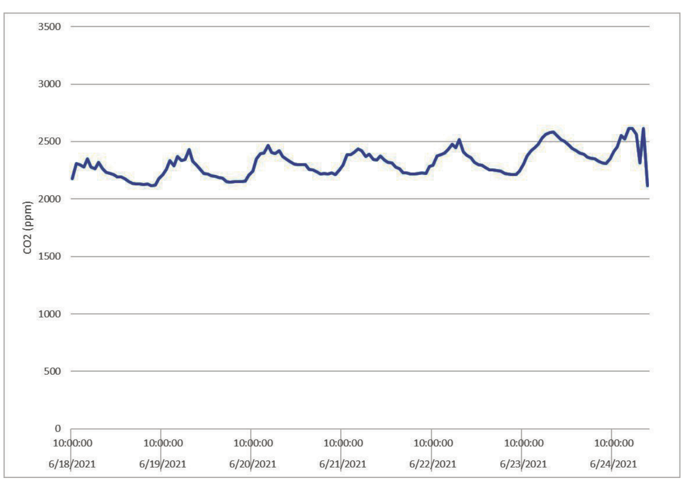

Figure 13. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 18-24 June 2021.

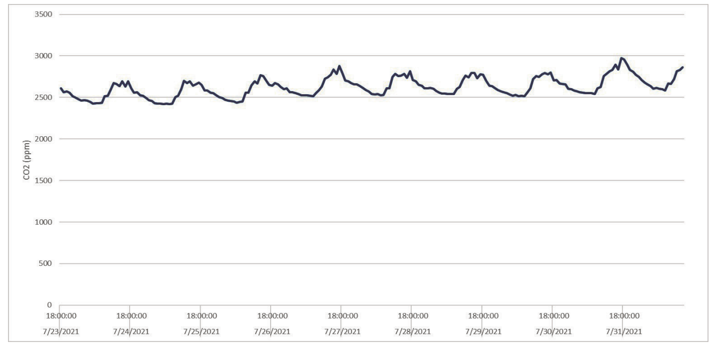

Figure 14. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 23-31 July 2021.

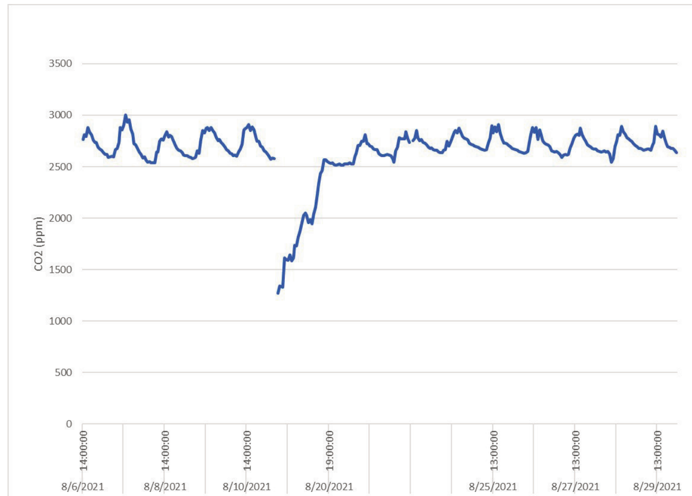

Figure 15. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 6-10 August and 19-30 August 2021.

July 2021 (Figure 14) and August 2021 (Figure 15), with a daily general increase of 300 to 400 ppm. The maximum CO_2 level usually occurred in mid-afternoon, with a minimum at about 0800.

A sudden decrease is seen in August 2021, when the data logger was replaced in the cave after charging on 19 August with a CO_2 level of 1274 ppm. Sudden decreases also occurred in September 2021 (Figure 16) and October 2021, with CO_2 levels plummeting from near 3000 ppm to less than 750 ppm. CO_2 levels then increased.

Checking on temperatures outside the cave, I discovered that these major decreases corresponded to temperature drops below the ambient cave temperature of about 52°F (Figure 17).

Discussion

Temperature and Humidity

When the electricity to the cave is turned on, it goes to a main transformer at the Giant's Ear and then goes to four

Figure 16. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 9-22 September and 27-30 September 2021.

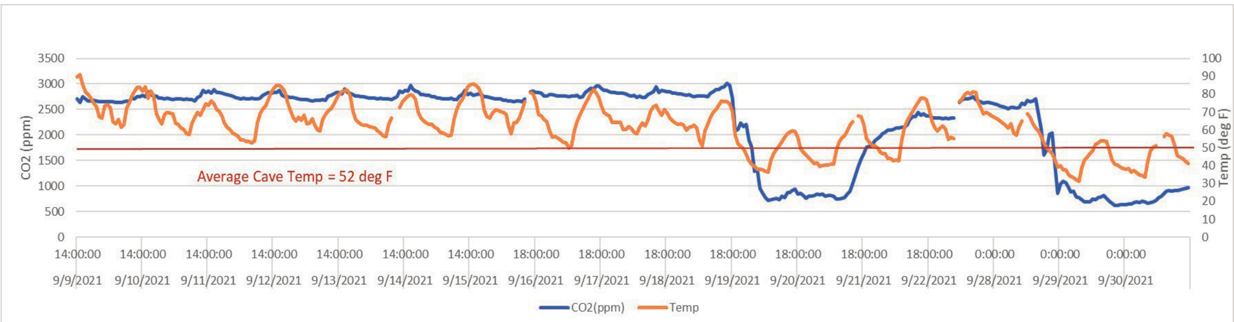

Figure 17. Carbon dioxide levels in the Lodge Room, Lehman Caves, from 9-22 September and 27-30 September 2021 overlaid with hourly temperatures from outside the cave entrance.

relay panels: Giant's Ear, Civil Defense, Doghouse, and Cypress Swamp. A small heater is installed in each relay panel to help keep the electrical components in it dry. So, heat is being added to the cave not only due to light bulbs and human body temperature, but also due to these heaters.

Reducing these temperature and humidity fluxes is one of the goals of the new cave lighting system. Hopefully we can help restore a more natural cave climate by having the lights on less (only when we need them) and by eliminating extra heaters in the cave by using newer technology.

The increase in temperature and decrease in humidity appear to remain somewhat localized along the tour route. The control station in the Talus Room did not show fluctuation in cave temperature, even when the cave was closed for over a year. This is reassuring from a management perspective that at least some parts of the cave appear to have a natural climate regime. However, it would be ideal to help areas along and close to the tour route have a more natural climate by reducing heat from lights.

Carbon Dioxide

Carbon dioxide levels in the cave are not at dangerous levels for humans, however, above 2400 ppm, the process of condensation corrosion occurs (Lario and Soler, 2010). It appears that this level is reached for a good part of summer, with daytime values the highest. With CO_2 levels this high, this also means that speleothems are not growing during this period.

Additional study is needed to help differentiate increases in CO_2 due to humans versus natural levels such as decomposition in the epikarst.

Conclusion

This unexpected cave closure allowed for cave baseline climate conditions to be documented, as well as giving the Park a better understanding of how tours impact parts of the cave environment. Additional climate monitoring and analysis will help us better understand how the cave is affected by tours and infrastructure as well as seasonal and annual variations.

Acknowledgements

Thanks to Robert Reinhart for cave visitation data and the many park staff and volunteers for helping to download data loggers.

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Effects of Visitation Patterns on Carbon Dioxide Concentrations Within Carlsbad Cavern

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Abstract
Carlsbad Cavern, as a renowned show cave, faces potential hazards to its natural resources due to human visitation. Exhalation from visitors leads to elevated levels of CO_2 in the air within the cave, which could pose a significant threat to human life and to the sensitive cave environment. At high concentrations of CO_2, the human body suffers a multitude of negative physiological effects, cave speleothems experience slowed growth or even dissolution, and the resident flora and fauna could have their habitats disrupted. Thus, the National Park Service seeks to develop an improved understanding of the driving mechanisms behind CO_2 levels in the cave. In this study, we investigated the relationship between human visitation patterns and elevated CO_2 levels throughout seasonal shifts and the lifting of COVID-19 visitation restrictions. We used Wöhler CDL 210 devices to continuously monitor CO_2 levels at three key locations within the cave. The CO_2 data was compared against visitation data obtained from ticket sales and a TRAFx Infrared Trail Counter. We conclude that human visitation is strongly correlated to the daily average CO_2 range, and that the effects of visitation on CO_2 levels experience a short time delay. The results of this study suggest that future visitation policy at Carlsbad Cavern may need to be designed to limit the amount of CO_2 buildup and prevent the degradation of the cave environment.

Summary
Carlsbad Cavern, located in southeastern New Mexico, is an extremely valuable cave that has been designated as a UNESCO World Heritage Site because it has many spectacular cave formations, ancient fossils, and types of animal and plant life within it. The cave is open to the public, and people often travel to it to see the massive cave formations and bat flights. However, when people go inside the cave, they breathe out carbon dioxide, which can harm the health of other people and damage the cave environment if there is too much of it. To protect the visitors and the cave, we studied how visitation affects the amount of carbon dioxide in the cave. We found that human visitors strongly influence the levels of carbon dioxide in the cave. These results could be used to determine whether visitation at the cave needs to be limited in order to prevent too much carbon dioxide from building up and damaging the cave's irreplaceable natural resources.

Introduction - Carlsbad Caverns National Park
Due to the incredible geological, historical, and ecological significance of Carlsbad Caverns National Park, preserving its natural resources is of utmost importance. The park, located in the Guadalupe Mountains of southeastern New Mexico, is home to an environment of rich natural biodiversity and geological formations. Carlsbad Caverns National Park has been designated as a UNESCO World Heritage Site and is renowned for its eponymous show cave, Carlsbad Cavern. Geologically, the cave contains a large variety and quantity of splendid speleothems (Figure 1), which are cave formations such as stalagmites and stalactites formed over hundreds of thousands of years by the deposition of carbonate compounds.

Figure 1. The Doll's Theater speleothem formation in Carlsbad Cavern, featuring soda straw stalactites.

In addition, the Permian Capitan Reef serves as the host rock for the Big Room of Carlsbad Cavern, exposing

Figure 2. Outline of Visitor Use Management Framework steps. From NPS (2016).

numerous ancient fossils and granting visitors a unique glimpse into the past (NMBGMR, 2021). The cave is also rare in its hypogenic formation. Typically, most caves are epigenic, where rainwater migrates downward into the soil and dissolves limestone. In contrast, Carlsbad Cavern was formed when naturally occurring sulfuric acid in the ground migrated upwards and dissolved the limestone rock from below (Sendra et al., 2014). Furthermore, the cave plays a critical role in the Chihuahuan Desert ecosystem, hosting cave swallows, endemic invertebrates, and a colony of over 160,000 Brazilian free-tailed bats (Strong, 2006).

Visitor Use Management Framework

The Visitor Use Management (VUM) Framework is a system utilized by the National Park Service (NPS) to effectively manage visitation policy (NPS, 2016) (Figures 2 and 10). The process consists of continually monitoring, evaluating, and responding to ever-changing conditions within the park in order to both protect the invaluable natural resources and the visitor experience. As such, the NPS uses VUM studies to observe trends in the park and subsequently alter or maintain current policy.

Currently, the possible detrimental effects of elevated carbon dioxide (CO_2) levels on the cave speleothems and human health are of great concern. In response to this possible threat, the NPS is monitoring CO_2 levels in Carlsbad Cavern as part of an ongoing VUM study to determine whether visitation is strongly correlated with elevated CO_2 levels. Past research suggests a strong correlation between visitation and elevated CO_2. For example, a study conducted at the Balcarka Cave in the Czech Republic found that human respiration could triple natural baseline CO_2 levels during extended visitation (Lang et al., 2015). However, the past years of this VUM study have yielded inconclusive results due to unforeseen errors in instrumentation and poor data quality (Meyer, 2019; Mangipudi, 2020). As such, there is a need for an updated study that corrects for such errors and utilizes improved data.

Sources and Impacts of Elevated CO_2 Concentrations

CO_2 is a colorless gas that is found naturally as a trace gas in Earth's atmosphere at concentrations of approximately 400 parts per million (ppm). When humans respire, they consume oxygen and release CO_2 as a waste product. However, in enclosed spaces, CO_2 concentrations can build up and displace oxygen in the air, resulting in detrimental effects that can range from mild discomfort to death by asphyxiation (Bonino, 2016) (Figure 3). Due to the popularity of Carlsbad Cavern and the high visitation levels, current CO_2 concentrations in the cave are a substantial safety concern. Furthermore, anecdotal evidence has shown that up to 960 individuals may congregate in the elevator line on peak visitation days, potentially leading to harmful CO_2 buildup (Meyer, 2019).

Elevated CO_2 concentrations in the air can also have detrimental effects on cave speleothems. Normally, cave water contains dissolved CO_2, allowing it to become supersaturated with calcite. In normal CO_2 conditions, when cave water meets air with a lower CO_2 partial pressure, the CO_2 will degas and the calcite is deposited

CO_2 Concentration	Effect on Humans
300-400 ppm	Outdoor
350-1,000 ppm	Concentrations typical of occupied indoor spaces with good air exchange
1,000-2,000 ppm	Complaints of drowsiness and poor air
>2,000 ppm	Ventilation is necessary! Lung ventilation increases by 50 percent, headache after several hours exposure
2,000-5,000 ppm	Headaches, sleepiness and stagnant, stale, stuffy air; Poor concentration, loss of attention, increased heart rate and slight nausea may also be present; Lung ventilation increases by 100 percent, panting after exertion
5,000 ppm	Workplace exposure limit (as 8-hour TWA) in most jurisdictions; TLV-TWA (40-hour work week)

Figure 3. Effects of CO_2 on human physiology. TLV-TWA refers to threshold limit value time weighted average. From Meyer (2019).

alongside because its saturation point has decreased, creating a speleothem (Fairchild et al., 2007). However, if the CO_2 partial pressure of the ambient air is too great, the CO_2 in the water cannot degas, impeding the deposition of calcite and the growth of speleothems (Baldini, 2010). Furthermore, CO_2 concentrations in excess of 2400-2900 ppm could even lead to the corrosion and degradation of valuable speleothem formations (Dragovich and Grose, 1990). As such, if analysis finds that CO_2 levels are strongly correlated to human visitation patterns, the NPS must take into consideration the well being of the visitors and staff, and the preservation of the park's natural resources when designing new visitation policy.

Current Study

With a more recent and expanded data set, prior awareness of past errors, along with an improved understanding of CO_2 dynamics, the analysis in this current study may yield more conclusive results that can be extrapolated for future use. Based on the results of this study, the NPS may use the data to adopt new strategies and visitation policies in order to prevent excessive or harmful CO_2 levels within the cave. Data from the study may also be utilized in predictive models to determine a theoretical maximum visitor capacity for the cave (Guirado et al., 2019).

Methods

Data Collection - Visitation Data

The primary set of visitation data was obtained from the daily amount of ticket sales. Each ticket sold is considered as one human entering the cave. This method of collecting visitation data is unspecific, as it provides no information about the location of the visitors at a given time. A secondary set of visitation data was collected using a TRAFx Infrared Trail Counter, which detects the number of individuals entering the nearby vicinity and logs visitation every hour. Currently, the counter is only installed at the Big Room Junction and is not calibrated. Normally, the calibration process involves an individual standing next to the counter and manually adjusting the device to account for any over or under counting. Due to COVID-19 restrictions, the calibration has not been completed. Thus, the exact amount of visitation the TRAFx device logs will often be incorrect (e.g., the log may detect more people than tickets actually sold for a given day). However, the relative amounts of visitation are still correct (i.e., the device will correctly identify that more people were present in the area at 9 A.M. than 11 P.M.) and can be used for general comparison on a short-term time scale.

CO_2 Data

The National Park Service currently employs 7 separate Wöhler CDL 210 auto-logging CO_2 monitoring devices to track CO_2 levels. The Wöhler devices measure CO_2 with nondispersive infrared lasers and are programmed to log the ambient CO_2 concentration every 5 minutes. The monitors are cycled through three different locations within the cave: the elevator, Big Room Junction (BRJ), and King's Palace (KP) (Figure 4). Within each location, a Wöhler device is installed in a location that visitors cannot approach too closely to prevent interference in recorded CO_2 levels. Data analyzed in this paper were collected from August 2019 to July 2021.

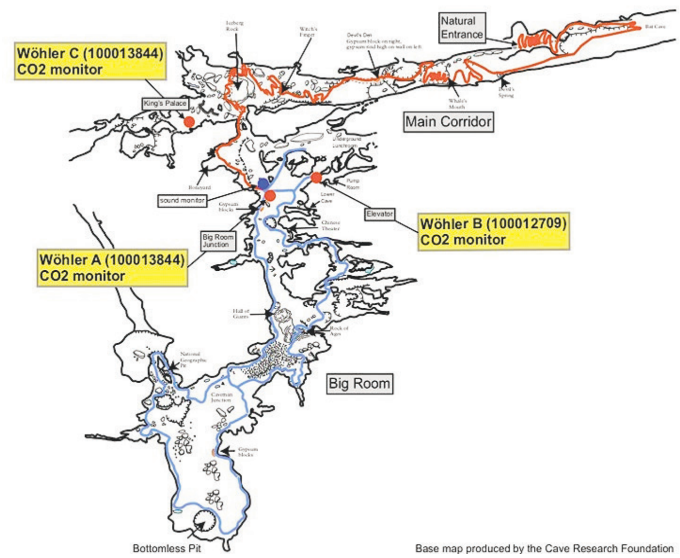

Figure 4. Map of Carlsbad Cavern marking the 3 different locations where the Wöhler CDL 210 loggers were located. From Meyer (2019).

In order for the Wöhler CDL 210 devices to accurately measure CO_2 concentrations, they first must be calibrated in outdoor air conditions to a CO_2 level of 400 ppm. However, the Wöhler devices are hard-coded by the manufacturer to begin an Auto Baseline Calibration (ABC) approximately every 6.5 days, leading to incorrect CO_2 readings. During an ABC, the Wöhler device searches for the lowest CO_2 concentration recorded in the past 6.5 days and assumes it is 400 ppm, making that value the new baseline CO_2. The CO_2 levels in the cave are typically higher than outdoor air and an ABC will manifest as a sharp, instantaneous drop in CO_2 levels, as seen in Figure 5. To prevent the presence of ABCs in the data, the Wöhler loggers were brought to the surface every 5 to 6 days, manually reset and calibrated, and then placed back within the cave, thus restarting the 6.5-day ABC timer. Due to park closures, bad weather, COVID-19, and other unpredictable circumstances, timely retrieval is not always possible and

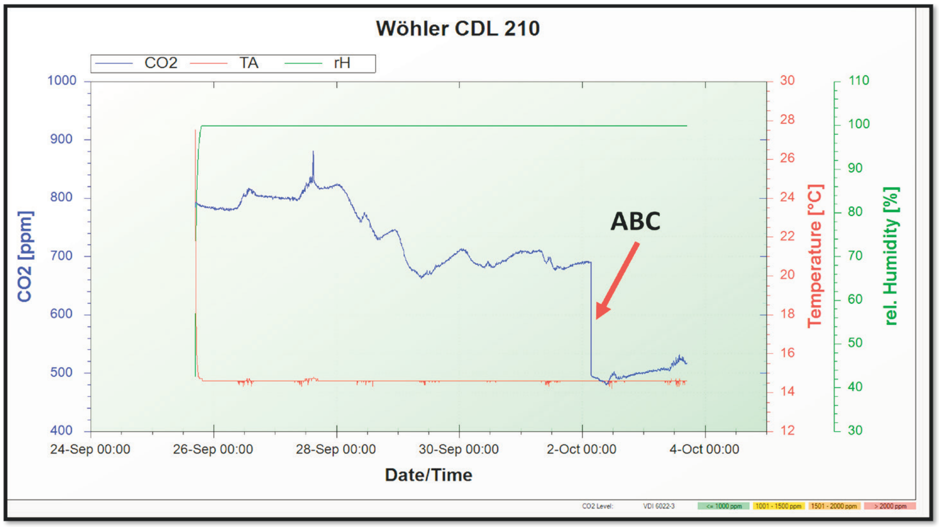

Figure 5. Wöhler CO_2 data with Auto Baseline Calibration (ABC) labeled.

there is a substantial amount of data affected by the ABC. As such, it is necessary to correct for all ABCs present in the data to ensure accurate data analysis.

Data Processing

Data Cleaning

All data processing and analysis was completed in the R programming language and Microsoft Excel. The CO_2 database was initially sorted into the 3 different locations. The data from all locations was merged into one consolidated data set and sorted chronologically. Each file in the data set was manually verified and any duplicate or corrupted files were removed from the data set. Anomalies in the data such as sudden spikes, dips, and ABCs were noted in a log for future reference. When Wöhler loggers are first turned on, typically the first 50 minutes of CO_2 readings are unreliable because the device needs to acclimate to the high humidity of the cave. As such, the first 10 readings (5 minute sample period), are removed from each log.

Correcting ABCs

ABCs, as mentioned previously, are present in a substantial number of the CO_2 logs and can have large impacts on the data. To solve this problem, a script was written to detect sudden drops in CO_2 data and add the amount of the drop to all data points following the ABC, effectively restoring the data to its correct level. The script would only begin searching for an ABC starting at 6 days and 8 hours of collection time to minimize the chance of a false positive from standard fluctuations. The script outputted which logs contained an ABC and each of the ABCs was manually verified in case there were detection errors. Furthermore, only the first instance of an ABC can be corrected. If the device is left in the cave for about 13 days and the device calibrates twice, the data past the second calibration date cannot be adjusted because the correct offset amount is too difficult to calculate. All data past 12 days is thus truncated to remove second ABCs from the data set. However, only minimal amounts of data were lost in this removal process because the CO_2 devices rarely remained in the cave for such extended periods of time.

Data Analysis

Due to the lack of accurate readings from the TRAFx trail counter, visitation data from the device cannot be used to observe trends over long periods of time. However, because the device can still correctly display relative increases and decreases in visitation, it is still valuable for short-term comparisons of visitation and CO_2 increases precisely within the BRJ. As such, BRJ CO_2 data was plotted against one day with visitation, and one day with no visitation to observe hourly trends.

The ABC-corrected data was separated back into 3 different categories for each of the monitoring locations. Individual days with insufficient amounts of data were pruned from the data set. Directly comparing CO_2 levels against visitation does not fully reveal the correlation between the two variables because CO_2 accumulates over time. Instead, a daily average CO_2 range was compared with visitation to see whether visitation correlates with larger daily CO_2 increases. Each day was separated into night hours and day hours to determine the maximum and minimum CO_2 levels for each day. The night hours were considered to be from 00:00 to 10:00 A.M., in order to only capture the baseline CO_2 level before peak daily visitation began. Five maximum CO_2 values were selected from the day hours while five minimum CO_2 values were selected from the night hours. By taking the average of the maximum and minimum CO_2 levels and subtracting the minimum average from the maximum average, the daily average CO_2 range (DAR_{CO2}) was calculated. Furthermore, seasonal shifts in temperature regimes can cause large fluctuations in CO_2. Most notably, summer months have significantly higher CO_2 levels than winter months due to the seasonal temperature differential altering cave airflow dynamics. Thus, the data was then separated into winter and summer months and then plotted against daily visitation. For each plot, a linear regression was performed, and the strength of linear correlation was determined using the Pearson correlation coefficient (Mindrila and Balentyne, n.d.).

Results

General CO_2 Trends

To gain a general understanding of how CO_2 levels were affected by seasonal patterns and unique visitation circumstances such as the COVID-19 pandemic, CO_2 was first plotted against time. Figure 6 shows every single CO_2 reading logged by the elevator CO_2 monitors during the entire collection period. The shift from the summer regime to the winter regime is clearly seen in the significant drops in CO_2 levels. However, the 2020 summer CO_2 levels are noticeably lower than the 2019 summer CO_2 levels, most likely due to COVID-19 restrictions limiting visitation in the cave. The CO_2 levels in the most recent data (June and July 2021) appear to be climbing to higher levels compared to summer 2020 due to an easing of COVID-19 restrictions and visitation slowing rising.

Figure 6. All CO_2 readings at the elevator plotted against time. Gaps in data can be attributed to a combination of missing logs and bad readings.

TRAFx Visitation and CO_2

TRAFx data was used to understand how CO_2 levels reacted to visitation on a short time scale. Figure 7 and Figure 8 each shows one day of BRJ CO_2 data plotted against TRAFx visitation for BRJ in the winter of 2020-2021. Figure 7 displays data from a normal day of visitation while Figure 8 displays data from a day with no visitation due to park closure. Notably, CO_2 levels appear to mirror visitation patterns with a short delay on the day with visitation, and steadily decrease on the day with no visitation.

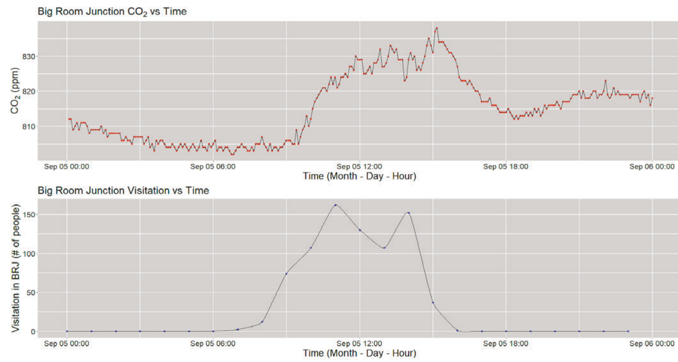

Figure 7. Graphs of CO_2 levels (top) and visitation (bottom) at the Big Room Junction over 24 hours on September 5th, 2020.

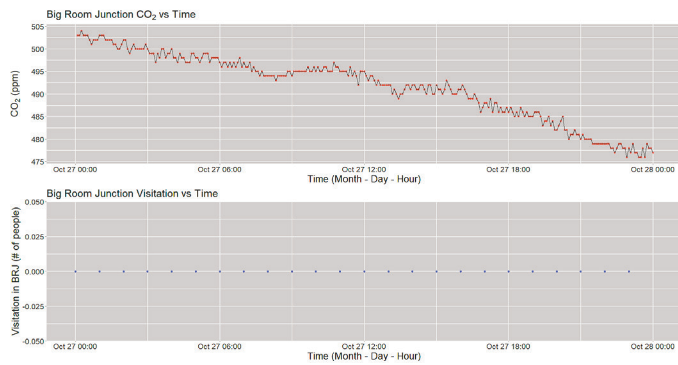

Figure 8. Graphs of CO_2 levels (top) and visitation (bottom) at the Big Room Junction over 24 hours on October 27th, 2020.

Daily Visitation and DAR_{CO2}

The seasonally separated data set is represented in Figure 9, which compares both summer and winter data. DAR_{CO2} at the elevator and BRJ sites appear to be strongly correlated with visitation in both the winter and summer as the Pearson $R > 0.7$ (Mindrila and Balentyne, n.d.). The DAR_{CO2} at KP is only moderately correlated with visitation, as $0.5 < R < 0.7$. The slopes of each linear regression in the winter data are larger than the slopes of the same location during the summer, suggesting that each visitor is contributing more CO_2 to the cave during the winter.

Discussion

TRAFx Visitation and CO_2 Delay

Although the TRAFx data could not be used to conduct rigorous statistical analysis due to uncalibrated results, the graphs revealed a clear trend in the CO_2 fluctuations when compared to visitation. In particular, CO_2 levels very closely followed the relative visitation levels on the

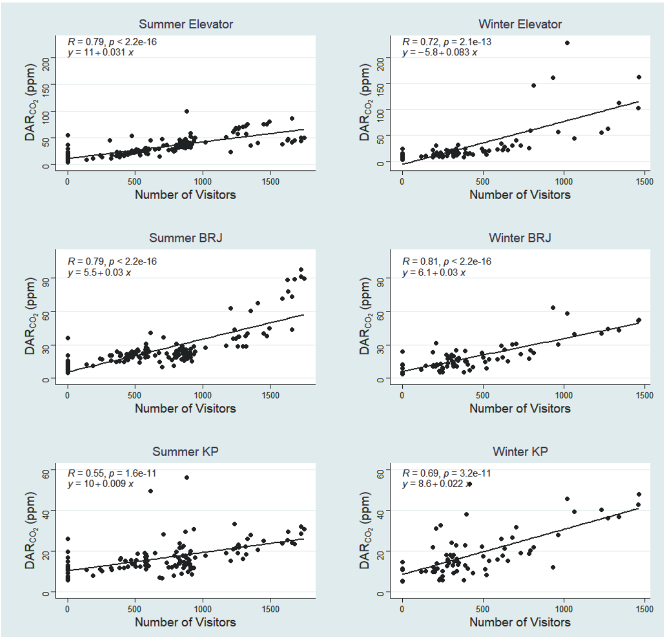

Figure 9: Summer (left) and winter (right) DAR_{CO2} values plotted against park visitation for all 3 locations.

day with visitation, but consistently decreased on the day with no visitation. As such, the CO_2 concentrations most likely rose in response to increased visitation, and when no visitation was present, the cave subsequently began ventilating CO_2 out of the air through natural air exchange, leading to a downward trend. These patterns suggest a strong correlation between the two variables, at least on the short-term scale of a daily period. It is also important to note the apparent delay of approximately 1 to 2 hours between the rise in visitation and a subsequent increase in CO_2 levels. The delayed effect of CO_2 rise may be taken into consideration in the future when considering park visitation policy and open hours for Carlsbad Cavern.

Correlations Between Visitation and DAR_{CO2}

Correlations Strength by Location

The data displayed in Figures 11 and 12 reveal that strong correlations exist between visitation and DAR_{CO2} at the elevator and BRJ sites. These correlations remain relatively steady during both the summer and winter months. However, the KP site had a significantly lower correlation coefficient throughout the year compared to the two other cave locations; thus, DAR_{CO2} was only moderately correlated to visitation. The most likely reason for this discrepancy is that KP had no direct visitation during all plotted time periods due to COVID-19 restrictions. KP is normally only accessible via guided tours, but these guided tours were not offered since the initial COVID-19 shutdown in 2020. The CO_2 levels at KP were still affected by the CO_2 trends in other locations such as the BRJ and elevator because air circulates and exchanges throughout the cave, but the correlation is lower because the air exposure is indirect. Overall, visitation was observed to be moderately or strongly correlated to DAR_{CO2} at all study locations, and a clear link can be established between visitation and CO_2 levels in the cave.

Correlations Strength by Season

In terms of winter and summer differences in CO_2 levels, no definite conclusion can be drawn from the correlation coefficients as they are relatively similar across both seasons, and neither season consistently had higher R values. The winter data does appear to have greater rates of DAR_{CO2} increase vs. visitation as seen in the larger slopes of the regression equations. This difference is unexpected, as the cave typically has better natural ventilation in the winter months, which should in theory lead to less CO_2 increase per visitor present in the cavern. However, the seasonal data is imbalanced due to the winter data only including the winter of 2020-2021 (COVID-19 restrictions in place), while the summer data includes the summer of 2020 (COVID-19 restrictions in place) and a portion of the ongoing summer of 2021, when maximum visitation increased from 1000 to 2000 visitors per day. Thus, the winter data currently lacks a large number of days when visitation rates were above 1000 visitors per day, making a confident extrapolation more difficult, and possibly resulting in abnormal regression slopes. Additional data from the winter of 2021-2022 with normal visitation rates is needed to form more concrete conclusions and reveal new trends that will improve the understanding of CO_2 dynamics.

Future Work

Continuing to consistently monitor data throughout the coming months and years as COVID-19 restrictions ease will be of great importance for further research. Currently, analysis is limited by the lack of CO_2 data with normal visitation levels, and expanding the data set will allow for more confident statistical analysis and comparisons between seasonal CO_2 trends. Once the TRAFx counter has been calibrated, precise and long-term plotting of TRAFx data against CO_2 will be possible and may yield more accurate correlations. Another area of interest is how visitation affects nightly CO_2 ventilation and the cave's ability to return to baseline levels in different weather conditions. Improved understanding of cave ventilation dynamics could allow the NPS to develop a comprehensive predictive model to determine the safe maximum visitation allowed in a given time period and set weather conditions. Furthermore, the ABC correction script developed in this study can be utilized in all future CO_2 data collected by the NPS and will prove extremely valuable for any future investigations concerning CO_2 monitoring.

Conclusions

There is a strong positive correlation between daily average CO_2 range and increased visitation throughout the year. The CO_2 effects of visitation are most pronounced in cave locations with heavy visitation while areas with no visitation are affected to a lesser degree. The immediate effects of visitation on CO_2 levels appear to be delayed by a short time period of approximately 2 hours. The conclusions drawn in this study may play an important role in the development of future visitation policy at Carlsbad Cavern in order to limit the amount of CO_2 present in the cave and prevent the environmental degradation of a critical ecological site. Combined with future research, the results of this study could be instrumental in creating an adaptive environmental model to determine maximum safe CO_2 and visitation thresholds for Carlsbad Cavern.

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Appendix A - Additional Graphs and Figures

Figure 10: Outline of Visitor Use Management (VUM) Framework. From NPS (2016).

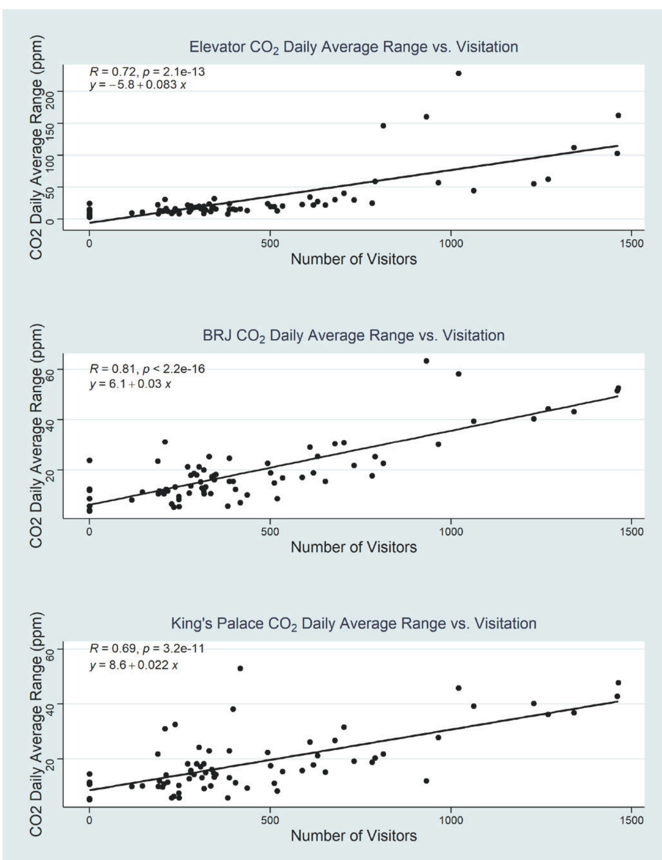

Figure 11: Winter DAR_{CO2} plotted against park visitation for all 3 locations (2020/12/01 - 2021/02/28).

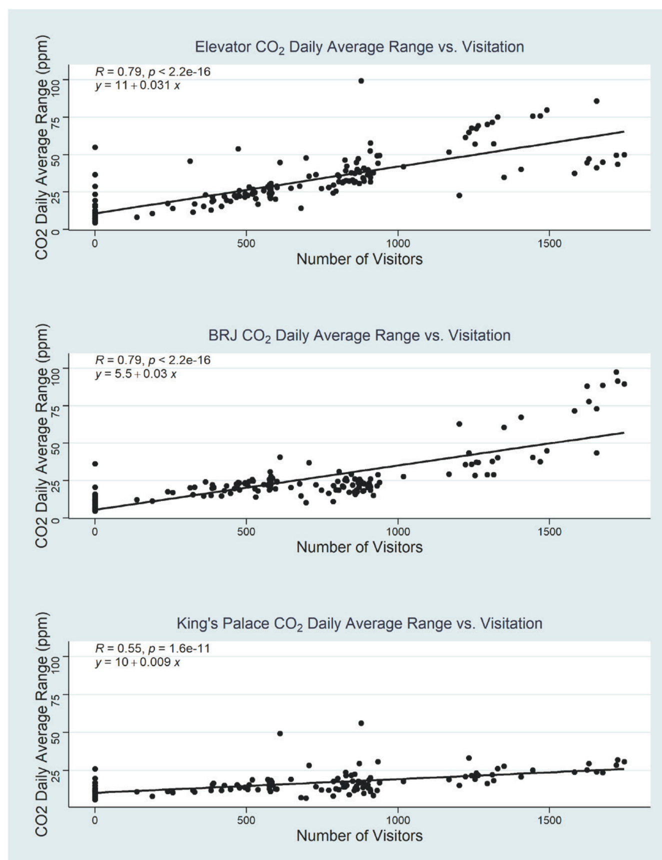

Figure 12: Summer DAR_{CO2} plotted against park visitation for all 3 locations (2020/05/01 - 2020/08/20, 2021/05/01 - 2021/07/24).

How Much Land Does It Take to Protect a Cave

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Abstract
The protection of significant caves often requires more than control of the cave entrance. Complex connections with the surface can be unique to each cave and will dictate the amount of land needed to adequately protect cave resources. As the most biodiverse cave west of the Mississippi River, and habitat for multiple species of conservation concern, Tumbling Creek Cave has been a focal point for karst studies by the Ozark Underground Laboratory for over half a century. The many conservation achievements at Tumbling Creek Cave are the result of numerous studies aimed at understanding the hydrogeological nature of the cave system and the fauna within. Many of those achievements have occurred by improving land use on the surface. The story of cave protection efforts at Tumbling Creek Cave can provide a framework for cave managers when determining how much land is needed to protect a cave.

Introduction
Tumbling Creek Cave, located in Taney County, Missouri, USA, is the most biodiverse cave west of the Mississippi River and has been designated a National Natural Landmark in recognition of its outstanding biological and geological resources (Elliott, 2007). Most of the land overlying the cave was purchased in 1965 for the purpose of karst and cave research facilities and 12 additional parcels have subsequently been purchased. The property is operated by Tom and Cathy Aley as part of the Ozark Underground Laboratory (OUL), a privately owned hydrogeological consulting firm specializing in groundwater and land use investigations in karst landscapes. The OUL has developed many of its methodologies through empirical research conducted over a fifty-year period at Tumbling Creek Cave. OUL staff regularly conduct field tours and workshops in and around Tumbling Creek Cave to educate professional and academic groups about karst terrains and cave ecosystems.

Tumbling Creek, a subterranean stream with perennial flow, is habitat for the endemic and federally endangered Tumbling Creek Cavesnail (*Antrobia culveri*). The cave is also habitat for three other federally listed species including the Gray Bat (*Myotis grisescens*), Indiana Bat (*Myotis sodalis*), and Northern Long-Eared Bat (*Myotis septentrionalis*). An additional endemic troglobite, the cave millipede Chaetaspus aleyorum, is found only in Tumbling Creek Cave. The existence of these species of concern, as well as the rich biodiversity of the cave in general, has driven over 50 years of conservation efforts to protect the Tumbling Creek Cave ecosystem. Much of that protection has occurred on the surface, including the cleanup of 42 dumps, restoring kilometers of gully erosion, planting 75,000 trees to establish forested riparian areas, restoring over 93 hectare (ha) (230 acres) of prairie, glade, and woodland habitat, improving 13 on-site sewage systems including one at a small rural school, and constructing a cave gate capable of allowing safe passage for pregnant Gray bats.

These efforts resulted from an increased understanding of the cave system through research. Studies conducted by the OUL have shown that intimate connections between the surface and subsurface necessitate conservation action above ground to protect the cave and its fauna below. Extensive work at Tumbling Creek Cave has produced many lessons about cave protection, one of which is the amount of land needed to protect a cave. The purpose of this paper is to help cave managers identify issues that will help prioritize land protection efforts based on lessons learned while working at Tumbling Creek Cave and elsewhere.

Past Perspectives on Cave Protection
Historically, cave protection focused primarily on gating the natural entrances to caves. Controlling cave entrances allowed managers to maintain access for cave enthusiasts and researchers, as well as prevent trespass from vandals and artifact hunters. Many cave protection efforts involve

acquisition of small tracts of land to control and maintain access to significant caves. An article published in the NSS News 2020 Members Manual gives an accounting of acreages for 17 cave preserves owned or managed by the National Speleological Society (Soukup, 2020). The preserves range in size from 2 to 32 ha (5 to 80 acres), with an average size of 9 ha (23 acres).

Cave gates were routinely used in the 20th century; however, their prevalence increased with the arrival of White Nose Syndrome (WNS) to the United States and subsequent declines in bat populations. In an attempt to protect bats from further disturbance, many state and federal agencies began installing locked gates on public land cave entrances and implementing cost-share programs for private landowners to do the same.

Eventually, the need for land protection above cave systems became apparent. In many states, private property rights extend to the center of the earth and ownership of the entrance to a cave system does not legally entitle one to access passages that lie under adjoining private properties. Show caves were especially vulnerable to these legal disputes. At Missouri's Onondaga Cave in the 1950s, tours had been conducted for 17 years in passages located under several different properties (Weaver and Johnson, 1980). One of those property owners dug another entrance into the cave under his property, built a fence to separate passages from the original tour route, and started providing his own cave tours. The feud climaxed years later in the Missouri Supreme Court with the original tour operator losing the case. Ownership of land overlying tour routes became an essential business practice.

As research in hydrogeology increased the understanding of how water and contaminants move through karst systems, the scope of cave protection expanded. At the first National Cave Management Symposium in 1975, the word "karst" was absent from the title. Thirty-one percent of papers presented at that meeting focused on the management of cave visitors, while only 9% focused on cave research (Aley, 2017). By 1985, the word "karst" had made its way into the meeting title of the National Cave and Karst Management Symposium. During that symposium, 24 papers presented topics on cave research and only one paper focused on cave visitor management. It was clear that the focus amongst the cave community was expanding to include even the small, inaccessible karst connections so important to cave protection.

A Growing Understanding of Caves

In over half a century of hydrogeological investigations conducted at Tumbling Creek Cave and elsewhere, the OUL has learned much to help answer the question of the amount of land needed to protect a cave. Developments in the study of karst hydrogeology have expanded the range of possible threats to cave protection from very localized concerns to landscape scale issues. These lessons can assist cave managers in determining the information needed to best protect significant cave resources.

Epikarst and Lateral Groundwater Flow

The network of solutionally enlarged openings in the upper part of soluble bedrock units is called the epikarst (Palmer, 2007). The thickness of the epikarst zone can range between 0 to 100 m (Aley, 1997). The use of fluorescent tracer dyes has enabled hydrogeologist to measure lateral groundwater flow in the epikarst zone (Aley and Kirkland, 2012). In one study at Tumbling Creek Cave, tracer dyes were introduced into a small sinkhole on a hillside near mapped portions of the cave (Aley, 2003). Under relatively low flow conditions, tracer dyes were detected in three drippage zones inside the cave at points located 143, 186, and 192 m lateral distance from the dye introduction point. The vertical elevation change from the dye introduction point to the drippage zones in the cave was approximately 15 m. Under high flow conditions, dye was not detected at any of the three drippage zones, but was detected at a spring approximately 150 m lateral distance from the sinkhole. Travel time from dye introduction to initial dye detection in the cave under low flow conditions was less than 24 hours.

Similar work conducted at Blanchard Springs Caverns in Arkansas illustrates how properties of the epikarst have the potential to convey contaminants over long lateral distances into sensitive cave systems (Aley and Kirkland, 2012). In 1971, the U.S. Forest Service constructed a paved parking area as part of the development of Blanchard Springs Caverns. The parking lot was not located directly over known portions of the cave, but it was higher in elevation than the cave passages, and drainage from the pavement had been directed into groundwater recharge pits filled with gravel. The pits were located beneath the pavement and were designed to maintain near-natural flow of water into the cave system. Due to concern about contaminants entering the cave through the parking lot pits, a tracer dye was introduced into the pits. The dye was detected at drippage zones in the cave 24 hours later. Lateral flow was measured up to 239 m from the dye introduction point to detection sites within the cave. As a result, the Forest Service recognized the potential for groundwater contamination, the drainage pits were sealed, and storm water was re-routed (Aley and Kirkland, 2012).

Contrary to the philosophy of protecting a cave by preserving the entrance, or even the land directly above the cave, investigations of water moving laterally through the vadose zone illustrate the need to protect lands overlying the epikarst associated with those cave systems. These surface inputs through the epikarst have the potential to transport contaminants hundreds of meters laterally to water features in caves. Epikarst features such as shallow sinkholes have historically served as convenient dumps for rural America. While this practice has slowly become less common, legacy dumps still remain and can pose significant threats to groundwater quality and the health of cave fauna. Forty-two dumps have been identified in the recharge area of Tumbling Creek Cave. Many of these dumps were located on properties that had not been purchased by the Aleys. Since Tumbling Creek Cave is a National Natural Landmark, grant money was awarded to provide cost-share for dump cleanup on lands owned by the Aleys and neighboring properties. Over a six-year period, a total of 131 tons of trash was removed from all 42 dumps at a cost of $50,000.

Cave Recharge Areas

The land surface that contributes water to a cave system is known as a cave's recharge area. In caves where water enters primarily through ceiling drippage, the recharge area can be relatively small and localized above the cave system. However, in caves with flowing streams, the recharge area can be surprisingly large. Aley et al. (2008) found that recharge areas for 24 known Ozark Cavefish (*Troglichthys rosae*) sites ranged in size from 0.3 - 103.9 km^2 with a mean size of 22.9 km^2. Protection of cave streams, caves with episodic flooding, and associated aquatic fauna relies greatly on good land use practices in cave recharge areas. Changes in vegetative cover due to various land use practices can affect groundwater quality (Kellner et al., 2015). Unlike the relationship between surface watersheds and streams, cave recharge areas are not constrained by topographic features and can often cross watershed boundaries. Surface observations of stream basins are inadequate in determining recharge areas of cave streams. Therefore, recharge area delineation using tracer dyes is an essential tool in cave conservation. The size, character, and land use of a cave's recharge area directly informs managers of the actions needed to protect cave stream fauna.

Efforts to protect populations of the Tumbling Creek Cavesnail (*Antrobia culveri*) have included over 60 groundwater traces to delineate the recharge area. These investigations have helped identify a recharge area of over 23 km^2 with travel rates as high as 6.3 km/day observed. The most direct conduits for discrete recharge to caves are sinkholes and losing streams. A major losing stream segment that contributes water to Tumbling Creek Cave is located in an adjacent topographic watershed approximately 4 km straight line distance from the cave. Due to poor grazing practices, large amounts of sediment were eroding from these lands and depositing in the stream in Tumbling Creek Cave. The property was eventually acquired and cost-share programs were utilized to help rehabilitate the land. Fencing was constructed to exclude livestock from 61 ha (150 acres) of reforested riparian areas. Several kilometers of eroded stream banks were stabilized and erosion gullies were repaired and revegetated. Logging roads were revegetated and then closed. Livestock densities were reduced and a deferred rotational grazing system was established on the property. Sediment loads in the cave stream have since decreased and much of the aquatic habitat has been restored.

In addition to work at Tumbling Creek Cave, the OUL has conducted over 40 recharge area delineations for federally listed threatened and endangered species and state species of conservation concern in Missouri, Arkansas, Oklahoma, and Illinois (Aley et al., 2008). These delineations help researchers and managers better understand the complex karst hydrology associated with caves of interest and help identify vulnerable portions of recharge areas. The OUL has conducted vulnerability mapping for most of the recharge area delineations mentioned above. Vulnerability mapping has assisted cave managers in decision making based on the hydrological setting and likely land use practices. Making accurate threat assessments using recharge area delineation and vulnerability mapping is crucial to protecting underground streams and their associated cave fauna.

Contaminant Migration Through Subsurface Air Flow

In karst landscapes, underground air moves in response to changes in barometric pressure, or to differences in elevations and differences between surface and subsurface temperatures. Conn (1966) discussed barometric cave winds in a classic airflow paper on Wind Cave and Jewel Cave, South Dakota. The air movement in response to differences in elevations and temperatures is called convective airflow. There can be substantial air movement between caves and the surface through natural entrances, fractures, sinkholes, unsaturated soils, and other features. Convective airflow is the dominant mechanism involved in the underground movement of contaminated air and provides additional pathways by which caves can be at risk from land use on the surface.

Trichloroethylene (TCE) is a solvent that has been extensively used at tens of thousands of sites for decades. It can move underground as a dense free-product liquid. It is slightly soluble in water so it can also be transported in groundwater and can volatilize into underground air. It is the Houdini of chemicals, a master of escaping from confinement, and toxic in both water and air. It is probably encountered at hazardous waste sites more commonly than any other toxic compound and can persist underground for decades or longer. TCE concentrations in workplace air are federally regulated by the Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) at sites impacted by a spill or discharge great enough to come under the purview of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly referred to as Superfund.

Long distance movement of air contaminated with TCE has significantly impacted operations at two American show caves and has the potential to affect others. Due to confidentiality agreements, the authors cannot identify the involved caves. In both cases, TCE was never used on the cave properties or the immediately adjacent properties, but was extensively used and disposed of at one or more industrial or commercial sites located 5 to 8 km from the caves. Discharges from these sites brought the caves under the EPA's 6 $\mu g/m^3$ target limit. Evidence suggests that TCE-contaminated underground air moves seasonally by convective air flow through the unsaturated karst network from waste sites located at higher elevations toward lower elevation areas under warm weather conditions. Under cool weather conditions, the direction of underground air movement is from lower elevation areas toward higher elevation areas; those higher elevation areas are not necessarily limited to the likely source area for the waste.

Control of the TCE problem in the two show caves has been neither simple nor inexpensive. Extraction of contaminated air through large diameter borings constructed into known or inferred cave passages has been necessary. Substantial and unique microclimate studies have been needed. Contaminated air extraction creates other problems including desiccation of speleothems or condensation on some cave surfaces. In some cases, these impacts can be lessened by irrigating areas that contribute water to impacted cave passages. In both cases with which the authors are familiar, the cave operations owned undeveloped lands suitable for construction of airflow control features. At a minimum, owning or controlling all land overlying important caves is important, including land overlying passages that might initially appear to be of negligible value. Subsurface contaminated air movement is not bound by surface watersheds or even groundwater recharge areas. This makes comprehensive cave maps and an understanding of airflow connections important management tools, even when commercial and industrial sites may be several kilometers from significant caves.

Alteration of Surface Hydrology

Changes in surface hydrology can impact the groundwater gradient in karst terrains. Bull Shoals Dam was completed in north-central Arkansas in 1952 for the purposes of flood control and hydropower. The dam impounded the White River, creating an 18,000-ha (45,000-acre) reservoir operated by the US Army Corps of Engineers. The pooling effects of the dam extend upstream into portions of Missouri, including the downstream reaches of Big Creek in eastern Taney County. Tumbling Creek Cave, and the sensitive biota within, has not escaped the consequences of the Bull Shoals Dam. There are upwards of 25 springs that drain the cave stream and discharge into Bear Cave Hollow (a tributary of Big Creek) or Big Creek itself. Downstream reaches of both streams, along with the springs fed by Tumbling Creek Cave, are inundated by the Bull Shoals reservoir when lake levels are at flood pool.

A significant portion of federally designated "Critical Habitat" for the Tumbling Creek Cavesnail exists as inaccessible bedrock openings underlying the valley between the natural entrance of Tumbling Creek Cave and the springs discharging into Bear Cave Hollow and Big Creek. These habitats are most at risk when Bull Shoals reservoir is filled to flood pool. The natural groundwater gradient maintains adequate velocities to keep fine sediments suspended in the groundwater and moving through the Critical Habitat. However, when Bull Shoals reservoir inundates Big Creek and Bear Cave Hollow at or near flood pool, the groundwater gradient and resulting flow velocities are reduced by up to 50% of the natural condition. As a result, sediment comes out of suspension and settles into the interstitial spaces, destroying critical habitat for the cavesnail and other aquatic species.

The construction of Bull Shoals Dam has had additional consequences for fauna in Tumbling Creek Cave. The inundation of several springs draining the cave has created a hydrological connection for surface dwelling crayfish to invade the cave and prey on sensitive aquatic cave organisms, including the Tumbling Creek Cavesnail. The Gapped Ringed Crayfish (*Faxonius neglectus*) is a native epigean crayfish occurring in the White River Basin of southern Missouri, but is an invasive species within Tumbling Creek Cave due to facilitated movement by the anthropogenic activity of dam construction (Mouser et al., 2019). The Gapped Ringed Crayfish has migrated up these new pathways into the cave and poses a significant threat to the Tumbling Creek Cavesnail, which is a food item of the crayfish.

Over a seven-year period, trapping events have been conducted through cost-share programs provided by the Missouri Department of Conservation. By the end of 2020, over 6,000 crayfish had been removed from Tumbling Creek Cave. Additionally, a crayfish barrier was constructed downstream of the most sensitive cavesnail habitat, and crayfish observations have decreased significantly in that area. An increase in cavesnail population estimates has coincided with the crayfish removal efforts, but the altered hydrological conditions that have facilitated the crayfish invasion remain. During the period of 2015 to 2018, the average annual duration of water levels at or near flood pool in the Bull Shoals reservoir was 85 days per year. These scenarios affecting cavesnail habitat downstream of the accessible passages of Tumbling Creek Cave illustrate how alterations in surface water hydrology can have severe consequences on cave systems, even when those alterations are hydrologically down gradient of a cave.

How Much Land Does It Take to Protect a Cave?

The answer is, it depends. Each cave has unique reasons for protection. Aesthetics, cultural resources, preservation of speleothems, protection of water quality in cave streams, and conservation of cave biota are just some of the factors that will dictate management activities. To protect a cave, one must protect its karst lands above. To grasp the challenges involved in cave protection, managers must improve their understanding of their specific cave and its unique hydrological connections to the surface. Consequently, as cave managers discover threats that could adversely impact important cave resources, the amount of land needed to protect the cave will also tend to increase.

As evidenced by the progression of topics presented at National Cave and Karst Management Symposia, there has been a shift in the focus of cave protection from visitor management to ecological integrity. As that body of knowledge becomes more robust, the philosophy of acquiring postage stamp parcels to protect cave entrances is proving inadequate for meaningful cave conservation. Similar to topics presented at cave symposia, the surface lands needed to protect caves is expanding in scope. Increasing one's understanding of a cave system can lead to the daunting task of prioritizing land protection efforts. The history of protection efforts at Tumbling Creek Cave can provide insight into how cave managers might go about these efforts.

The Entrance

Entrances are integral features of caves that must be protected. The natural entrance of Tumbling Creek Cave was acquired late in the chronology of conservation efforts for the cave. The initial purchase of Tumbling Creek Cave in 1965 included 51 ha (126 acres) of land overlying about 90% of the known cave passages, but it did not include the cave entrance. A shaft entrance was constructed and used to provide access for research and educational programs in the cave for over three decades. Before the natural entrance was acquired, occasional trespass and vandalism in Tumbling Creek Cave occurred. Eventually the natural entrance was purchased, crowning 35 years of strategic acquisitions to protect all lands overlying Tumbling Creek Cave.

Tumbling Creek Cave is home to a significant population of federally endangered Gray bats. These bats are vitally important to the cave by providing tremendous amounts of energy to the system in the form of guano. While past surveys in the mid-1960s had estimated populations of 150,000 Gray bats, significant population declines were noted in bat counts by 1998, prior to the acquisition of the cave entrance (Elliot and Aley, 2006). Prior to the Aleys' ownership of the natural entrance, a cave gate was located approximately 200 m upstream of the natural entrance to prevent cave trespass. This original gate seemed to prevent bats from fully using upstream passages of the cave. The natural entrance was finally acquired in 1999, and in 2004, the old cave gate was removed and a chute gate was constructed at the entrance to facilitate the passage of pregnant female bats. The new gate was constructed through a partnership between the OUL, the Missouri Department of Conservation, and the American Cave Conservation Association (ACCA). At the time, it was thought to be one of the largest chute gates in the world. By 2005, Gray bat population estimates had increased from about 20,000 to over 40,000 bats, and recent exit flight surveys have estimated nearly 80,000 bats. While other factors may have contributed to the rebound of the bat population in Tumbling Creek Cave, it is clear that acquisition of the natural entrance and the construction of the bat-friendly cave gate were important management steps in protecting the cave ecosystem.

Epikarst and the Recharge Area

Studies conducted by the OUL at Tumbling Creek Cave and other karst systems have demonstrated how water can reach cave systems through extensive hydrogeological connections. Once in a cave, water can continue to create new passages, deposit or dissolve speleothems, affect cave meteorology, and provide habitat for sensitive aquatic species, many of which are highly endemic and often imperiled. The complicated processes by which water moves into karst terrains must be considered in cave protection efforts. Flow paths in the epikarst and recharge area must be determined for each specific cave. This information can then be used to identify potential threats to water quality and prioritize the most vulnerable areas for land protection.

As understanding of Tumbling Creek Cave increased and new groundwater flow paths were discovered, it became clear that additional lands were needed to adequately protect the cave. The recharge area for Tumbling Creek Cave is over 23 km^2. Approximately 25% of the recharge area is part of the Mark Twain National Forest; however, the majority is in private ownership with a variety of land use practices. Recharge area delineation and vulnerability mapping were used to identify the highest priority lands for acquisition and for forming partnerships to help improve land use on those properties that could not be protected through acquisition.

Buffer Areas

Buffer areas are those areas that may not directly contribute groundwater to a cave, but may have indirect influences on its hydrology, ecology, or airflow connections. As a result, these areas should be considered important to the overall health of a cave. The inaccessible passages immediately downstream of Tumbling Creek Cave in Big Creek valley were originally acquired as part of the lands containing the cave's natural entrance. Eventually, these passages were determined to be Critical Habitat for the Tumbling Creek Cavesnail, as well as conduits for the invasion of Gapped Ringed Crayfish from Bull Shoals reservoir. This buffer area between the cave and the reservoir has proven extremely consequential for the cavesnail given the reservoir's effects on groundwater gradient and invasive species migration into the cave.

Buffer areas can also be important in protecting caves from the intrusion of contaminated air. It is likely that most caves that discover air contamination problems will not own or control sufficient land to be able to address their problem through management of underground airflow patterns. Lambert and Harman (2020) identified 72 atmospheric karst features (points where airflow could be observed either entering or exiting the ground) in a West Virginia karst area about 8.2 km long by 2.3 km at the widest point. They commented that all of the features responded to surface temperature as if they were all tied together in a single system rather than as a collection of smaller systems. In the case of airflow contamination, TCE is not the only hazardous volatile compound subject to substantial lateral movement in the underground air of karst areas. Those involved with planning for the long-term protection of caves need to recognize that both past and present land uses, even kilometers from the cave, may yield underground air of undesirable quality to the cave. Land uses including landfills, industrial plants, and even small operations such as auto repair shops are potential problem sources for creating undesirable or hazardous air quality in caves. Buffer areas can provide opportunities to mitigate airflow contamination issues should they arise in caves.

Natural Communities

Caves are not isolated from the surface. Groundwater derived from the surface sculpts caves in karst terrains and provides habitat for subterranean aquatic organisms. Cave fauna that are strictly bound to subterranean environments (troglobionts) and those that move between surface and sub-surface environments (troglophiles) both depend on sources of energy brought into caves from the surface. Surface vegetation and soil health directly impact groundwater quality and quantity. Nelson (2010) states that the historic condition of natural vegetation cover and the ability of intact soils to absorb moisture are critical to the flow characteristics of nearby groundwater. Maintaining these important connections at the surface relies greatly on the health of terrestrial natural communities.

This paper has outlined the expanding perspective of lands required for cave protection from very localized geographic focus for the protection of cave features to landscape scale protection of recharge and buffer areas. However, it is not enough to strictly own or control these lands. The ultimate goal for cave protection is maintaining and restoring the terrestrial natural communities of those lands to preserve the delicate connections with the caves below. Intact natural communities include vegetative cover comprised of deep rooting perennials that increase water infiltration, prevent soil erosion, and sequester carbon. Healthy natural communities can also ensure the provision of energy to cave food webs by providing ample prey items and foraging habitat for bat populations. As the climate warms, many surface organisms, including plants, can move with changing environmental conditions. Conversely, cave-adapted species are stuck in place and have little opportunity to adjust to new climatic conditions. A mosaic of healthy natural communities on the landscape can create ecosystem resilience, and buffer against the effects of climate change on cave fauna.

Conclusion

Protecting caves with gates and preserving natural entrances through land acquisition are necessary first steps for cave management. Public policies such as the Federal Cave Resources Protection Act of 1988, and NGO programs like the National Speleological Society's Nature Preserves, have been effective at protecting significant cave entrances and controlling access to the passages beyond. Subsequent steps should include protection of lands immediately over cave passages, key features in the epikarst, and lands in the recharge area where water inputs to the groundwater system are highly localized and have the greatest potential to affect cave ecosystems.

It may not be a realistic goal to acquire all the lands needed to protect a cave, especially caves with extensive recharge areas or those located in highly populated areas. Owning and managing large tracts of land is very costly and time consuming. In the case of Tumbling Creek Cave, relationships with neighboring landowners, state and federal agencies, conservation groups, and the local community have proven essential. To build these productive partnerships, managers must determine the unique reasons for protection, understand surface connections in detail, accurately identify vulnerabilities, and share that information with partners. These actions will help direct time and resources towards comprehensive land management strategies that can effectively protect caves.

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The Acquisition and Protection of Clarksville Cave: A Tale in Five Parts

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Abstract
Ask cavers whose formative caving years were spent in the northeastern United States, "which wild cave was your first?" and the answer that you will hear more often than any other is: Clarksville Cave. Located in Albany County, New York, this roughly 4,800-ft long cave with five entrances boasts one of the longest histories of any cave in the state, with exploration dating back at least as far as 1811. Today, it is the centerpiece of the Northeastern Cave Conservancy's (NCC's) most popular and well known preserve.

The story of how the NCC's Clarksville Cave Preserve came into existence and has grown into what it is today begins in earnest in 2001, and this twenty-year tale has not yet reached its conclusion. While each of the NCC's other cave preserves has entered its portfolio in a single acquisition, the Conservancy first purchased a sizable portion of Clarksville Cave with one entrance in 2004, and has been steadily working to acquire and protect more of the cave ever since. Each opportunity to expand the preserve has presented itself under unique circumstances, some relating to a fatality, rescues and rescue trainings, foreclosures, friendly neighbors, and neighbors who've become deeply involved with the NCC. We will explore each chapter in the NCC's ongoing journey to protect the entirety of this very special cave, with the hope that other groups seeking to protect more of a cave system they currently hold a portion of, may glean some ideas to help make that dream a reality.

Poster Presentations

Void Inspection and Mitigation in Drilled Shaft Foundations

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Abstract
Previously undetected karst features are commonly encountered during construction within the Balcones Fault Zone in central Texas. To balance the needs of infrastructure support and aquifer protection, construction projects located within karst recharge zones should include procedures for void response and mitigation. Among the procedures can be details for void mitigation in drilled shaft (DS) foundations. The Austin District of the Texas Department of Transportation (TxDOT) has revised their standard practices to include example void mitigation details which were first applied during the MoPac Intersections Project in Travis County. Details for small- and medium-sized voids were made from combining state guidance for the protection of sensitive features on the Edwards Aquifer and the project's general excavation methods. Input was sought from project engineers and local geoscientists who partnered with TxDOT. Large-sized voids required feature-specific mitigation planning. Optimal down hole video results required that standard inspection procedures be followed to identify voids. The contractor received training in the procedures and conducted DS inspections. Professional geoscientists confirmed voided zones and sound bedrock at the base of DS. A tight-fitting ring on steel casing was used to minimize loss of concrete into a void. The bridge DS at La Crosse Avenue in Austin had the most voids. Post construction integrity tests showed mitigation was successful despite having massively voided zones. This best practice presentation draws from a project that included new bridges and retaining walls in karst terrain. Such projects involve engineering and geoscience work, the safety of the public, and the environment.

Counting Cave Shields: A Lehman Caves Study

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Abstract
Lehman Caves, located in White Pine County, Nevada, has been open to the public as a show cave since 1885. The cave has been federally protected since 1922, leading up to its incorporation into Great Basin National Park in 1986. Thousands of visitors each year make the trip to Lehman Caves to experience its rich history and many beautiful features. One such feature found in Lehman Caves, cave shields, are a unique and rare type of speleothem. Park lore estimates around 300 cave shields exist within the cave, but an extensive investigation of the shields had not been conducted. In early 2020, a Geoscientist-in-the-Park partner found, measured, and documented every visible cave shield in Lehman Caves. Results of the study indicate a total of 504 cave shields in Lehman Caves, possibly more than any other cave on earth. Additionally, it was discovered that multiple morphologies of cave shields may exist, dependent on bedrock jointing and fracturing. This integrated study within Lehman Caves provided a better understanding of the quantity and distribution of the shields and postulate how they grow and develop, filling a critical information gap for the park.

Introduction

Cave shields are relatively rare speleothems found in a limited number of caves around the world. Little research has been done on them.

One cave particularly noted for cave shields is Lehman Caves (Figure 1), located in White Pine County, Nevada. The cave has been open to the public as a show cave since 1885. It became a national monument in 1922 and was incorporated into Great Basin National Park in 1986. Thousands of visitors each year make the trip to Lehman Caves to experience its rich history and many beautiful features. Park lore estimated around 300 cave shields exist within the cave, but an extensive investigation of the shields had not been conducted.

What is a Cave Shield?

Cave shield formation is still puzzling. It is hypothesized that cave shields form along joints or cracks in the ceiling, wall, and floor of the cave through the process of capillary action. Calcite-rich water under hydrostatic pressure moves through the joints and cracks within the bedrock. As this water loses carbon dioxide to the cave chamber, it precipitates calcite on either side of the crack, creating an extension of the crack. This builds disks of concentrically layered calcite separated by a thin, capillary-sized crack. The thin, planar crack is referred to as a medial crack (Figure 2). The result is two thin calcite disks separated by a thin, water-filled void (Hill and Forti, 1997; Palmer, 2007).

New shield growth occurs along the outer rim where CO_2 degasses, and the seep water becomes supersaturated with calcite (Hose, 2018). Periods of increased water flow can inundate the capillary seepage causing gravitational water to deposit secondary growths at the bottom and rim of the shield in the form of dripstone (Palmer, 2007; Hose, 2018).

Methods

A Geoscientist-in-the-Park was hired to lead a cave inventory project in early 2020. Within that inventory, she designed and implemented the cave shield study. Each shield-like feature was assigned a number, marked on a map, and measured (width, azimuth, inclination). Any nearby joints or fractures were also measured. Medial cracks were noted, as well as location of the cave shield within the passage (floor, ceiling, or wall; Figure 2).

Results

In total, 504 visible cave shield features were identified and measured. A few findings:

- 156 shield features display a visible medial crack
- 167 shield features are located on the ceiling
- 34 shield features are located on the floor
- 303 shield features are on cave walls or other speleothems (Figure 3)
- The largest shield was 3 m (10 ft) across
- The average shield width was 0.6 m (1.8 ft) across
- Average azimuth direction was 168.8 degrees
- Average inclination was -9.0 degrees

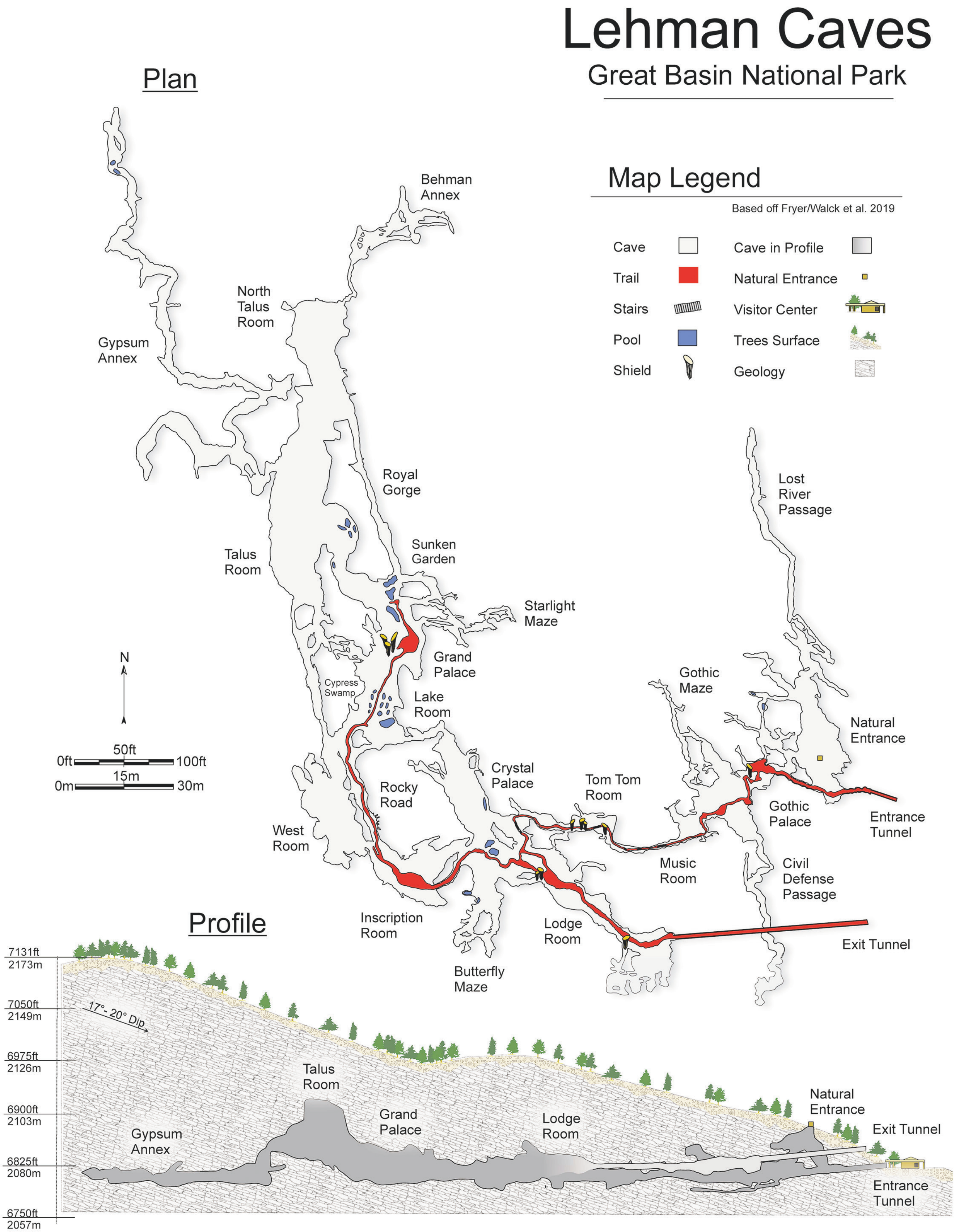

Figure 1. Lehman Caves is a 3-km (2-mile) long cave in Great Basin National Park, located in east-central Nevada. The cave is developed in the Middle Cambrian Pole Canyon Limestone, which has been locally metamorphosed.

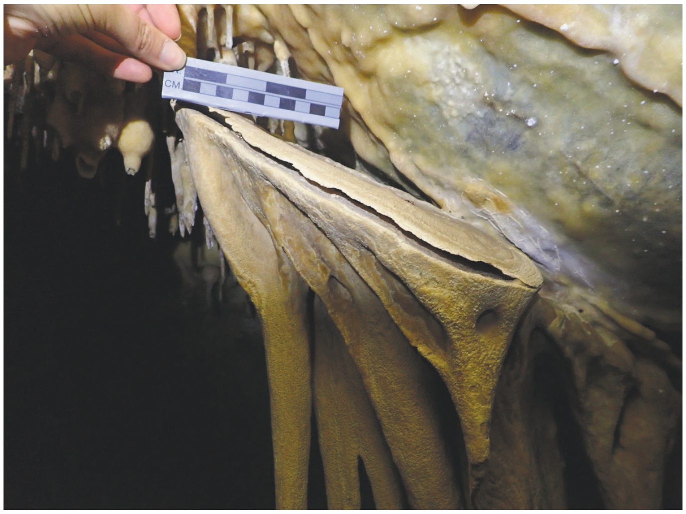

Figure 2. On the left, the medial crack in this cave shield is easily seen, separating the two plates of the cave shield. On the right, one of the 34 cave shields that appeared to originate from the floor.

- About 100 cave shields showed evidence of condensation corrosion

Most shields were covered in secondary deposits on both the top and bottom of the feature (Figure 4). These deposits included columns, helictites, coralloids, draperies, stalactites, and soda straws. Only 61 shield features were identified as having a smooth appearance, either on the top or the bottom.

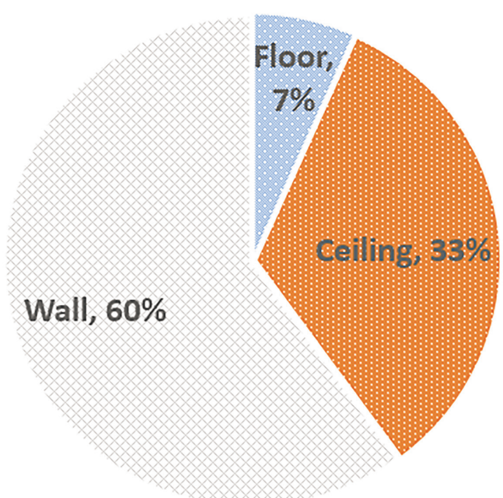

Figure 3. Cave shield location was predominantly on cave walls, followed by ceilings and floors.

Discussion

This integrated study within Lehman Caves provided a better understanding of the quantity and distribution of the shields, and postulated how they grow and develop, filling a critical information gap for the Park. More work is needed to understand their origin and why so many are found in this particular cave.

Figure 4. Cave shields covered in secondary deposits located in the Grand Palace Room.

Literature Cited

Hill, C.A., and P. Forti (eds.). 1997. Cave minerals of the world. Second edition, National Speleological Society, 463 pp.

Hose, Louise. 2018. The geologic story of Lehman Caves. Report for Great Basin National Park, Baker, Nevada, 13 pp.

Palmer, A.N. 2007. Cave geology. Dayton, Ohio: Cave Books, 454 pp.

Acknowledgements

Becca Miller volunteered at the Park during this time period and helped greatly with field work.

Is Trapping Success in Texas Blind Salamanders (*Eurycea rathbuni*) Influenced by Season, Aquifer Level, or Precipitation?

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Abstract

The Center for Conservation and Research at San Antonio Zoo conducts research and conservation projects that focus on rare and endangered species and ecosystems, both locally and internationally. The Texas blind salamander (*Eurycea rathbuni*) is restricted to the San Marcos pool of the Edwards Aquifer and is federally listed as endangered. The Center for Conservation and Research at San Antonio Zoo and the United States Fish and Wildlife Service have been collecting salamanders to bolster research and captive assurance colonies, respectively. Research goals include development of breeding and husbandry protocols, gathering morphometric data, pathogen screening, and obtaining genetic material for ongoing population genetics studies.

Trapping success of this species is highly variable, and little is known about the influence environmental conditions may have on trapping results. We seek to explore how environmental factors such as seasonality, rainfall, and aquifer levels may influence trapping success.

Data collected from 2016 to present has been compiled from seven sites where traps or drift nets were utilized. In addition to trapping data, San Marcos historic rainfall records provided by NOAA, and information on aquifer levels from the Edwards Aquifer Authority will also be analyzed. These comparative analyses of relationships among environmental factors and trapping results are forthcoming, and may provide insight on preferred environmental conditions, salamander activity, and improvements to existing trapping protocols.

Conservation and Endangered Species Management in Williamson County, Texas

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Abstract

The Williamson County Conservation Foundation (WCCF), formerly known as the Williamson County Karst Foundation, was formed in December 2002 for the purpose of providing for the conservation and perhaps the eventual recovery of endangered and threatened species in Williamson County, Texas. The Foundation is overseen by a seven-member Board of Directors, including two Williamson County Commissioners. As the administrator of the Williamson County Regional Habitat Conservation Plan (WCRHCP), the WCCF partners with the county and developers to streamline endangered species permitting while advocating for responsible development and providing holistic conservation. The WCCF oversees the monitoring and management of over 50 caves on over 1800 acres of karst preserves. The United States Fish and Wildlife Service (USFWS) recognizes 5 Karst Fauna Areas (KFAs) benefiting *Texella reyesi* and *Batrisodes texanus* that are a part of the WCCF preserve system, while another 2 KFAs are currently proposed. Future endeavors of the Foundation include continuing to fund monitoring and research of *Eurycea naufragia* and *Eurycea chisholmensis* and expanding karst preserve acreage and KFAs in the county.

Development of a Geology Trail: A Subglacial Landscape; Clarksville Preserve, New York State

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Abstract
The Northeastern Cave Conservancy (NCC) programs are focused mainly on the conservation of caves and karst, inclusive of geological research oriented toward public education. The Clarksville Preserve is widely used by schools, colleges, scouts, cavers, and the public. While numerous websites provide general information, NCC outreach may be bolstered via a user-friendly program designed to generate interest in surficial geologic features through correlation with underlying cave features. To this end, the NCC is developing a 1,200-m geologic trail.

This poster provides detailed descriptions and photographs of seventeen interpretive stops, each being designed to be accessible via smartphones using customized QR codes. Individual stops are designed for trail users to envision karst resources within the context of an evolving landscape, with emphasis on how karst features developed beneath glacier ice during early deglaciations. Trail stops highlight massive overland flow beneath 150-m thick stagnant glaciers pressed against Wolf, Cass, and Bennett Hills to the south, with water depths ranging up to 3 m. Subglacial meltwaters cascaded over cliffs, down wide channels, carved a deep gorge, and roared into joints; forming shafts, canyons, and tubular conduits within the 1,500-m long Clarksville Cave. Together, these conduits served as a major subglacial drainageway, with flow coalescing from dozens of surficial inputs over thousands of years under thinning ice. Through time, the levels of subterranean conduits dropped as meltwater downcut through the Onondaga Limestone, ending with a succession of stream-borne glacial sediments and cobbles. Subglacial inflow to the cave is now absent, resulting in an underfit hydrologic flow regime.

Monitoring Air Quality in Caves With a Butane Lighter

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Abstract
In lieu of expensive air quality monitors, for decades cavers have used cheap butane lighters to gauge whether it is safe to enter caves. Past studies comparing the effects to the flame of a butane lighter under different levels of oxygen have been the basis for why butane lighters have been considered a useful tool by so many cavers.

In an attempt to verify past results, the City of Austin Balcones Canyonlands Preserve staff utilized two different CO_2 meters: the Vaisala Data Logging CARBOCAP GM70 Handheld CO_2 Meter, and the Telaire 7001 CO_2 meter. Taking measurements in caves with high CO_2 levels, Preserve staff were able to determine the impacts to the flame of a butane lighter under varying levels of CO_2.

Increased Thunderstorms Across the Southern Great Plains – Beneficial or Harmful to Karst Dependent Organisms?

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Abstract
Using 30 to 50-thousand-year-old stalactites from Williamson County caves, Maupin et al. (2021) found that thunderstorms in the Southern Great Plains of the United States are increasing in intensity and frequency. Assessing changes in storm characteristics under different climate scenarios remains highly uncertain due to limitations in climate model physics. They analyzed oxygen isotopes from the stalactites to assess past changes in thunderstorm size and duration. Storm regimes shifted from weakly to strongly organized on millennial timescales and were coincident with well-known abrupt climate shifts during the last glacial period. Current analysis suggests that thunderstorm organization in the Southern Great Plains is strongly coupled to changes in large-scale wind and moisture patterns. These changes in circulation may be used to assess future predictions and paleo-simulations of mid-latitude thunderstorm climatologies.

The analysis of past climate regimes encapsulated within stalactites may give clues regarding future macroscale rainfall scenarios across the Southern Great Plains and more specifically, rainfall across the karstic landscape of Texas with the assumption of a rapidly warming climate. On its face, the potential for increased rainfall across this region may prove beneficial for terrestrial organisms that depend on a saturated atmosphere in karst voids (i.e., troglobites) or those species reliant upon a permanently wetted aquifer (e.g., stygobites). However, stronger thunderstorms capable of dropping large amounts of rain within a short duration may not be beneficial if flooding negatively impacts the subterranean ecosystem. We explore potential impacts to subterranean fauna with the assumption that a hotter Texas is a wetter Texas.

Literature Cited
Maupin, C.R., E.B. Roark, K. Thirumalai et al. 2021. Abrupt Southern Great Plains thunderstorm shifts linked to glacial climate variability. Nature Geoscience, 14(6):396-401.

Appendix A

AGENCY GUIDE TO CAVE AND MINE GATES

Jerry Fant, Jim Kennedy, Roy Powers, Jr., and William Elliott

October 2021 Revision

AGENCY GUIDE TO CAVE AND MINE GATES
Fourth Edition, 2021

Publication History:

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Authors:

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Bat Conservation International
Missouri Department of Conservation

Citation:

Fant, J., J. Kennedy, R. Powers, Jr., and W. Elliott. 2009 (2021 edition). Agency guide to cave and mine gating. American Cave Conservation Association, Bat Conservation International, and Missouri Department of Conservation. 32 pp.

Contents:

Cover: Half-gate at Bone Hole Cave, Kentucky, with the late Mastergater, Roy Powers. Photo by Jerry Fant.

Back Cover: Chute Gate supported by Bay Window, Bat Cave, Oregon County, Missouri. Photo by Jim Kennedy.

Introduction

You may have questions about “cave gates”, “mine gates”, or “bat gates,” and have trouble finding good references. We can use all three terms interchangeably, depending on the situation. The four authors have a cumulative 150+ years of experience in protecting cave and mine resources, and have put together this publication to help answer some of your questions. This guide is not intended to become a how-to manual on building gates to protect cave and mine resources, or to reduce liability at those sites, particularly abandoned mines. It is, however, intended to guide resource managers in making the best decisions on why, how, when, and who should build such gates.

Over the years many hundreds, if not thousands, of gates have been constructed across the United States to secure cave and mine entrances. Some are good, being both secure and ecologically transparent. Others, poorly planned and designed, have had severe detrimental effects on the very resources they were built to protect.

Over the years, much research by the American Cave Conservation Association, Bat Conservation International, and the US Fish and Wildlife Service has helped aid the evolution of cave and mine gates, to the point where we now know what features are essential. An “industry standard” design with accepted standard variations is now widely accepted by the National Park Service, US Fish and Wildlife Service, Bureau of Land Management, US Forest Service, NGOs such as The Nature Conservancy and the National Speleological Society, and many state wildlife agencies and conservation departments. Many years have been put forth in this endeavor, but techniques and designs continue to evolve, and it is imperative to stay abreast of the latest advances and not rely on older information, or the published literature, which can be confusing or even contradictory.

The designs discussed in this guide are the current industry standard airflow design gates in use in much of the United States. If building gates more than a year or so past the date of this publication, please contact the authors for the latest updates.

Basic Cave Gate, Lower Entrance to Bacon Cave, Virginia. Photo by Jim Kennedy.

Why gate?

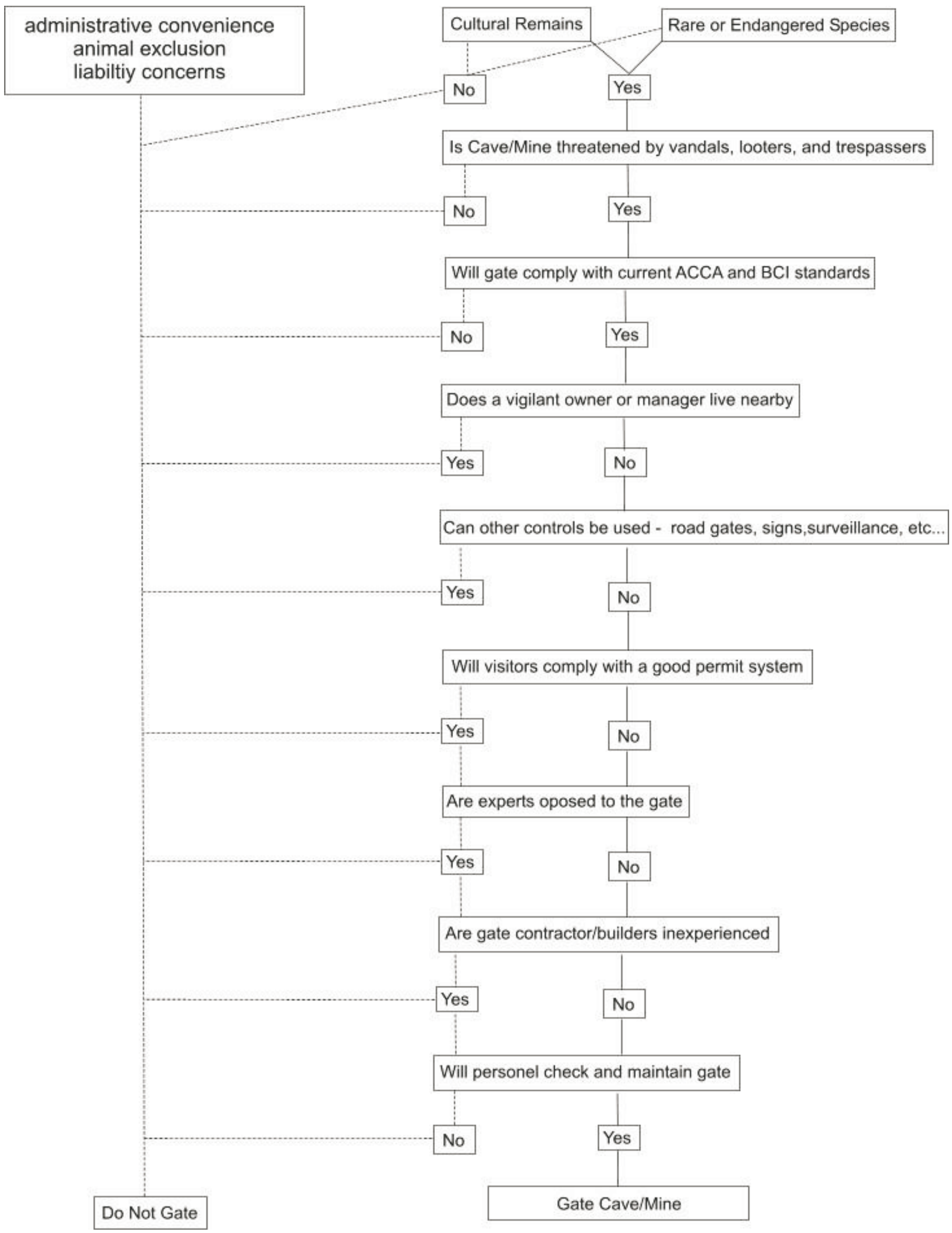
The decision to gate is never easy. On the downside, there are the costs of construction and the disruption of the natural aesthetics. First and foremost, you must ask yourself about what resources and what threats are present. Are there cultural remains? Are there endangered species? Or are there inherent dangers present? If the answer to the first two questions is yes, to what point are they threatened? Can the site withstand minimal impact? If so, can signage alone detour the casual visitor? If you are making the decision to gate a cave based on inherent danger, there are many state laws which already grant protection from such visitation, at least regarding caves. You should consult your attorney before making your decision, as in some instances the gate may actually increase your liability. Abandoned mines, of course, are a very different story.

Below the following section is a simplified flowchart to aid in decision-making. In most cases there will be many more factors involved than those illustrated in making the final decision to gate a cave.

SOME QUESTIONS TO BE ASKED BEFORE DECIDING TO GATE

Administrative convenience — Is the gate being planned simply because the agency doesn't have the experience or resources to provide more active, involved management? Would limited resources be better used for signage and public education?
Animal exclusion — Many animals are essential components of the cave ecosystem. Not only do they seek shelter in the caves/mines, but they also produce much needed nutrients for other cave/mine dwelling organisms. Will a gate impede animal or nutrient flow into the underground ecosystem?
Liability concerns — Most states have laws protecting landowners from liability associated with allowing free access to their caves, and gates are not necessary. However, abandoned mines are automatically considered human health hazards, and closure is the first option. Gating a mine instead using a more permanent physical closure (such as backfill) may allow the mine to be used by bats and other animals, if suitable, as well as provide continued access to archeological and mineralogical resources.
Historical remains — Are there archeological or paleontological resources in the cave or mine that are threatened by visitation and in need of protection?
Rare or endangered species — Does the cave/mine contain species which are listed on a state or federal rare or endangered species list, meriting additional protection?
Vandalism — Is cave/mine threatened by vandals, looters, and trespassers? Has the cave shown past evidence of such? If not, will conditions soon change which will put the cave in danger of such activities?
Stewardship — Does a vigilant owner or manager live nearby, or does someone visit the area often enough that intruders will be seen or heard as they enter the site?
Other closure methods — Can other controls be used, such as road gates, signs, surveillance, etc.? Can other measures be used to control access to the site? All of these measures still require maintenance and monitoring. Or does the site lend itself to permitted entry? Some caves can withstand seasonal or minimal impact. Will visitors comply with a good permit system if a good permit system is in place? Will visitors stay out of the site during periods of closure?
Gate design — Will the gate comply with current industry standards? The ACCA / BCI designs are accepted by the US Forest Service, Bureau of Land Management, US Fish and Wildlife Service, National Park Service, many state agencies, and major conservation groups across the United States. They are designed to lessen the impact on the area immediate to the gate and to have minimum effect on the site's airflow, and thus the microclimate. Over thirty years of research has been invested into these gate designs.
Stakeholder buy-in — Are there valid concerns over the design or placement of the gate? Is another closure method more appropriate? Will the proposed gate location destroy cultural remains, disturb natural settings, or alter the airflow characteristics of the cave/mine?
Contractor suitability — Cave/Mine gating is a technical subject that requires knowledge and experience. General welding contractors and in-house maintenance personnel rarely have the abilities to properly construct a quality gate, even with detailed plans and direct supervision by a knowledgeable agency representative, unless that person is an experienced cave gate designer. Knowledge of the site's ecology, especially bat use, is necessary before a gate is built.

Monitoring and Maintenance — Are there adequate personnel and resources to periodically check and maintain the gate? Gates must be checked for breaches on a regular schedule and repaired immediately. Locks should be well-maintained, and replaced when broken or malfunctioning. The biological impacts of the gate must also be monitored, to assure that it is not having a negative impact on the site. Is the gate performing its function of protecting the resource while excluding people?



Placement of gates, and Variations on the standard design

Once the decision is made to proceed to protect the cave or mine with a gate, there are several designs based on specific criteria. One important criterion that is common to all gates is **placement**. Other criteria may be very specific to the type of resource which is to be protected. Much emphasis has been placed on the design of gates in which bats are present. These types of gates are also dependent upon what type of bat is present and the time of year. The standard airflow gate design (basic gate) has proven extremely effective in also protecting other resources, such as cultural sites and invertebrate biology.

Placement – The gate should be placed in such an area that does not restrict airflow. This means that the smallest cross-sectional area should not be gated to save on material cost. Restricting the airflow causes changes in the temperature, pressure, and humidity levels deep into the cave or mine. These changes, although small, have great consequences on the ecosystem. If bats are present, gate placement should also not impede bat flight. Placement of the gate within easy to monitor areas is imperative, as any tampering can then be easily detected. Gates should also be placed in areas of competent bedrock, for security.

BASIC GATE DESIGN

The **Basic Gate** design is a vertically placed, two-dimensional grid of bars across the cave or mine passage. The spacing of the bars is critical to allow access of small bats and other small mammals, but not wide enough to allow human entry. The bars are constructed of 4” angle iron, oriented apex up to maximize the airflow through the gate. Bars are oriented horizontally, with vertical supports spaced widely. The gate is anchored to bedrock with 1” steel pins. An expanded metal “skirt” is used to prevent tunneling under the gate. The basic design is widely used even where there are no bats currently present. A **Folded Gate** is a Basic Gate with a Cupola Gate top, and is used primarily on small entrances in sinkholes.

Basic Gate, Bat Cave, Kentucky. Photo by Jim Kennedy.

Seventy-foot-wide Basic Gate, Weaver Cave, Alabama. Photo by Sharon Brewer.

Folded Gate (in progress) on Dunbar Corporation Mine #3, Pennsylvania. Photo by Jim Kennedy.

VARIATIONS ON THE BASIC GATE DESIGN

The **Half Gate**, or Fly-over Gate, is a variation of the Basic Gate (which is sometimes also called a Full Gate). The Half Gate is designed for entrances or passages that have high vertical relief, typically over 20’ (6m), and are used most often for large maternity colonies of bats. The bottom of the Half Gate consists of the bottom of a Basic Gate constructed high enough so that a ladder will not reach the top. Special attention must be given to support columns, since they are not attached to the ceiling. Expanded metal mesh is then attached horizontally extending forward (and sometimes rearward, if warranted) to stop attempts at climb-overs.

Half Gate, stepped to match the ground contour, Great Spirit Cave, Missouri. Photo by Bill Elliott.

Half Gate (in Progress), Bat Cave, Oregon County, Missouri. Photo by Jim Kennedy.

The Basic Gate with Window is also a variation on the standard gate design. The introduction of the window provides a larger protected flight space for bats, similar to the Half Gate or Chute Gate, which is described below. They can only be constructed in an entrance with an overhanging bluff, or well inside a large passage. The window is placed between a section of horizontal bars with expanded metal extending out the bottom and sides to prevent persons from climbing over and into the site. This type of gate is also used where there are large numbers of bats present.

Basic Gate with Window, Bacon Cave, Virginia. Photo by Jim Kennedy.

Basic Gate with Window, Gorman Cave, Texas. Photo by Jim Kennedy.

The **Chute Gate** is specifically used on caves or mines in which large numbers of bats inhabit for maternity or hibernacula, but for which the entrance configuration does not allow a Half Gate or Window Gate to be constructed. These gates are a design combination of a Basic Gate or Cupola Gate and an extended covered Window. The standard part of the gate will sometimes have a Bay Window (see below) added for a cantilever support for the Chute. The Chute extends beyond the Basic Gate at an angle to reach a height greater than a ladder will reach, thereby making entry more difficult for unauthorized persons while permitting unimpeded bat flight. The chute is covered with heavy gauge expanded metal. The size of the chute is determined by the expected number of bats and the physical size of the entrance.

Chute Gate on a Cupola, Grigsby Cave, Virginia. Photo by Jerry Fant.

Chute Gate with a supporting Bay Window, Tumbling Creek Cave, Missouri. Photo by Bill Elliott.

Cupola Gate Also sometimes called a "Cage Gate", these gates are designed to protect vertical pit and mine entrances. A free-standing box of four Basic Gates is built around the vertical opening, a minimum of 4' (1.2m) in height. The center top opening is then covered with additional angle iron or heavy gauge expanded metal. The height discourages vehicle traffic, and allows bats to slowly gain altitude and fly out the sides of the box, thus avoiding predators. A **Semi-Cupola Gate** is built into a hill or outcrop, and may only have two or three sides instead of four. A **Flat Gate** is just the top of a cupola gate, built to maintain airflow, but never placed over an entrance used by bats.

Cupola Gate, Powells Cave, Texas. Photo by Jim Kennedy.

Semi-cupola Gate, Weaver Cave, Alabama. Photo by Jim Kennedy.

Flat Gate under construction, Weaver Cave, Alabama. Photo by Jim Kennedy.

Flat Gate raised slightly for critter access, Bering Sink Cave, Texas. Photo by Jim Kennedy.

Some caves or mines may require a variation of different types or styles of gates, but the key components of the Basic Gate should remain. Specifications are covered on the design in the next section. A cave-gating specialist should be consulted during the initial stages of planning. A list of specialists and other resources can be found in the appendix.

Gate Design Specifications

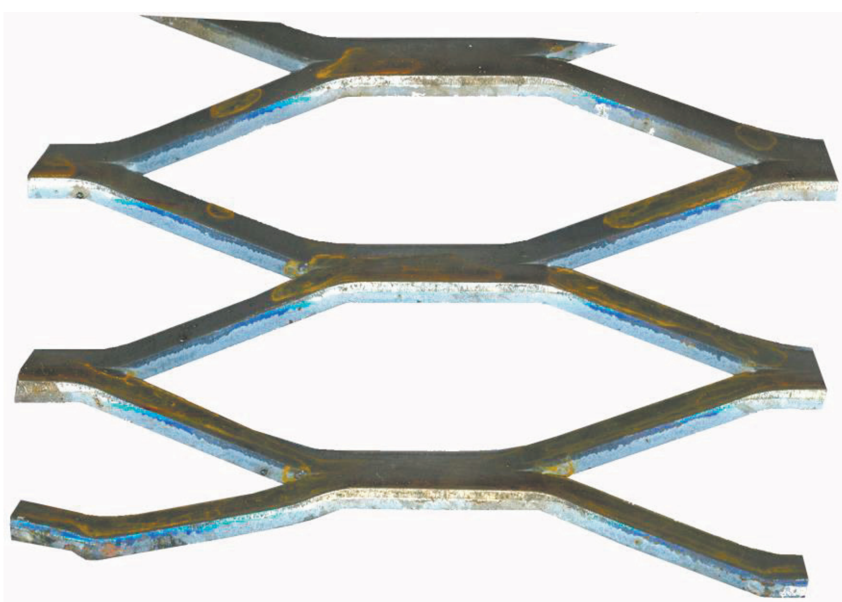
The gate designs developed by the American Cave Conservation Association and Bat Conservation International have been in use for over twenty years. Much research into the integrity, airflow characteristics, and bat use has shown these to be the state of the art in modern cave and mine gating. For this reason, major land management agencies and organizations have adopted these designs as their standard. This section covers the general design specifications for these gates. For more information contact any of the authors or attend one of their sponsored Cave and Mine Gating Workshops.

Basic Gating Materials (all gate material is of mild steel)

- Sill: 4" x 4" x ⅜" angle iron
- Columns: 4" x 4" x ⅜" angle iron
- Horizontal Bars: 4" x 4" x ⅜" angle iron
- Header Bar: 4" x 4" x ⅜" angle iron
- Footers: 4" x 4" x ⅜" angle iron
- Pin Plate: 4" x 4" x ⅜" angle iron *or* 6" x 6" x ⅜" angle iron
- Hangers: 6" x 6" x ⅜" thick flanged angle iron
- Stiffeners: 1½" x 1½" x ¼" angle iron
- Pins: 1" cold rolled steel round bar
- Bat Guard/Torsion Plate: 4" x ¼" flat bar
- Expanded metal: EM3 (4" x 2" diamond raised ¾") (also called 3-pound expanded metal grating)

For Half Gates, Windows, and Chutes (in addition to the above materials)

- Main support for expanded metal: 4" x 4" x ⅜" angle iron
- Additional support for expanded metal: 2" x 2" x ⅜" angle iron
- Expanded metal: EM3 (4" x 2" diamond raised ¾")



EM3, sometimes called 3-Pound Expanded Metal Grating, showing size of openings (to scale).

Design The gate shall have a weight-supporting bottom sill spanning the width of the passage, consisting of 4" x 4" x ⅜" or 6" x 6" x ⅜" angle iron, depending on the span and substrate. The vertical support columns are connected to the sill at the greatest separation possible, but not exceeding 15' (4.6m). The sill and columns rest on solid bedrock floor if possible. If not, they should rest on an expanded metal (EM3) skirt with at least 2 feet of EM3 both fore and aft of the gate. The columns are supported by 4" x 4" x ⅜" angle iron footers, which also serve to prevent lifting of the expanded metal. Additional footers may be added as necessary to provide added security for the expanded metal skirt. The vertical columns are ideally plumb to the longitudinal (front to back) axis of the cave, but can be off plumb on the perpendicular axis (side to side) if necessary to take advantage of wall attachment points, or to provide increased bat flight space in irregular passages.

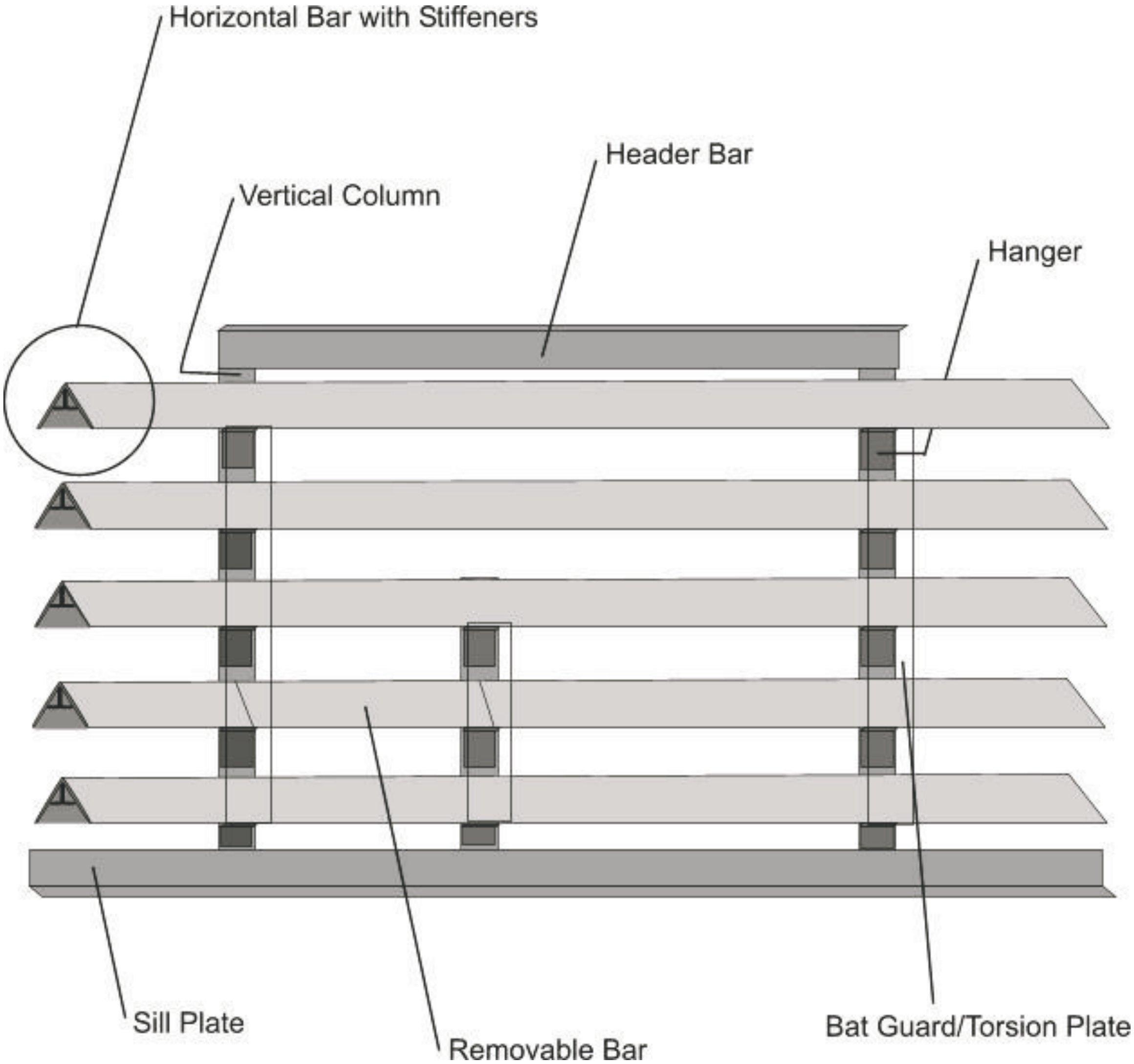
All columns and select horizontal bars are attached to the cave or mine walls with pins cut from 1" cold rolled steel round bar and a minimum of 8" long. They are pounded into 1" holes drilled into the solid bedrock walls, at least 6" deep and preferably 10" or more. The pins are then welded to Pin Plates cut from angle iron with a hole for the pin on one side, which is then welded to the gate itself.

The horizontal bars have two stiffeners inverted and placed inside the 4" x 4" angle and welded to the 4" x 4" angle every two to three feet of its length. The completed horizontal bar is to be placed on 6" x 6" x ⅜" thick flanged angle iron hangers. The hangers are connected to the vertical support columns so that the height from the top of one horizontal bar is 5¾" from the bottom of the bar above it.

A 4" x 4" x ⅜" angle iron header bar is welded to the top of the vertical support columns. The bat guard/torsion plate is welded to the front side of the hangers on all vertical support columns. The opening or door should be no less than 38" wide by 14½" tall. This allows a loaded rescue litter to be passed through the gate in case of an emergency. Removable bars (see upcoming diagram) are the most secure, but can be unwieldy for high-traffic use. In that case, a hinged door panel may be constructed as an alternative, but requires more care in engineering to assure long-term functionality without compromising the structural integrity or security of the gate.

Gates are typically left unpainted. The average projected life of a cave or mine gate is about 20–30 years, but may be many more in a dry, stable environment. The lifespan can be substantially less in areas of extreme weathering, or when attached the gate is installed in a corrosive area. Gate designs continue to evolve, and gates need to be replaced as new and better options become available.

Cross-section of 4-inch angle-iron bar with 1½-inch stiffeners welded inside (to scale).



Basic Gate schematic, showing nomenclature of parts.

Construction timing

After the decision is made to gate (as opposed to using some other protective measures), and deciding which type of gate to use, the next decisions involve the timing of the construction when to gate. Special attention must be made to several items, including:

Funding — Appropriate and substantial funding must be approved and secured prior to gating. There are many sources where your funding may come from: grants, contributions, budget approvals, in-kind contributions, etc.

Seasonality — Weather can play a major factor in the construction of a cave or mine gate. Rainy seasons will hinder the movement of steel to the site along with making the handling of steel extremely dangerous at the gate site. Cold winter temperatures can slow the construction process due to dexterity and site access. If snow and ice are present on site then lifting and moving steel will become more dangerous. Extremely high temperatures can present problems with worker dehydration, and must be monitored carefully. Any of these conditions can create a hazardous work site and will add considerable time to the construction of the cave gate. Biological impact, such as bat activity, may limit the available working window at the site (see next section below).

Species use — Considerations must be made to the species which inhabit the cave or mine. These species include vertebrates and invertebrates which may be listed as Threatened or Endangered both federally and by state, species which are not listed but are considered at risk ("Species of Concern"), and endemic species. Sites with rare species or high biodiversity are especially important. While some species live deep inside the cave or mine, many others will use the entrance area near where most gates are constructed. With bats, you should avoid any disturbance from gate construction during the summer months if the site is a nursery colony or has other summer use, and during the fall swarming period if the cave or mine is a hibernaculum. Consult with experts if you are unsure of specific dates or usage patterns.

Personnel — Organizing personnel is also important, as it is often difficult to schedule adequate help for the timely completion of the gate. Outside contractors usually present fewer problems, as they will utilize their own personnel, but that convenience comes with a higher price tag. Many gates are built using agency personnel or volunteers, keeping costs to a minimum but creating more logistical headaches. If on a tight budget, be sure to schedule the gating project far enough in advance to make use of as many in-house personal and volunteers as necessary.

Gate Contractors

There are several options for the actual construction of the cave or mine gate. These options are listed in order of preference, listing the pros and cons of each.

***Gating Specialists**,* such as Kennedy Above/Under Ground LLC, are extremely well versed in the design, placement, and construction of gates in less than optimum conditions. They are knowledgeable of many subterranean ecosystems and their relationship to the construction of the proper gate. Specialists are also experienced with cave and mine microclimates and their relationships to subterranean biota. They are knowledgeable in geomorphology and the engineering processes related to gate construction. Specialists have learned the tricks of the trade, usually increasing the efficiency and construction of the gate process and providing a higher-quality product. In most instances, cave-gating specialists can build the proper gate in less time than alternative builders. There are very few of these specialists certified in the construction of cave and mine gates, and they usually require travel, lodging, and meal reimbursement added to the cost of the gate. Even with these additional expenses the total budget for hiring a gating specialist is often equal to or less than for other contractors. Many specialists in the field can offer a variety of options affecting the construction costs: full hired crew; supervisor, cutter, and welder (with other labor provided by the agency); or as an on-site advisor for an unrelated crew.

Agency Personnel may include biologists, geologists, botanists, or maintenance departments tasked with the management of local cave and mine resources. While there may well be excellently trained and dedicated people working in those fields, they usually lack the overall knowledge and engineering required to properly address each aspect of designing, placing, and constructing a cave or mine gate. In-house gating projects may be generally cost effective, but may require several times longer to complete due to other obligations of the persons involved. For example a cupola-style gate recently constructed at a National Park took six weeks, whereas a gating specialist could have completed the same gate within 9 days or less. Gating workshops are scheduled periodically to assist those decision makers in understanding the ins and outs of the gating process, helping them to decide which options are available and what might work best for their sites.

Outside Consultants/Welding Contractors are generally the most expensive and least qualified to construct cave gates. Although the actual welding may be exceptional, the overall knowledge of the underground resources and potential impacts on them is practically non-existent. Even with detailed plans these contractors will have the most difficulty with equipment and personal in less than optimum conditions. And their lack of experience will be especially apparent if confronted with a non-standard gate. Without the proper training and certification, the time for the outside contractor to build a quality gate may be 4 to 6 times longer than the specialist. And in the case of the low-bid option, you usually get what you pay for.

There are many aspects in the construction of a cave gate that requires much experience to learn. A bad gate design and project practices put many things in jeopardy, ranging from resource impact to worker safety. Detrimental results of a bad gate design may not show for many years. Improper placement of the gate may cause premature failure, compromising site security. With the limited resources available, it is always best to do it right the first time.

Post-gating actions

Scientific monitoring, such as temperature and other microclimate changes and biological inventories, should be carried out before and after gate building in order to have a yardstick by which to measure the effects of the gate, if any. If a bat site, it is critically important to document bat acceptance of the gate, and any behavioral changes, positive or negative, that occur as a result. Monitoring of the gate itself for signs of attempted illegal entry and vandalism must also be done on a regular basis to keep the site secure and prevent further damage, more expensive to repair.

We cannot state strongly enough the need for post-gate monitoring. Once the gate is completed the typical agency response is to assume their concerns over visitation and vandalism are over, and the site can then be blissfully ignored. This is not the case. No gate should be installed before a management plan has been developed for the resource. This management plan should include a monitoring schedule which includes the following:

- *Periodic checks for structural stability.* Is the gate, and the bedrock to which it is attached, still structurally sound? Are erosion or freeze/thaw cycles affecting surrounding rock and jeopardizing site security? Are the steel or welds weathering faster than expected, resulting in weaknesses that can be easily exploited?
- *Periodic checks for vandalism*. Has the gate been breached? Typical ways to circumvent the gate are digging under the gate, breaking the rock wall around the gate, digging another entrance, bending the bars, breaking a weld, cutting the bars, cutting the lock, or climbing over (if a Half Gate, Window Gate, or Chute Gate). In rare occasions, vandals will even forcibly remove the entire gate.
- *Periodic checks for erosional effects from natural processes*. Is there an accumulation of debris building up around the gate? This can cause gates to fail when water-flow is encountered. It can also block natural airflow currents, which in turn disturb the microclimate.
- *Periodic checks for opening functionality*. Locks need regular attention, requiring cleaning, lubrication (with graphite powder), or even replacement. Even McGard button head bolts need occasional lubrication, without which they become hard or even impossible to open. Doors and removable bars should be opened periodically, to ensure that the gate has not settled, rendering them inoperable.
- *Periodic checks for biological integrity.* A site that has been gated to protect a population of bats or other animals, including invertebrates, must maintain a fairly narrow set of parameters to keep those populations healthy. And be sure that brush or vines are not encroaching on the cave gate, reducing its effectiveness.

If the gate is not ensuring optimal conditions, then it must quickly be modified, or even removed or replaced. Pre-gate monitoring of temperature, humidity, and animal abundance and distribution provides simple baseline data by which post-gate conditions can be compared. Pre-gate monitoring is highly recommended before any gate project is undertaken.

A breached gate that is not repaired rapidly is not protecting the resources from human threats. There are many natural forces that can also damage a gate, such as tree falls, rock falls, siltation, freezing and thawing, aging (rust), and running water. Checks should include close visual inspections as well as manual investigations. Vandals can be quite clever, sometimes cutting a bar, replacing it on the gate, and disguising it with mud to make it appear uncut. Often the breached area is away from the actual door or removable bar entry point, making it less likely to be noticed. Some vandals will go to extreme measures to destroy a gate or gain entry to a protected resource. A good monitoring schedule should be maintained monthly, or at a minimum of every six months in remote areas. Once a problem has been noted it should be repaired immediately.

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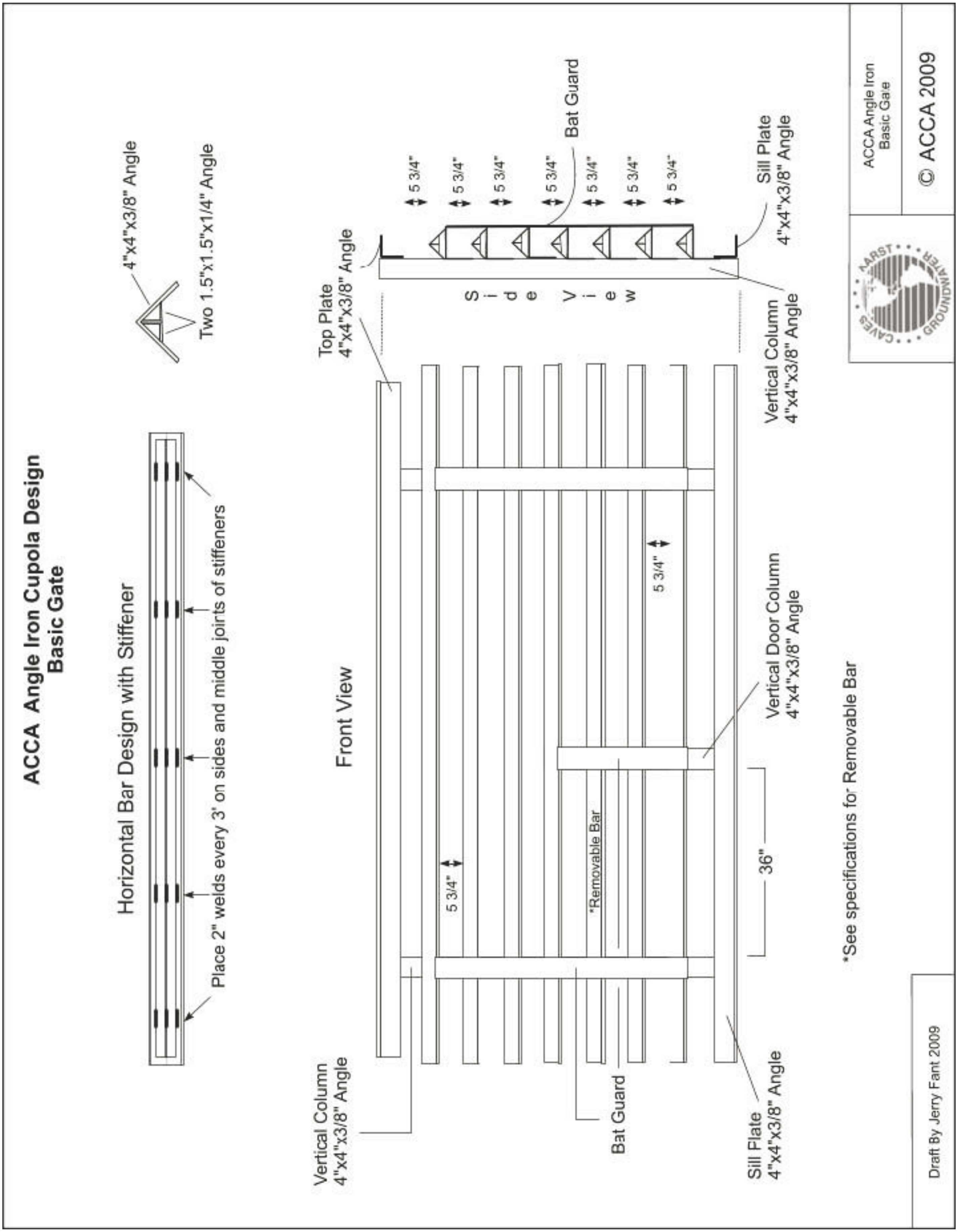
Gate Designs

(following pages)


ACCA Angle Iron Cupola Design
Basic Gate
Horizontal Bar Design with Stiffener
4"x4"x3/8" Angle
Two 1.5"x1.5"x1/4" Angle
Place 2" welds every 3' on sides and middle joirts of stiffeners
Front View
Top Plate
4"x4"x3/8" Angle
Side View
Bat Guard
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
Sill Plate
4"x4"x3/8" Angle
Vertical Column
4"x4"x3/8" Angle
5 3/4"
Vertical Door Column
4"x4"x3/8" Angle
*Removable Bar
5 3/4"
36"
*See specifications for Removable Bar
Vertical Column
4"x4"x3/8" Angle
Bat Guard
Sill Plate
4"x4"x3/8" Angle
Draft By Jerry Fant 2009
ACCA Angle Iron
Basic Gate
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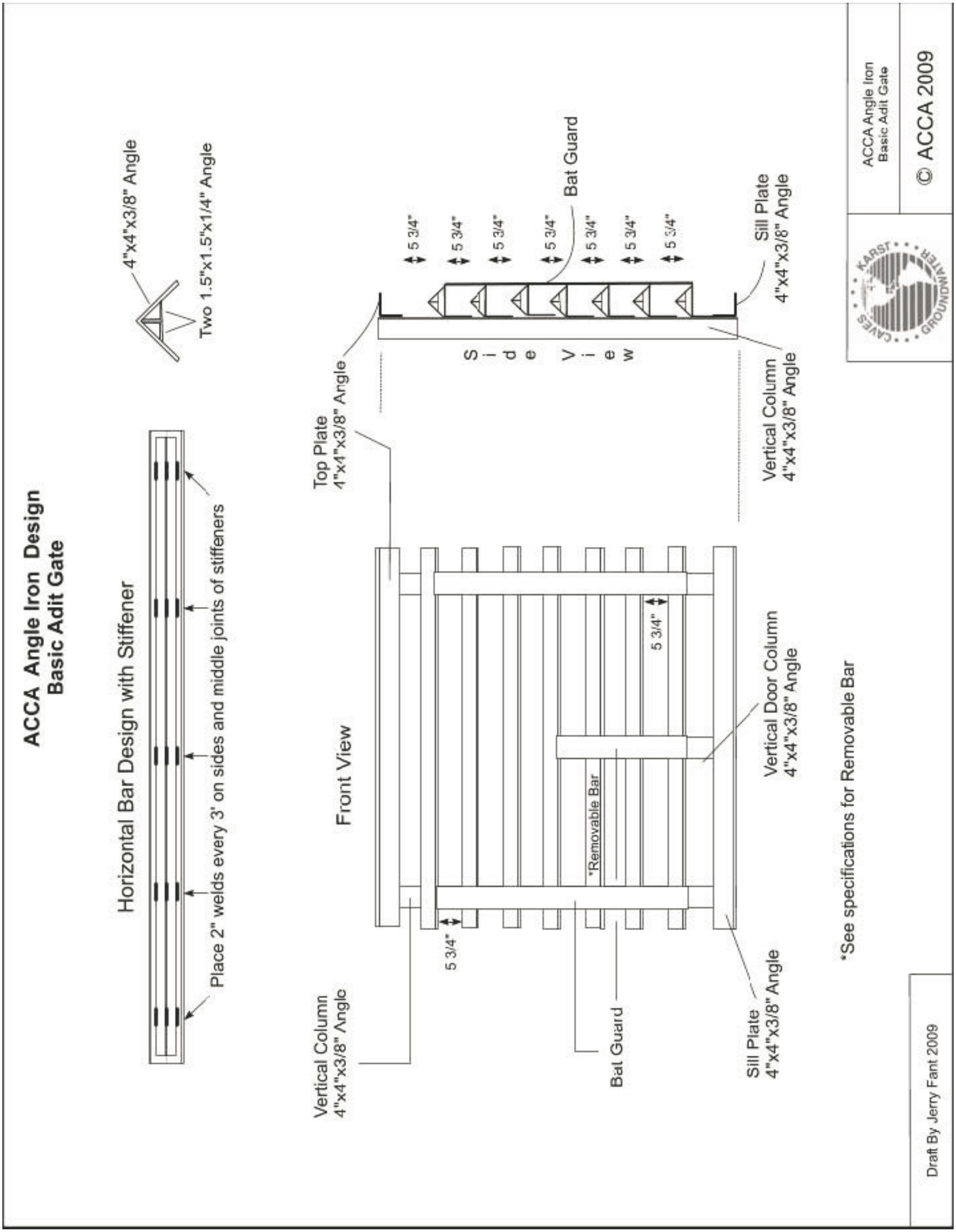
ACCA Angle Iron Design
Basic Adit Gate
Horizontal Bar Design with Stiffener
Place 2" welds every 3' on sides and middle joints of stiffeners
4"x4"x3/8" Angle
Two 1.5"x1.5"x1/4" Angle
Front View
Top Plate
4"x4"x3/8" Angle
S i d e V i e w
Bat Guard
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
5 3/4"
Sill Plate
4"x4"x3/8" Angle
Vertical Column
4"x4"x3/8" Angle
5 3/4"
*Removable Bar
5 3/4"
Vertical Door Column
4"x4"x3/8" Angle
Vertical Column
4"x4"x3/8" Angle
Bat Guard
Sill Plate
4"x4"x3/8" Angle
*See specifications for Removable Bar
ACCA Angle Iron
Basic Adit Gate
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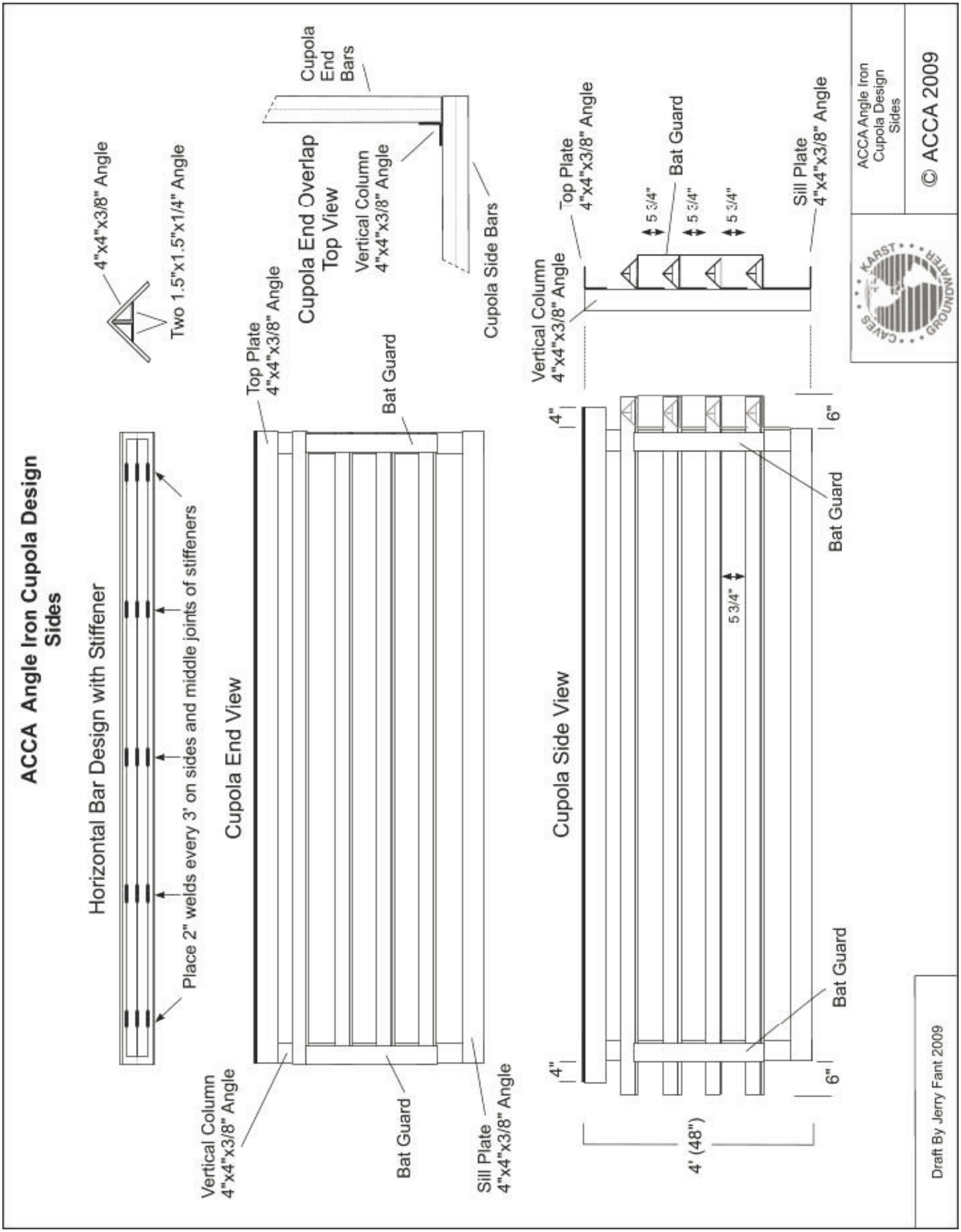
ACCA Angle Iron Cupola Design
Sides
Horizontal Bar Design with Stiffener
4"x4"x3/8" Angle
Two 1.5"x1.5"x1/4" Angle
Place 2" welds every 3' on sides and middle joints of stiffeners
Cupola End View
Top Plate
4"x4"x3/8" Angle
Bat Guard
Vertical Column
4"x4"x3/8" Angle
Bat Guard
Sill Plate
4"x4"x3/8" Angle
Cupola End Overlap
Top View
Cupola End Bars
Vertical Column
4"x4"x3/8" Angle
Cupola Side Bars
Cupola Side View
Vertical Column
4"x4"x3/8" Angle
Top Plate
4"x4"x3/8" Angle
Bat Guard
5 3/4"
5 3/4"
5 3/4"
Sill Plate
4"x4"x3/8" Angle
4"
6"
Bat Guard
5 3/4"
Bat Guard
4"
6"
4' (48")
ACCA Angle Iron
Cupola Design
Sides
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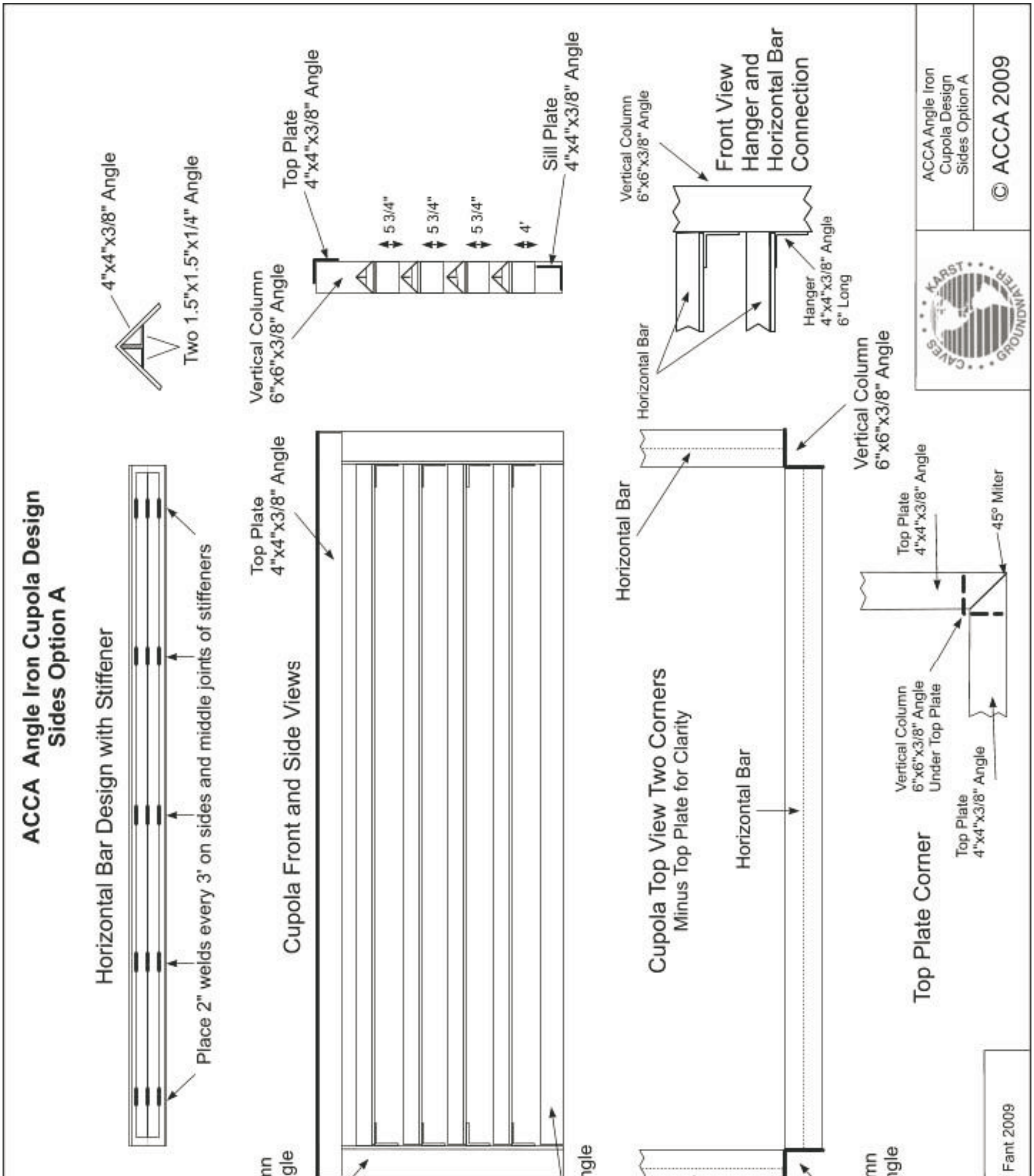
ACCA Angle Iron Cupola Design
Sides Option A
Horizontal Bar Design with Stiffener
4"x4"x3/8" Angle
Two 1.5"x1.5"x1/4" Angle
Place 2" welds every 3' on sides and middle joints of stiffeners
Cupola Front and Side Views
Top Plate
4"x4"x3/8" Angle
Vertical Column
6"x6"x3/8" Angle
Sill Plate
4"x4"x3/8" Angle
5 3/4"
5 3/4"
5 3/4"
4'
Cupola Top View Two Corners
Minus Top Plate for Clarity
Horizontal Bar
Vertical Column
6"x6"x3/8" Angle
Front View
Hanger and
Horizontal Bar
Connection
Hanger
4"x4"x3/8" Angle
6" Long
Top Plate Corner
Top Plate
4"x4"x3/8" Angle
45° Miter
Vertical Column
6"x6"x3/8" Angle
Under Top Plate
ACCA Angle Iron
Cupola Design
Sides Option A
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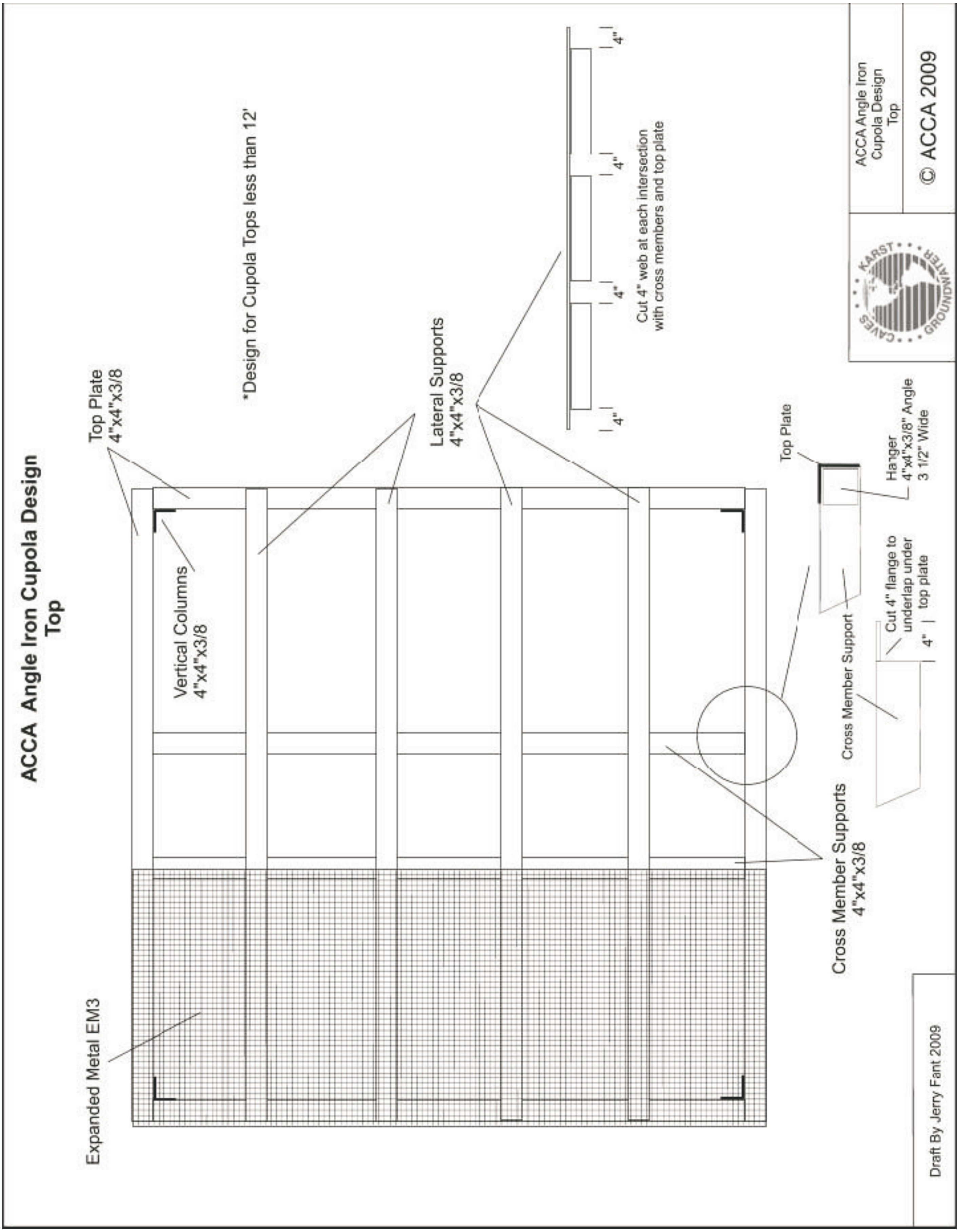
ACCA Angle Iron Cupola Design
Top
Top Plate
4"x4"x3/8
*Design for Cupola Tops less than 12'
Vertical Columns
4"x4"x3/8
Lateral Supports
4"x4"x3/8
4"
4"
4"
4"
Cut 4" web at each intersection
with cross members and top plate
Expanded Metal EM3
Cross Member Supports
4"x4"x3/8
Top Plate
Hanger
4"x4"x3/8" Angle
3 1/2" Wide
Cut 4" flange to
underlap under
top plate
4"
Cross Member Support
ACCA Angle Iron
Cupola Design
Top
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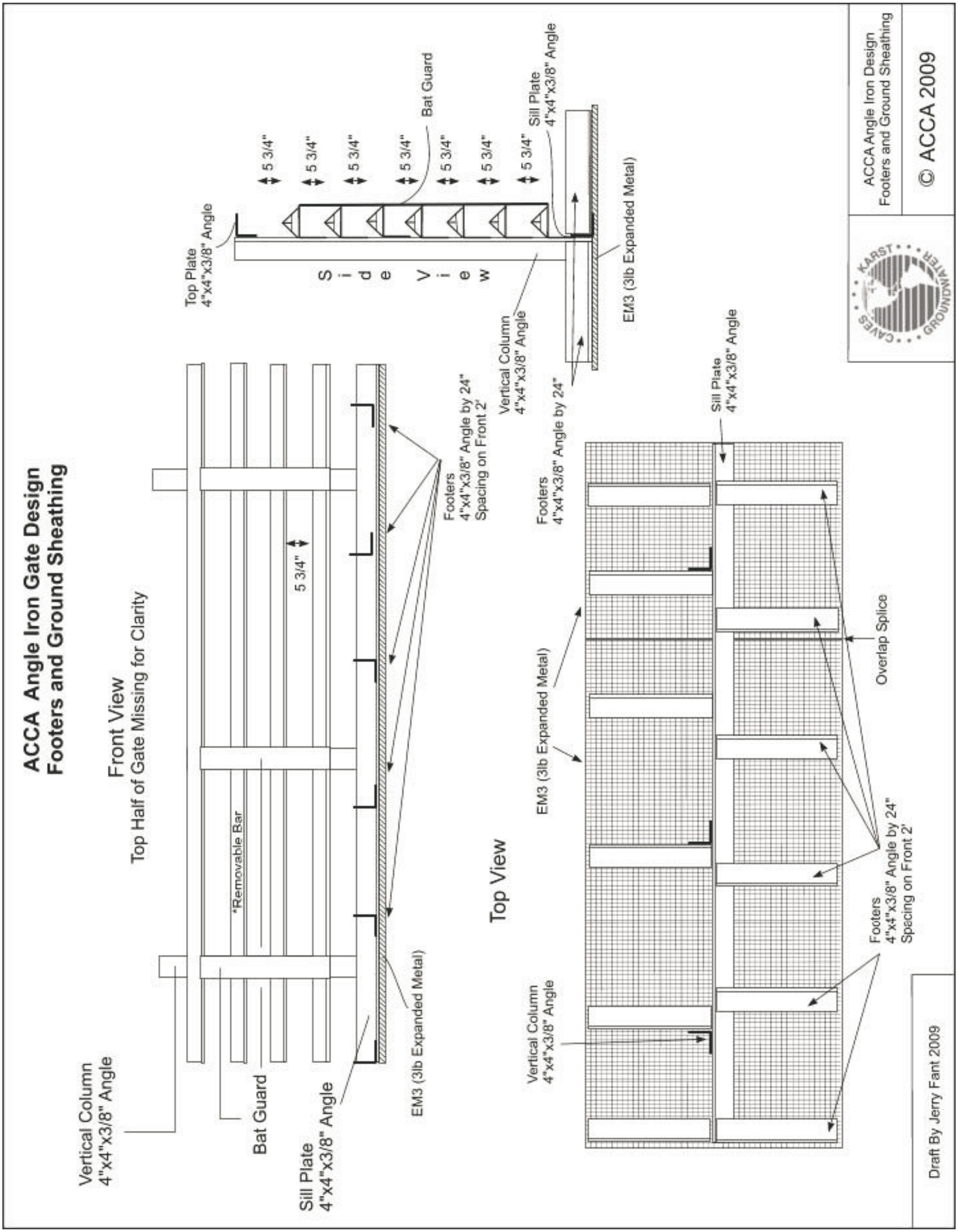
ACCA Angle Iron Gate Design
Footers and Ground Sheathing
Front View
Top Half of Gate Missing for Clarity
Vertical Column
4"x4"x3/8" Angle
Bat Guard
Sill Plate
4"x4"x3/8" Angle
*Removable Bar
5 3/4"
EM3 (3lb Expanded Metal)
Footers
4"x4"x3/8" Angle by 24"
Spacing on Front 2'
Top Plate
4"x4"x3/8" Angle
Side View
Bat Guard
5 3/4"
Sill Plate
4"x4"x3/8" Angle
Vertical Column
4"x4"x3/8" Angle
4"x4"x3/8" Angle by 24"
EM3 (3lb Expanded Metal)
Top View
EM3 (3lb Expanded Metal)
Footers
4"x4"x3/8" Angle
Sill Plate
4"x4"x3/8" Angle
Overlap Splice
Footers
4"x4"x3/8" Angle by 24"
Spacing on Front 2'
Vertical Column
4"x4"x3/8" Angle
ACCA Angle Iron Design
Footers and Ground Sheathing
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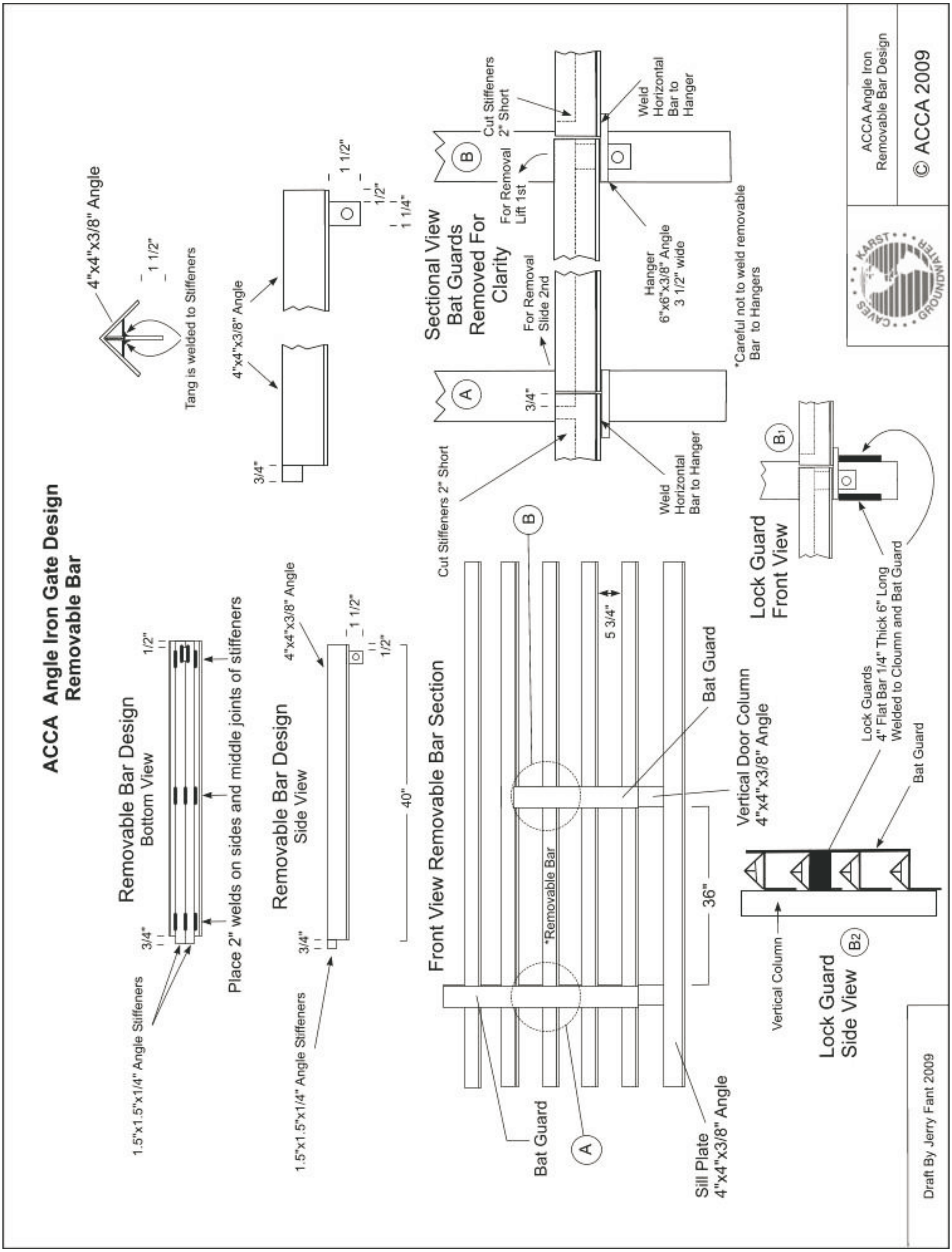

ACCA Angle Iron Gate Design
Removable Bar
Removable Bar Design
Bottom View
1.5"x1.5"x1/4" Angle Stiffeners
3/4"
1/2"
Place 2" welds on sides and middle joints of stiffeners
Removable Bar Design
Side View
1.5"x1.5"x1/4" Angle Stiffeners
4"x4"x3/8" Angle
1 1/2"
40"
Front View Removable Bar Section
*Removable Bar
Bat Guard
Sill Plate
4"x4"x3/8" Angle
36"
5 3/4"
Vertical Door Column
4"x4"x3/8" Angle
Cut Stiffeners 2" Short
4"x4"x3/8" Angle
Tang is welded to Stiffeners
Sectional View
Bat Guards
Removed For
Clarity
For Removal
Slide 2nd
For Removal
Lift 1st
Cut Stiffeners
2" Short
Weld
Horizontal
Bar to Hanger
Hanger
6"x6"x3/8" Angle
3 1/2" wide
*Careful not to weld removable
Bar to Hangers
1 1/4"
Lock Guard
Front View
Lock Guards
4" Flat Bar 1/4" Thick 6" Long
Welded to Cloumn and Bat Guard
Lock Guard
Side View
Vertical Column
ACCA Angle Iron
Removable Bar Design
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