

An aerial photograph of a village nestled in a valley. The village consists of several traditional wooden houses with dark, tiled roofs. The houses are surrounded by lush green forests on the steep slopes of the surrounding mountains. In the foreground, there are terraced fields, some of which are brown, suggesting they might be dry or recently harvested. The overall scene is a picturesque representation of a rural, mountainous landscape.

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NCKRI SYMPOSIUM 6 Proceedings of the 15th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst and the 3rd Appalachian Karst Symposium

2018

NCKRI SYMPOSIUM 6

**Proceedings of the
15th Multidisciplinary Conference on
Sinkholes and the Engineering
and Environmental Impacts of Karst
and the
3rd Appalachian Karst Symposium**

Edited by: Ira D. Sasowsky,
Michael J. Byle, and Lewis Land



www.nckri.org



NATIONAL CAVE AND KARST RESEARCH INSTITUTE
SYMPOSIUM 6

PROCEEDINGS OF THE 15TH
MULTIDISCIPLINARY CONFERENCE ON
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ENVIRONMENTAL IMPACTS OF KARST**
AND THE 3RD
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Images showing pre-construction setting and newly built Five-hundred-meter Aperture Spherical radio Telescope (FAST). This instrument, completed in 2016, is the world's largest filled-aperture radio telescope and was built within an extremely large karst depression, Dawodang, in Pingtang, Guizhou, China. Images courtesy Dr. Boqin Zhu, National Astronomical Observatories of China. See paper by Zhu et al., this volume.

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FOREWORD

Welcome to the Fifteenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst and the Third Appalachian Karst Symposium. This year our meeting returns to the eastern United States, and to one of the cradles of karst studies from the prior century: the Appalachians of Virginia and West Virginia. Early cave exploration and science in this region occurred in tandem with groundbreaking European studies in speleology. In 1930 William Morris Davis published his comprehensive “Origin of Limestone Caverns,” making use of sites in the Appalachians, as well as others. Important documentary compilations of Virginia caves by McGill (1933), Douglas (1964), and Holsinger (1975) appeared over the years, along with William Davies’ “Caverns of West Virginia.” In January of 1941, the National Speleological Society (NSS) was founded in nearby Washington, D.C. by cavers who were very active in the Appalachian karst regions. Through their publication of the “NSS Bulletin,” later “The Journal of Cave & Karst Studies,” a golden era of North American cave exploration and science was developed and documented. The work and discovery continue to this day, as both pure exploration and science move forward side-by-side.

The Sinkhole Conference, established in 1984 by Dr. Barry Beck, has a long history of bringing together scientists and engineers with interests in applied aspects of karst settings. The eastern U.S. with its population centers and dense infrastructure, is a critical locale with numerous examples of the challenges of co-existence with caves and sinkholes. This was one spur for the convening of the first Appalachian Karst Symposium (Kastning & Kastning, 1991). Twenty-seven years later we are happy to co-convene the 15th Sinkhole Conference with the 3rd Appalachian Karst Symposium, to bring together scientists, engineers, managers, and others, who share a stake in understanding karst systems.

Since 2011 The Sinkhole Conference has been sponsored by the National Cave and Karst Research Institute (NCKRI), a congressionally-created non-profit organization dedicated to pure and applied research on caves, karst phenomena, and karst hydrology. This year NCKRI joins with the Karst Waters Institute (KWI) as co-sponsors of the meeting. KWI, which is incorporated in West Virginia, has the mission to improve the fundamental understanding of karst water systems through sound scientific research and the education of professionals and the public. Both organizations, along with supporting groups indicated in these Proceedings, welcome you and hope you will have a great week at the National Conservation Training Center, Shepherdstown, West Virginia.

Ira D. Sasowsky, Proceedings Editor
University of Akron
Akron, Ohio



FIGURE 60.—Cross-section of Shenandoah Valley, Virginia
After Virginia Geological Survey.

Interpretation of the folded limestones of the Shenandoah Valley by Davis
(1930)

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KEYNOTE SPEAKER

AN APPALACHIAN MYSTERY: THE HYDROGEOLOGY OF MOUNTAIN LAKE IN GILES COUNTY, VIRGINIA. LEAKY LANDSLIDE OR COVERED KARST?

Chester (Skip) F. Watts

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Abstract

Mountain Lake, in Giles County, Virginia was the principal filming location for the 1987 movie *Dirty Dancing*, at a time when the lake was full. Starting in about 2002, water levels decreased significantly during the fall months and recovered only partially during the summer months. In 2008, the lake went completely dry and then nearly so again in 2011. Mountain Lake is one of only two naturally formed lakes in Virginia. At an elevation of 3,875 feet above sea level, it is a truly unique feature in the Valley and Ridge Province within the unglaciated southern Appalachians. A karst collapse origin for the lake has often been suggested. Recent geophysical studies suggest that the lake owes its existence, at least in part, to colluvial damming of an ancient water gap in the breached limb of a dissected plunging anticline approximately 6,000 years ago.

Major conduits are believed to form periodically within the colluvial dam allowing water and lake sediment to pipe through the debris until such time as the conduits become sufficiently clogged to again hold back nearly 100 feet of water depth. The colluvial deposits are likely never completely free of leaks, however it does appear that leakage varied in severity somewhat over the thousands of years. In 2013, the owners undertook a massive earthmoving project intended to restore the lake by filling depressions at the base of the dam, caused by the piping of lake sediment, with naturally available materials from the site. The effort was successful and water levels rose rapidly until encountering additional side conduits at higher elevations that now appear to control lake levels.

Radford University researchers have utilized dye studies, electrical resistivity, seismic refraction, side scan sonar, SCUBA, submersible ROV, unmanned aerial systems, and more to investigate the lake. Observations indicate

that the leaks overall are greatly reduced and that precipitation is nearly normal for this region, raising the question of whether changes within the watershed may also play a role by decreasing the inflow side of the water budget equation. In 2002, a part of the drainage basin was modified by the development of new cottages, parking lots, and storm water retention basins. Runoff modeling using the rational method reveals that annual surface flow to the lake has decreased from that area. Groundwater modeling reveals that infiltration beneath these stormwater retention basins lies outside of the groundwater divide for the system that provides base flow recharge to the lake, hence surface water captured by the retention basins appears permanently lost to the lake.

Biography

Dr. Skip Watts received his PhD from Purdue University in 1983. He teaches Geology Applied to Engineering and Hydrogeology at Radford University and Virginia Tech. Skip received several regional and national teaching awards, including the State Council for Higher Education's Outstanding Professor Award, Virginia's highest teaching honor, awarded by the Governor. He spent 18 months as a USGS Congressional Fellow serving Senator Joe Lieberman as a science adviser. He was named the 2003 Jahns Distinguished Lecturer speaking on the topics of Geology and Public Policy and Military Operations in Difficult Terrain. He appeared on The Weather Channel's documentary series *Storm Stories* in an episode entitled *SLIDE!* and as a guest on National Public Radio's Weekend Edition. Skip provides rock slope safety and stability consulting services for federal and state agencies as well as for private industry. He is presently serving as director of the Radford University GeoHazards Research Center, specializing in the use of unmanned aerial systems (UAS) for geologic mapping and investigating natural hazards of all types.

BANQUET SPEAKER

THE SCIENCE BENEATH THE OHIO STATE GEOTHERMAL FIELD FIASCO: A COOL STORY ABOUT A HOT TOPIC

E. Scott Bair

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Abstract

The geothermal wellfield at Ohio State University was designed to heat and cool five, 11-story dormitories. The estimated cost of the HVAC conversion project, including construction of 480 geothermal wells to a depth of 550 feet, was \$4.5M. An east coast company received the drilling contract based on cost and use of multiple air-rotary drilling rigs to complete the wells with 100 feet of steel casing through 80-90 feet of unconsolidated glacial deposits, with the remaining depth completed as 'open hole' through limestones and dolostones. No problems occurred drilling the first well.

However, while drilling the second well at a depth of 280 feet, the first well, located 30 feet away, began spouting water 10-15 feet in the air. Work on the second well was halted as drilling began at a third well about 200 feet away. The first and second wells spouted water as the drilled depth in the third well hit 400 feet. As well construction continued, as many as seven wells often could be seen simultaneously spouting water. Commonly, previously drilled wells that had spouted water did not spout water as new wells were drilled in close proximity. The drillers, who normally worked in crystalline rocks, had not seen anything similar to the number, erratic pattern, and irregular participation of spouting wells. Engineers maintained that the air-rotary rigs pressurized an existing 'fracture zone' at a depth of 250 to 400 feet creating the 'geysers'. Three test wells spaced across the geothermal did not encounter the 'fracture zone,' nor did several of the geothermal wells. Drilling proceeded for several months despite the numerous spouting wells and associated runoff problems.

The state and city cited the university with daily fines for violating ordinances limiting drainage to a nearby river and sediment loads to sewers. Shortly thereafter, the driller was fired, lawsuits threatened, a new bid

document released, and another company hired, one that proposed a different drilling method and a completion technique that would solve the problems caused by a well-known paleokarst zone. At least it was well known to local hydrogeologists and several faculties in the Earth Sciences Department. Ignorance delayed completion of the geothermal wells by a year and added \$4M to the overall project cost.

Biography

E. Scott Bair took his B.A. in geology from the College of Wooster and his M.S. and Ph.D. from Penn State University. Following graduate school he worked six years at Stone & Webster Engineering Corporation. Tired of corporate politics and remembering academe to be devoid of it, Scott joined the faculty at Ohio State University in 1985. Over his career he taught courses in earth science, water resources, environmental geology, speleology, petroleum geology, hydrogeology, field methods in hydrogeology, and groundwater flow modeling. In 1991, he received the Ohio State award for teaching excellence; as penance he served six years as department chair. Scott advised 34 graduate students who worked on projects funded by Ohio DNR, Ohio EPA, NSF, USEPA, USDOE, USDA, USGS, and Ohio State.

Scott likes to talk. He's given seminars at more than 90 colleges and universities in the U.S., Canada, and Japan, at several federal and state agencies, the Ohio Bar Association, Harvard Law School, and the National Research Council. From 1987 to 2015 he co-taught short courses for the National Ground Water Association (NGWA) including Principles of Groundwater Flow, Transport and Remediation; Aquifer Test Design and Analysis; Groundwater Control and Construction Dewatering; Artificial Recharge and Induced Infiltration; and Delineating Capture Zones of Wells for Contaminant

Remediation and Wellhead Protection. He is co-author of the semi-successful textbook *Applied Problems in Groundwater Hydrology*.

He is a Fellow of the Geological Society of America (GSA), recipient of its Birdsall-Dreiss Distinguished Lectureship, and former chair of its Hydrogeology Division. Scott was an associate editor of the journal *Ground Water* for 11 years, a member of the Ohio Hazardous Waste Facilities Board for three governors, a technical reviewer for the Centers for Disease Control investigation of male breast cancers at U.S. Marine Corps Base Lejeune, and a member of the USEPA Science Advisory Board on Hydraulic Fracturing. He received the George B. Maxey Award from GSA and the Keith E. Anderson Award from NGWA for his service to those organizations and his contributions to the greater groundwater community. Scott and his wife recently retired to the Outer Banks of North Carolina where they plan to lollygag in the sun and surf until rising sea level carries them away.

COUPLING DYE TRACING, WATER CHEMISTRY, AND PASSIVE GEOPHYSICS TO CHARACTERIZE A SILICICLASTIC PSEUDOKARST AQUIFER, SOUTHEAST MINNESOTA, USA

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Abstract

A decade of dye tracing in southeastern Minnesota within shallow, buried Cambrian siliciclastic units has revealed groundwater flow characteristics more commonly associated with carbonate karst aquifers. To understand the hydrologic system, several characterization methods were used on a pair of dye traces in central Winona County in southeast Minnesota. South of the City of Stockton, Minnesota, a deeply incised north-south trending valley and its tributaries contain a number of large springs and several sinking streams. In the project area, streams sink into the lower part of the Cambrian siliciclastic Jordan Sandstone or the upper portion of the underlying Cambrian St. Lawrence Formation. The St. Lawrence Formation consists of interbedded well-cemented siltstone, very fine-grained sandstone, and very thin shale. Most of the large springs found in deeply incised valleys in southeastern Minnesota emanate from the basal St. Lawrence and upper Lone Rock Formations. The Lone Rock is a siliciclastic unit consisting of fine-grained sandstone and siltstone with minor beds of shale and dolostone. Passive charcoal detectors were used to calculate dye-breakthrough velocities that ranged between 58–203 meters/day at one location and 47–72 meters/day at another. These velocities are consistent

with other trace velocities measured within siliciclastic units in southeastern Minnesota. Water samples collected at the sinking streams, springs, and a domestic well in the project area show elevated nitrate and chloride concentrations indicating anthropogenic impacts likely related to application of fertilizers and road salt. Passive geophysical data were collected at the sinking stream locations and at transects within two valleys to characterize depth to bedrock. At the sinking stream above mapped Jordan Sandstone, the depth to bedrock was determined to be 6.4 meters. The depth at the location mapped above the St. Lawrence Formation was determined to be 5.2 meters. These data suggest colluvium and alluvium layers are thicker than what was previously conceptually modeled in this setting. The results of these dye traces are consistent with others in southeast Minnesota showing that the siliciclastic St. Lawrence and Lone Rock Formations have conduit-flow properties similar to those found in carbonate karst aquifers.

Introduction

Underlying southeastern Minnesota is a broad structural geological depression containing a sequence of sedimentary Paleozoic bedrock layers that are Cambrian to Devonian in age (Mossler, 2008). In Minnesota, the

Cambrian rocks are generally dominated by siliciclastic materials and the Ordovician and Devonian rocks dominated by carbonates. These bedrock aquifers support domestic, agricultural and industrial water needs as well as more than one hundred trout streams that are fed by groundwater springs.

Decades of dye tracing in Minnesota focused on characterizing groundwater velocities and delineating groundwatersheds of the carbonate dominated Ordovician and Devonian rocks to improve groundwater management and protection in the region. In the last ten years, many hydrologic investigations in southeastern Minnesota have focused on characterizing sinking streams and groundwater flow directions and velocities in two siliciclastic dominated formations of the Cambrian system: the St. Lawrence and Lone Rock Formations (Green et al., 2008, 2012; Barry et al., 2015).

Multi-faceted characterization of secondary pore networks in siliciclastic-dominated units in southeast Minnesota that coupled outcrop and borehole geophysical observations has shown these siliciclastic units generally have bedding-parallel and vertically oriented apertures less than a few centimeters (Runkel et al., 2014). Vertically oriented apertures are likely developed from regional extension, thermoelastic contraction, or unloading associated with uplift and erosion (Underwood et al., 2003). The process by which bedding-parallel oriented apertures form remains enigmatic; recent studies suggest they appear to be mechanically developed although dissolution of interstitial carbonate cement within these units may also be a factor (Runkel et al., 2014). Although these units lack the large conduits typically associated with carbonate karst, dye tracing in these Minnesota siliciclastic units has recorded non-Darcian minimum groundwater flow velocities of 28–750 meters/day (93–2,460 feet/day). As a comparison, groundwater velocities in the overlying Galena-Spillville Karst System are much higher: 1.6–4.8 kilometers/day (1–3 miles/day) (Green et al., 2014).

These non-Darcian minimum groundwater flow velocities coupled with characteristic symmetric breakthrough curves with recession limbs that last months to years warrant classifying these shallow buried siliciclastic groundwater systems as pseudokarst. Hydrologically, pseudokarst is described as “... a predominance of subsurface drainage through conduit type voids, but

lack[ing] the element of long-term evolution by solution and physical erosion” (Kempe and Halliday, 1997).

This paper focuses on the geologic and hydrogeologic setting of southeastern Minnesota and describes the results of coupling dye tracing, water chemistry, and passive geophysics to characterize a siliciclastic pseudokarst aquifer in Winona County.

Geologic and Hydrogeologic Setting

In Winona County, a veneer of unconsolidated sediments that is generally less than 15 meters (50 feet) thick overlies sedimentary bedrock units from the Upper Cambrian through the Upper Ordovician in age (Steenberg, 2014; Lusardi et al., 2014).

A broad plateau of resistant dolostone of the lower Ordovician Prairie du Chien Group is dissected by numerous narrow valleys that ultimately drain east to the Mississippi River or south-southeast to the Root River (Figure 1). The stratigraphy underlying the Prairie du Chien is dominated by relatively easily weathered sandstone, siltstone, and shale layers of the Upper Cambrian Jordan, St. Lawrence and Lone Rock formations that form the valley slopes and floors (Figure 2).

The St. Lawrence Formation consists of well-cemented, thin-to-medium beds of siltstone, dolomitic

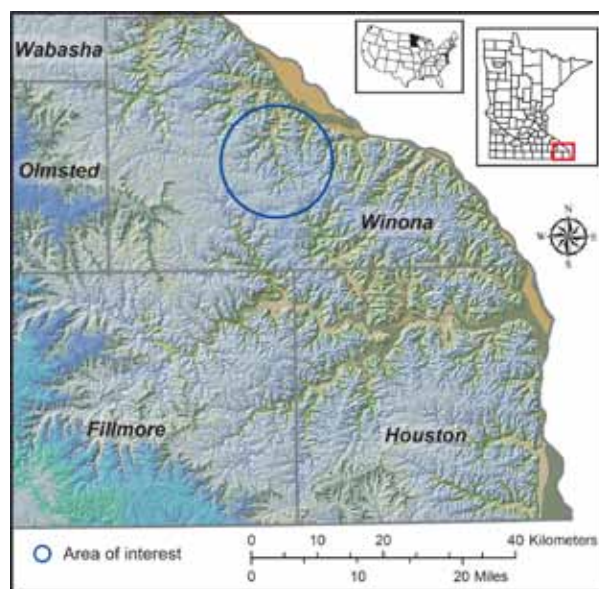


Figure 1. Study Area. Location of study area superimposed on the regional geologic setting of Paleozoic rocks in southeast Minnesota. Geologic map from Runkel et al., 2013.

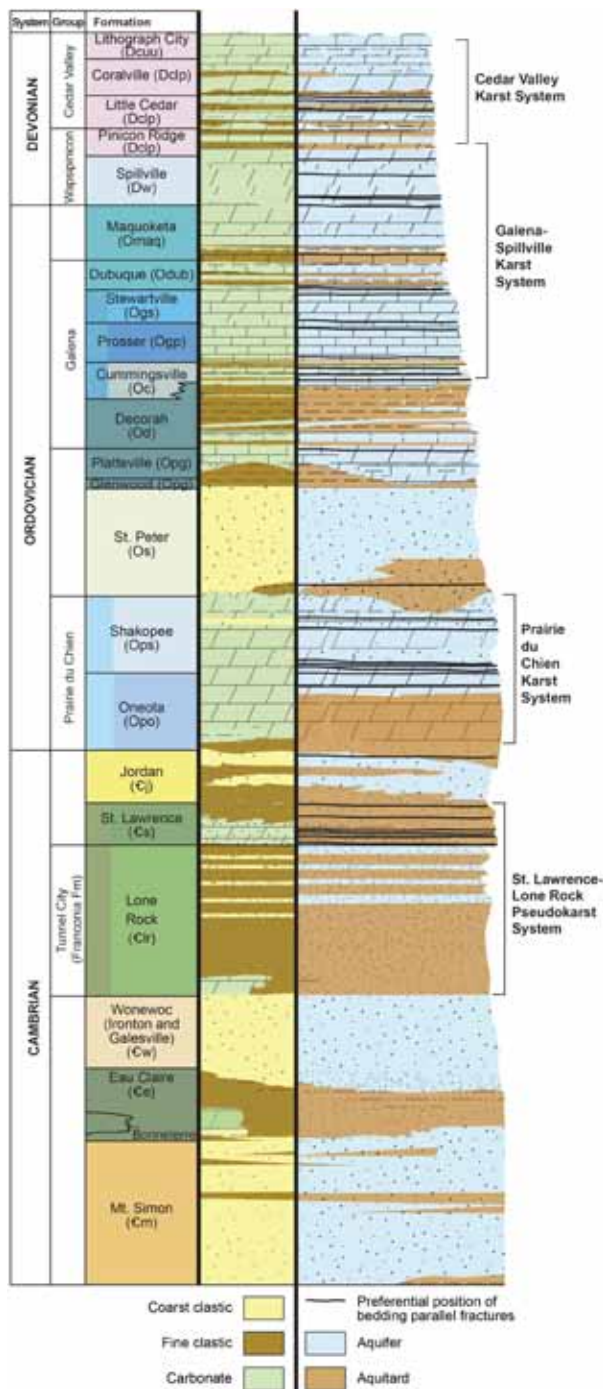


Figure 2. Geologic and generalized hydrogeologic attributes of Paleozoic rocks in southeast Minnesota. Modified from Steenberg, 2014. Regional karst system described in Runkel et al., 2013. Pseudokarst system described in Barry et al., 2015.

siltstone, very fine-grained sandstone and shale. In deep bedrock settings (buried by more than 15 meters [50 feet] of overlying bedrock), the St. Lawrence has a low matrix permeability and poor connectivity of fractures in a vertical direction, leading to a low bulk vertical conductivity. However, pervasive bedding-parallel secondary pore networks with high horizontal conductivity results in a marked anisotropy (Runkel et al., 2003). The low bulk vertical hydraulic conductivity for the St. Lawrence in deep settings has influenced guidance in the Minnesota Well Rules handbook, where it is classified as a confining layer (Minn. Dept. of Health, 2011). In southeastern Minnesota, the integrity of the St. Lawrence as an aquitard is diminished in shallow bedrock conditions (within 15 meters [50 feet] or less of the bedrock surface) and in the vicinity of deeply incised valleys. Vertical and bedding-parallel apertures are more abundant, better-connected and enhanced compared to deep bedrock settings. A transition from higher to lower aquitard integrity within 2,500 meters (8,200 feet) from eroded edges in incised tributary valleys to the Mississippi River has been estimated, using tritium and nitrate as tracers (Runkel et al., in prep).

The underlying Lone Rock Formation of the Tunnel City Group, is composed of fine-grained sandstone and siltstone with interbedded shale and dolostone (Mossler, 2008). High permeability bedding plane fractures are common in both St. Lawrence and Lone Rock, and springs are commonly found near the toe of the valley slopes emanating from each of these units. These springs supply cool isothermal water that forms the headwaters of the abundant trout streams in these valleys.

A geologic column for Winona County (Figure 2) displays both the lithostratigraphic and generalized hydrostratigraphic properties of the Paleozoic bedrock units in the county (Steenberg, 2014). Hydrostratigraphic attributes are generalized into either aquifer or aquitard using relative permeability. Layers assigned as aquifers are permeable, easily transmitting water through porous media, fracture networks, or conduits. Layers assigned as aquitards have lower permeability that vertically retards flow but may also contain high permeability bedding plane fractures that yield large quantities of water.

Methods

This investigation occurred in east central Winona County, south/southeast of the City of Stockton along

Stockton Valley Creek and its tributaries (area I in Figure 5). The project was initiated to characterize aquifer interaction for use in water resource protection and further map groundwater springsheds. The work occurred in two areas where a series of springs supply water to a private fish hatchery.

Dye tracing was conducted using fluorescent dyes and passive charcoal receptors that were deployed prior to the introduction of the dyes and changed at variable frequencies following dye introduction. Passive charcoal detectors were deployed for 6.5 months following the introduction of dye. Flow of dye through the hydrologic system was timed and mapped based on when and where dyes were recovered from passive detectors. Analyses of the passive detectors was performed at the University of Minnesota Department of Earth Sciences Hydrochemistry Laboratory using a Shimadzu RF5000 scanning spectrofluorophotometer and Fityk version 1.20 software.

Water chemistry was characterized using direct water samples from springs, sinking streams, surface water, and a residential well in the project area that were analyzed for anions. Anion concentrations were determined using a Thermo Dionex ICS-5000+ Ion Chromatography System. Spring and surface water samples were collected under base flow conditions.

Project area chemistry was coupled with regional groundwater chemistry collected as part of sampling for the Winona County Geologic Atlas, which is a project of the Minnesota DNR County Geologic Atlas (CGA) Program (Barry, in prep). CGA chemistry includes standard field parameters, cations, anions, trace metals, stable isotopes, and enriched tritium. Inorganic chemistry was analyzed at the Minnesota Department of Agriculture Laboratory. Isotopes were analyzed at the University of Waterloo.

The Minnesota Geological Survey routinely uses horizontal to vertical spectral ratio analysis (HVSr) in their County Geologic Atlas program to inexpensively and quickly determine depth to bedrock for geologic mapping. The HVSr method uses ambient noise and relationships between sediment thickness and shear waves to estimate thickness of unconsolidated sediment over bedrock. Sediments in valleys in southeastern Minnesota often have high amplitude HVSr peaks that

are representative of the strong impedance contrasts at the bedrock surface (Chandler and Lively, 2014). Depth to bedrock estimates were determined using HVSr collected using a Micromed Tromino Model TRZ tromograph and analyzed using Tromino Grilla software.

Stratigraphic interpretations of spring positions are based on the Winona County bedrock geology map. Mapping was developed using a combination of correlations to water well records from the County Well Index and field outcrop examination (Steenberg, 2014; Bauer and Chandler, 2014).

Project geospatial data including the locations of karst features, springs, and well locations are stored in parallel databases that share a relatable unique identifier. This unique identifier is used in the Minnesota Karst Feature Database (KFD), the Minnesota Spring Inventory (MSI), the County Well Index (CWI), and the Minnesota Groundwater Tracing Database (MGTD, in prep). The unique identifier is a ten character alpha-numeric field, but has been abbreviated for this report (e.g., 85B0000026 is abbreviated to 85B26).

Dye Tracing Results

Two traces were completed along Stockton Valley Creek and its tributaries. The first trace introduced 1.237 kilograms (kg) of 35 weight percent Uranine HS dye solution into an upstream riffle and discrete sinking stream point (85B26) located within the Jordan Sandstone subcrop at the north valley location. The second trace introduced 1.199 kg of 33 weight percent eosine dye solution into an upstream riffle and discrete sinking stream point (85B24) located within the St. Lawrence Formation subcrop in the southern valley location. Stream discharge was estimated to be 0.001–0.002 cubic meters per second (0.04–0.07 cubic feet per second) at the north valley pour location and 0.0012–0.0015 cubic meters per second (0.04–0.06 cubic feet per second) at the south valley pour location.

At the north valley investigative area (Figure 3), dye was detected at a number of springs and two flowing augmentation wells associated with the fish hatchery. We were unable to review well construction records for these wells; however based on local knowledge it is believed they are roughly 15 meters (50 feet) deep or less and completed in the Lone Rock Formation. Assuming a straight-line distance from the northern

stream sink (85B26) to the north pond spring (85A16) located at the hatchery complex, the estimated minimum peak groundwater velocity ranges from roughly 108 to 203 meters/day (354 to 665 feet/day).

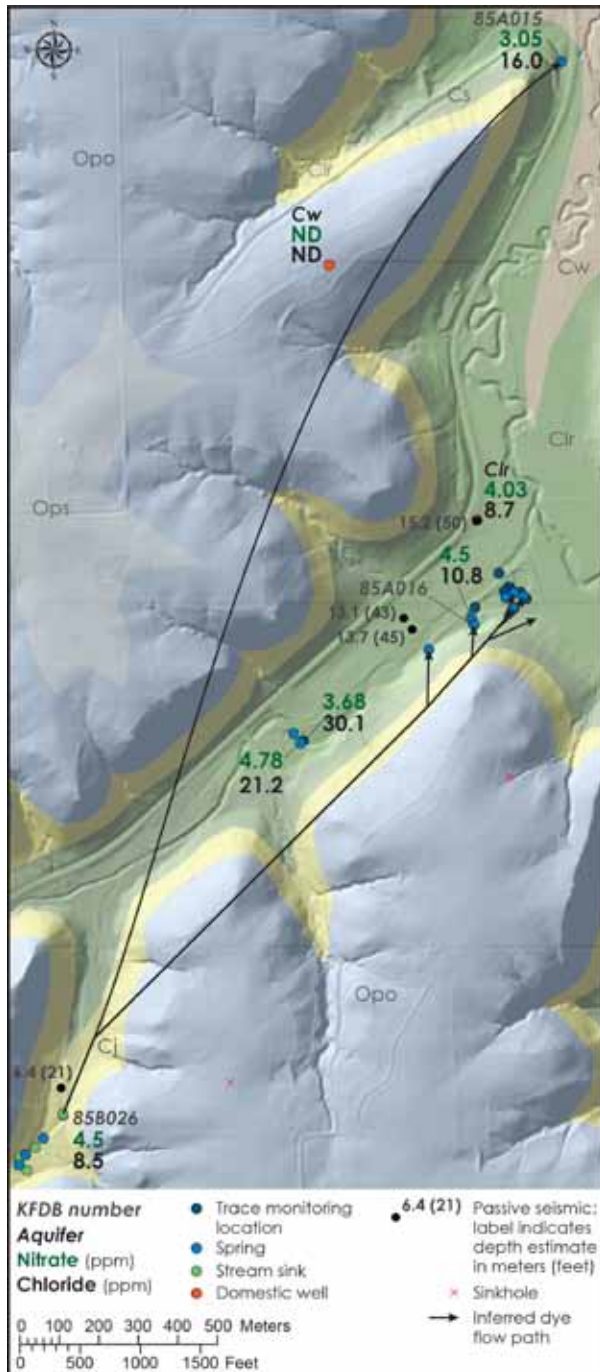


Figure 3. North Valley Investigation area. Paleozoic bedrock geology, inferred dye flow paths, estimated depth to bedrock, and select chemistry for springs and surface water in the north valley investigation area. Geologic map from Steenberg, 2014.

Uranine HS additionally emerged at a spring located approximately 1,350 meters (4,430 feet) to the north (85A15). Assuming a straight-line distance from 85B26 to 85A15, the estimated minimum peak groundwater velocity ranges from roughly 58 to 80 meters/day (190 to 262 feet/day). Dye recovered from the north valley trace traveled through the entire thickness of the St. Lawrence Formation and reemerged at a spring located in the mid to lower Lone Rock Formation.

At the south valley investigative area (Figure 4) dye first appeared at spring 85A29 located approximately 1,080 meters (3,540 feet) to the northwest of the sinking stream. Assuming a straight-line distance from the southern stream sink (85B24) to the spring, the estimated minimum peak groundwater velocity ranges from roughly 47 to 72 meters/day (154 to 236 feet/day).

Dye recovered from the south valley trace traveled through the St. Lawrence Formation, reemerging at a

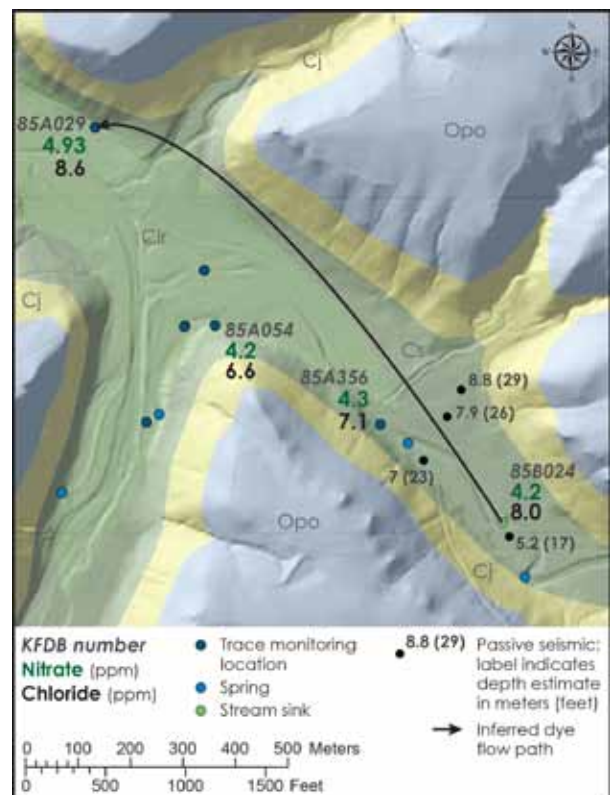


Figure 4. South Valley Investigation area. Paleozoic bedrock geology, inferred dye flow paths, estimated depth to bedrock, and select chemistry for springs and surface water in the south valley investigation area. Geologic map from Steenberg, 2014.

spring located near the contact of the basal St. Lawrence and Lone Rock Formations. Dye was also later detected at two passive detectors located at downstream surface water locations. These detects are consistent with direct surface water flow during high flow events or possibly hyporheic flow through streambed materials.

Previous traces have occurred in the vicinity (Figure 5). A trace was conducted in the early 1980s, east of the project area, at the Murphy landfill location (Dalglish and Alexander, 1984, area III in Figure 5). In 2014–2015, traces were conducted to the north-northwest near the City of Stockton (Barry and Green, 2015, area II in Figure 5).

The 2014–2015 Stockton vicinity traces occurred in the same siliciclastic units as these traces and determined minimum groundwater velocities of 28 to 127 meters/day (93 to 415 feet/day), similar to those determined from this work. The Murphy landfill trace was initiated in carbonate karst of the Prairie du Chien Group.

Water Chemistry Results

Standard field parameters were collected for water samples collected as part of these traces in the north and south valleys. Samples were analyzed for anion chemistry. Project samples were compared to regional groundwater samples collected in 2015 and 2016 at

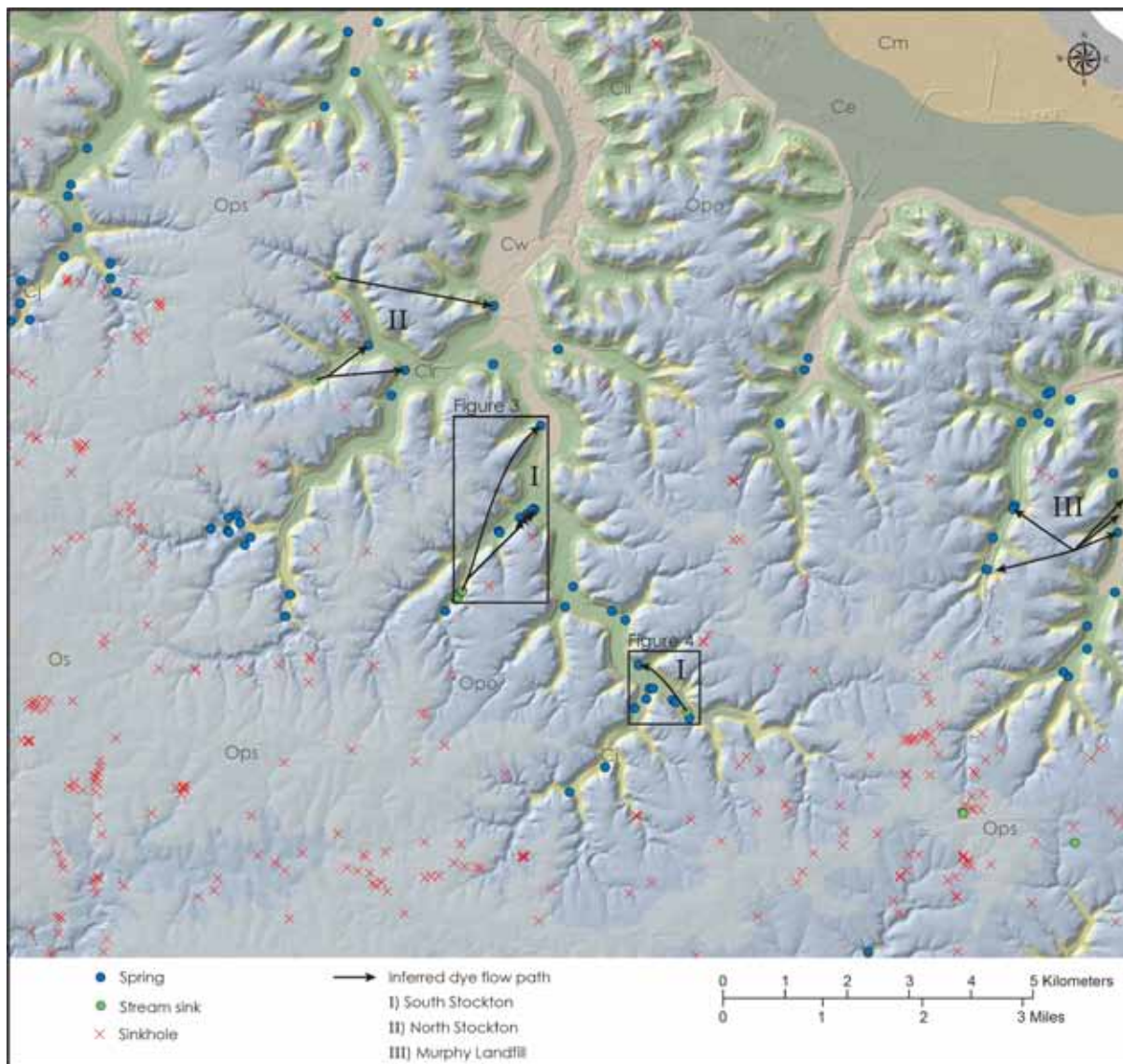


Figure 5. Project area dye traces. Paleozoic bedrock geology, karst features (springs, sinkholes, sinking streams), and the locations of dye trace investigations in the vicinity of the project area. Geologic map from Steenberg, 2014.

wells and springs within an 8,500 meter (28,000 feet) radius of the project area (Figure 6).

A suite of parameters, including nitrate, chloride, chloride/bromide, tritium, and dissolved oxygen, were used to determine anthropogenic influence, generalized residence time, and potential conduit networks of the collected water samples using the following rationales.

In Minnesota, the use of agricultural fertilizers, the application of road salts for winter time deicing, and water softener effluent can lead to elevated levels of nitrate and chloride in surface water and groundwater systems. Nitrate and chloride were used as geochemical indicators of recent human influence on groundwater using the following classification scheme. Nitrate concentrations greater than 1 part per million (ppm) are

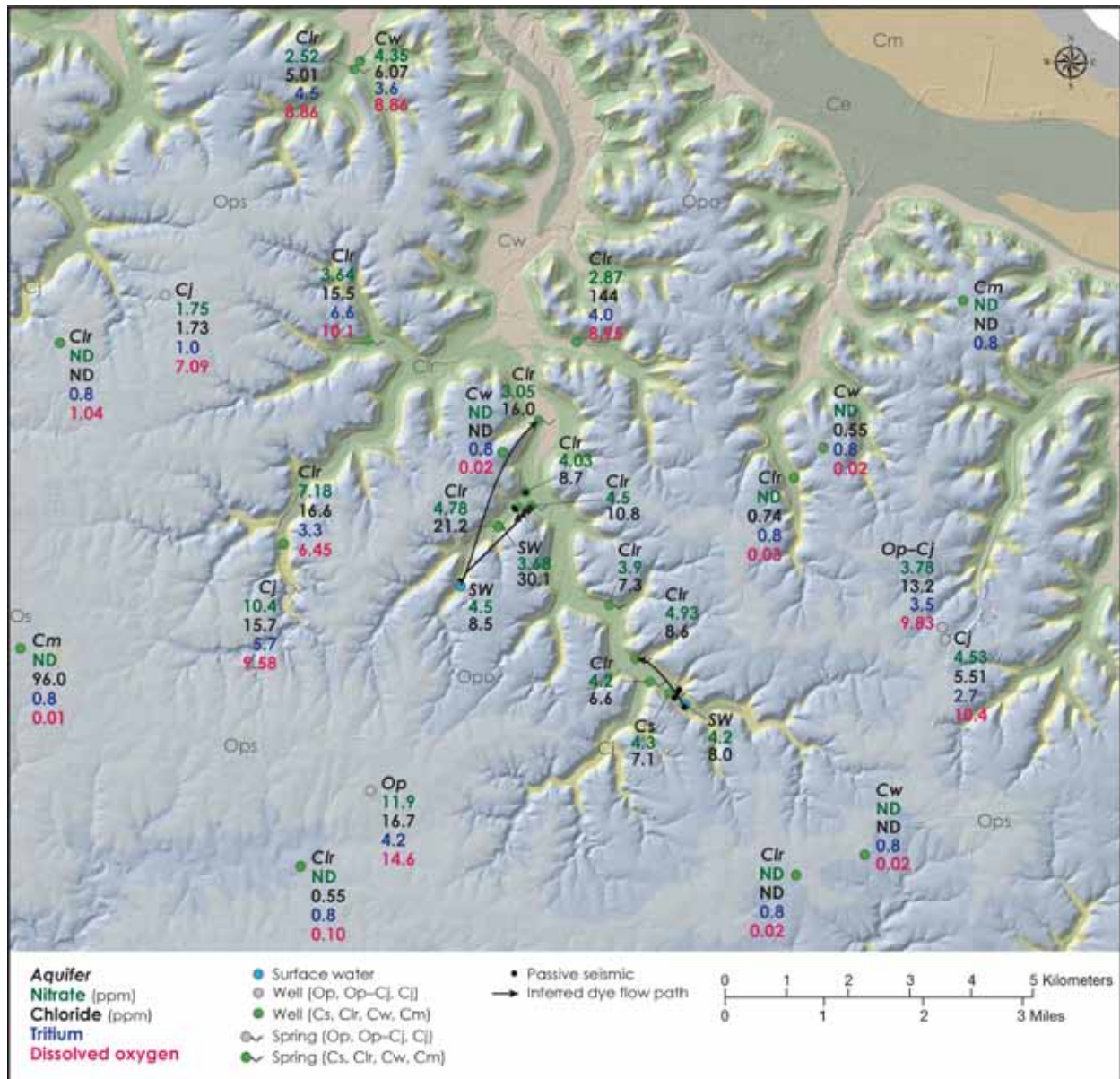


Figure 6. Project area water chemistry. Regional groundwater chemistry collected from Paleozoic aquifers located within 8,500 meters of the project area. Chemistry from wells completed in aquifers above the St. Lawrence Formation show anthropogenic influences. Near deeply incised valleys, the competency of the St. Lawrence as an aquitard is diminished, resulting in springs and wells with evidence of anthropogenic chemical signatures. Geologic map from Steenberg, 2014.

greater than background conditions and possibly indicate that an aquifer has been impacted by activities on the land surface (Minn. Dept. of Health, 1998; Wilson, 2012). Nitrate concentrations greater than 3 ppm indicate that an aquifer has been impacted by activities on the land surface (Minn. Dept. of Health, 1998).

Chloride concentrations greater than 5 ppm can additionally be used to indicate that an aquifer has been impacted by activities on the land surface. In Minnesota, most aquifers with non-detectable tritium (residence time approximately >70 years) that are not mixed with residual brine typically have chloride concentrations less than 5 ppm (Petersen TA, unpublished analysis of data in the DNR County Atlas Database, 2017). Naturally elevated chloride levels can be distinguished using Cl/Br ratios (Davis et al., 1998; Panno et al., 2006). In general, samples with chloride-to-bromide ratios below 300 are waters that have naturally elevated chloride.

Groundwater residence time is interpreted from the concentration of tritium. Atmospheric concentrations of tritium were greatly increased between 1953 and 1963 by atmospheric testing of nuclear weapons (Alexander and Alexander, 1989) allowing for estimation of residence time using tritium units (TU) present in a sample. The residence time of the water sample is adjectively described using the following schema.

- **Recent:** water entered the ground since about 1953 (8 to 15 TU).
- **Mixed:** water is a mixture of recent and vintage (greater than 1 TU to less than 8 TU).
- **Vintage:** water entered the ground before 1953 (less than or equal to 1 TU).

Elevated dissolved oxygen (D.O.) values can be coupled with the parameters listed above to characterize conduit flow and aquifers with rapid vertical recharge. D.O. collected at wells located a distance from incised valleys typically show a bifurcated pattern, where they are anoxic below the St. Lawrence and oxic above. Wells and springs located within or in close proximity to incised valleys typically have elevated D.O. For this paper, D.O. values greater than 1 mg/L are considered oxic; values less than 1 mg/L are considered anoxic.

Groundwater collected from wells and springs located stratigraphically above the St. Lawrence in general show

anthropogenic influences reflected by elevated nitrate and chloride, tritium ages <70 years, and oxygenated waters even at distances away from incised valleys (Figure 7, Table 1). These oxygenated waters are believed to reflect conduit networks that allow for rapid vertical recharge in a cascading scenario. Wells located at a distance from incised valleys and below the St. Lawrence typically have low nitrate, low anthropogenic chloride, non-detectable tritium, and are anoxic. Wells and springs located within or within close proximity to incised valleys generally have elevated nitrate, chloride, tritium, and/or dissolved oxygen. In this setting, wells typically do not have the full thickness of the St. Lawrence for protection or the St. Lawrence is compromised or absent. Our data further support the interpretation that the St. Lawrence is a competent aquitard under deep bedrock settings at distances from incised valleys. In proximity to incised valleys and under shallow bedrock conditions, the aquitard's ability to limit vertical flow is tenuous (Runkel et al., 2014). In this shallow setting, the St. Lawrence transitions from an aquitard to a pseudokarst aquifer.

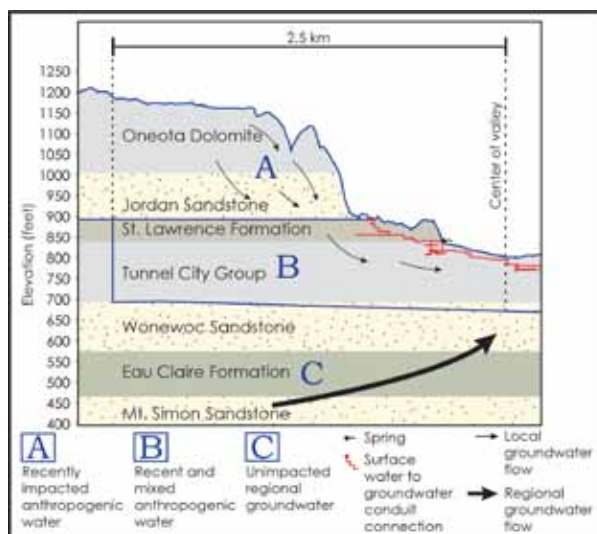


Figure 7. Generalized groundwater zones of influence of the project area. Groundwater from Zone A is generally impacted by anthropogenic influences and has detectable recent tritium concentrations. Groundwater from Zone B generally shows mixed anthropogenic influences and has detectable tritium with mixed concentrations. Groundwater from Zone C shows no anthropogenic influence and has non-detectable tritium concentrations.

RELATEID	Formation	Nitrate-N	Chloride	Dissolved Oxygen (mg/L)	Tritium	Bromide	Cl/Br	Well Completion Depth meters (ft)	Distance from center of Valley (km)	Influence Zone
Surface Water										
85X0000055	-	4.5	8.5	ns	ns	ND	-	-	0.10	B
85X0000056	-	4.2	8	ns	ns	ND	-	-	within	B
85X0000059	-	3.68	30.1	ns	ns	ND	-	-	within	B
Spring										
85A0000331	Cj	10.4	15.7	9.58	5.7	0.02	785	-	0.60	A
85A0000356	Cs	4.3	7.1	ns	ns	ND	-	-	within	B
85A0000029	Clr	4.93	8.6	ns	ns	ND	-	-	within	B
85A0000370	Clr	3.9	7.3	ns	ns	ND	-	-	within	B
85A0000015	Clr	3.05	16	ns	ns	ND	-	-	within	B
85A0000054	Clr	4.2	6.6	ns	ns	ND	-	-	within	B
85A0000376	Clr	4.78	21.2	ns	ns	ND	-	-	within	B
85A0000014	Clr	3.64	15.5	10.08	6.6	0.01	1550	-	within	B
85A0000330	Clr	2.52	5.01	8.86	4.5	ND	-	-	within	B
85X0000086	Clr	4.5	10.8	ns	ns	ND	-	-	within	B
Well										
268925	Ops-Opo	11.9	16.7	14.6	4.2	0.0308	542	85 (280)	3.70	A
219143	Opo-Cj	3.78	13.2	9.83	3.5	0.0135	978	91 (300)	0.90	A
219147	Cj	4.53	5.51	10.39	2.7	0.0248	222	102 (337)	1.00	A
107733	Cj	1.75	1.73	7.09	1	0.0183	95	100 (330)	1.20	A
737943	Clr	ND	ND	0.02	0.8	0.0067	-	156 (515)	2.40	C
564593	Clr	ND	0.55	0.1	0.8	0.007	79	164 (540)	4.90	C
107601	Clr	7.18	16.6	6.45	3.3	0.0383	433	38 (125)	within	B
624709	Clr	4.03	8.7	ns	ns	ND	-	28 (95)	within	B
446822	Clr	ND	0.74	0.03	0.8	0.0068	109	51 (168)	within	B
780784	Clr	ND	ND	1.04	0.8	0.0053	-	152 (500)	1.00	B
676724	Clr	2.87	144	8.95	4	0.0367	3924	29 (96)	within	B
655838	Cw	ND	ND	0.02	0.8	0.0067	-	198 (650)	2.50	C
667277	Cw	ND	ND	0.02	0.8	0.006	-	163 (537)	0.20	C
179226	Cw	ND	0.55	0.02	0.8	0.0067	82	188 (618)	0.60	C
127880	Cw	4.35	6.07	8.86	3.6	0.0136	446	28 (95)	within	B
603060	Cm	ND	96	0.01	0.8	0.429	224	351 (1154)	4.40	C
554227	Cm	ND	ND	0	0.8	0.0087	-	328 (1077)	0.50	C

Table 1. Summary of groundwater and surface water chemistry presented in this paper. Summary of select anion and isotope data presented in this paper. Influence zones are linked to conceptual model presented in Figure 7. ND=not detected, ns=not sampled

Springs in the St. Lawrence and Lone Rock Formations with elevated anthropogenic signatures, short residence times, and elevated D.O. are likely a mixture of impacted upper stratigraphic aquifers and un-impacted groundwater from lower aquifers. Previous work and the work in this paper have shown anthropogenically impacted waters appear to flow vertically downward in a “stair step” like pattern through conduit networks that are in proximity to the valleys (Runkel et al., 2013; Barry et al., 2015; Runkel et al., in prep). Groundwater chemistry from springs emerging in the St. Lawrence and Lone Rock Formations suggests mixing of upper stratigraphic recent tritium aged water with elevated nitrate and chloride with unimpacted vintage tritium aged water with low nitrate and chloride. Vintage tritium age water likely reflects older far-field regional flow

systems (Green et al., 2014). These mixtures typically create concentrations of nitrate in the 4–5 mg/L range, elevated chloride >8 mg/L, tritium values ranging from 1–7 TU, and D.O. concentrations similar to aerated surface waters (8–10 mg/L).

Up-gradient of the incised valleys, the St. Lawrence is a competent barrier to flow, with concentrations of nitrate, chloride, and tritium from wells cased below the St. Lawrence typically low and un-impacted.

Trend analysis of nitrate concentrations (1981 to present) from several St. Lawrence–Lone Rock springs in southeastern Minnesota shows steadily increasing nitrate levels (Runkel et al., 2014; unpublished analysis of Minnesota Department of Agriculture (MDA) spring

chemistry). Nitrate concentrations from springs sampled in this study are similar to concentrations collected by the MDA from the same hydrostratigraphic unit at springs located elsewhere in southeastern Minnesota. Continuous nitrate monitoring at several of these springs shows that nitrate concentrations typically fluctuate less than 0.5 mg/L following recharge events.

Passive Geophysical Results

Horizontal to vertical spectral ratio analysis (HVSr) was conducted on data collected at eight locations within the project area using a tomograph. The analyzed data had readily perceptible peaks that likely represent the bedrock surface. However, it is possible that multiple peaks and side lobes apparent in the processed data collected at some of the stations represent an uneven bedrock surface or non-discernable Quaternary stratigraphy. Passive data was collected next to a well in the project area and compared to the results of the well log. For this control location, the passive interpretation estimated 15.2 meters (50 feet) to the bedrock surface relative to the 18.3 meters (60 feet) to the bedrock surface shown in the well construction log.

At the discrete sinking stream point in the north valley, near 85B26, the depth to bedrock was determined to be 6.4 meters (21 feet). Depth to bedrock estimates for the north valley transect suggest a relatively uniform valley shape, with bedrock at or near land surface at the toe of the slope from the valley walls increasing to 12.2–15.2 meters (40–50 feet) below ground surface in the center of the valley.

Depth to bedrock was determined to be 5.2 meters (17 feet) at the discrete sinking stream point (85B24) in the south valley. Depth to bedrock estimates for the south valley transect suggest an asymmetric valley shape, with bedrock at or near land surface at the toe of the slope from the valley walls increasing from 6.1 meters (20 feet) below ground surface on the south side of the valley to 9.1 meters (30 feet) below ground surface on the north side of the valley.

Constraining the depth to bedrock in these valleys is an important tool in these analyses. It aids in identifying the depth to subcrop locally since homesteads with water well records within the valley are rare. It also has implications for groundwater flow velocities since water may be sinking and traveling within the alluvium before entering the bedrock system.

Conclusion

Dye trace flow paths and groundwater velocities, local and regional water chemistry results, and estimated depth to bedrock determined from passive geophysics have assisted in further characterizing a southeastern Minnesota pseudokarst aquifer.

Minimum groundwater velocities recorded for these traces are consistent with values recorded in similar settings and further demonstrate that conduit networks in the siliciclastic St. Lawrence Formation in incised valley settings are connected to conduit networks in the underlying siliciclastic Lone Rock Formation. In shallow bedrock settings, these networks exhibit high to very high horizontal and vertical hydraulic conductivity within the relatively low permeability rock matrix. This elevated hydraulic conductivity allows anthropogenically influenced surface water and groundwater to migrate to deeper depths in these settings.

Springs emanating from Paleozoic aquifers in southeastern Minnesota provide perennial discharge of cool water to the abundant trout streams of the area. Documenting groundwater flow dynamics and geochemical trends of southeastern Minnesota's groundwater system through dye tracing, geochemical analysis and detailed geologic mapping provides information to water resource managers, planners, and fisheries managers to make more informed decisions on how to manage and protect resources. Increasing concentrations of nitrate in surface water and groundwater in southeastern Minnesota has the potential to increase nitrogen saturation in fish hatcheries and in streams. Supersaturation of nitrogen gas in hatcheries and in-stream can cause pathological changes and mortality in fish (Machado et al., 1987).

The data and approaches outlined in this document have improved our understanding of flow dynamics in the vicinity of south Stockton. Observations made in this paper are similar to those made by others and are enhancing the understanding of groundwater flow in southeast Minnesota.

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GROUNDWATER FLOW SYSTEMS IN MULTIPLE KARST AQUIFERS OF CENTRAL TEXAS

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Abstract

Increased demand for groundwater in central Hays County is prompting studies to evaluate the availability of groundwater in the Trinity Aquifers of central Texas. These aquifers, consisting mostly of limestone, dolomite, and marl, exhibit varying degrees of karstification. Near the surface, karst features such as caves and sinkholes are evident, but are widely scattered. Even at depths greater than 400 m (1,300 ft), units that are mostly limestone show some degree of karstification where dissolution along fractures has caused development of conduits. Studies are being conducted to better understand the horizontal and vertical flow components of the Trinity Aquifers. These studies involve aquifer testing, groundwater geochemistry, geologic and structural mapping, flow-loss/gain measurements in streams, hydraulic head measurements, dye tracing, and installation of multiport monitor wells. The Middle Trinity Aquifer meets the definition of a karst aquifer due to its conduit permeability within soluble rocks. However, the same aquifer has contrasting properties that are separated by the complex Tom Creek Fault Zone. The westerly Hill Country Middle Trinity Aquifer is a shallow karst aquifer system characterized by rapid conduit flow and active surface and groundwater interactions. In this area, Middle Trinity units are situated at or near the surface. To the east, the Balcones Fault Zone Middle Trinity Aquifer is a deeply confined karst aquifer system with more limited conduit development, slower groundwater flow, and no direct surface-groundwater interactions. In this area, Middle Trinity units are encountered at depths of 150 m (500 ft) or greater. The results of this study will influence future

hydrogeologic and resource evaluations and modeling of the Middle Trinity Aquifer.

Introduction

With limited surface water, central Texas is fortunate to have the Edwards and Middle Trinity karst aquifer systems that provide a variety of groundwater resources. The karstic Edwards Aquifer has been recognized for decades as a vital groundwater resource, and thus many studies have been published from Hill and Vaugh (1898) to recent (Hauwert and Sharp, 2014) that characterize the nature of the aquifer and its groundwater flow system. However, few studies have focused on the karstic nature and groundwater flow system of the deeper part of the Middle Trinity Aquifer.

The Middle Trinity Aquifer of central Texas has been used as a source of water for many years, and water discharging from springs provides base flow to streams in the area. Base flows in streams that are fed by the Middle Trinity Aquifer provide recharge to the downgradient, karstic Edwards Aquifer. Rapid population growth in recent years has significantly increased the demand for groundwater. A combination of high rates of pumping and severe drought may cause undesired results such as water-supply wells going dry, worsening of water quality, and diminishment or cessation of flow from springs. Studies are being conducted to better understand the aquifers of central Texas so that proper management of these aquifers will allow for sufficient groundwater of good quality to be available for human and ecological purposes.

The study area traverses two major physiographic provinces in central Texas: the eastern edge of the Edwards Plateau (also known as the Hill Country) and the western edge of the Gulf Coastal Plains (also known as the Blackland Prairies) defined by the prominent Balcones Escarpment—the result of the Balcones Fault Zone (BFZ). These provinces are underlain by Cretaceous strata of the region and various geologic structures (Hill and Vaughn, 1898).

The political boundaries of the study area includes the middle and western third of Hays County (Figure 1), with the focus of study on the area between the western corner of Hays County, where the Blanco River enters the county from the west, and the multiport monitor well (Hays MP) about 9 km (5.8 mi) northeast of the village of Wimberley.

The Middle Trinity Aquifer has recently been described as having two interconnected aquifer zones related

to its physiographic and structural setting, degree of karstification, and depth beneath the surface (Hunt et al., 2017). The two aquifer zones are defined as: (1) the Hill Country Middle Trinity Aquifer (to the west), and (2) Balcones Fault Zone (BFZ) Middle Trinity Aquifer (to the east). This paper summarizes data that characterizes these two contrasting karst aquifer zones of the Middle Trinity Aquifer and develops the concept of groundwater flow between and within these two zones.

Methods

The overall study described in this paper synthesizes a number of other studies that include aquifer testing, groundwater geochemistry, geologic and structural mapping, flow-loss/gain measurements in streams, hydraulic head measurements, and installation of multiport monitor wells. Specific findings of those studies are described below.

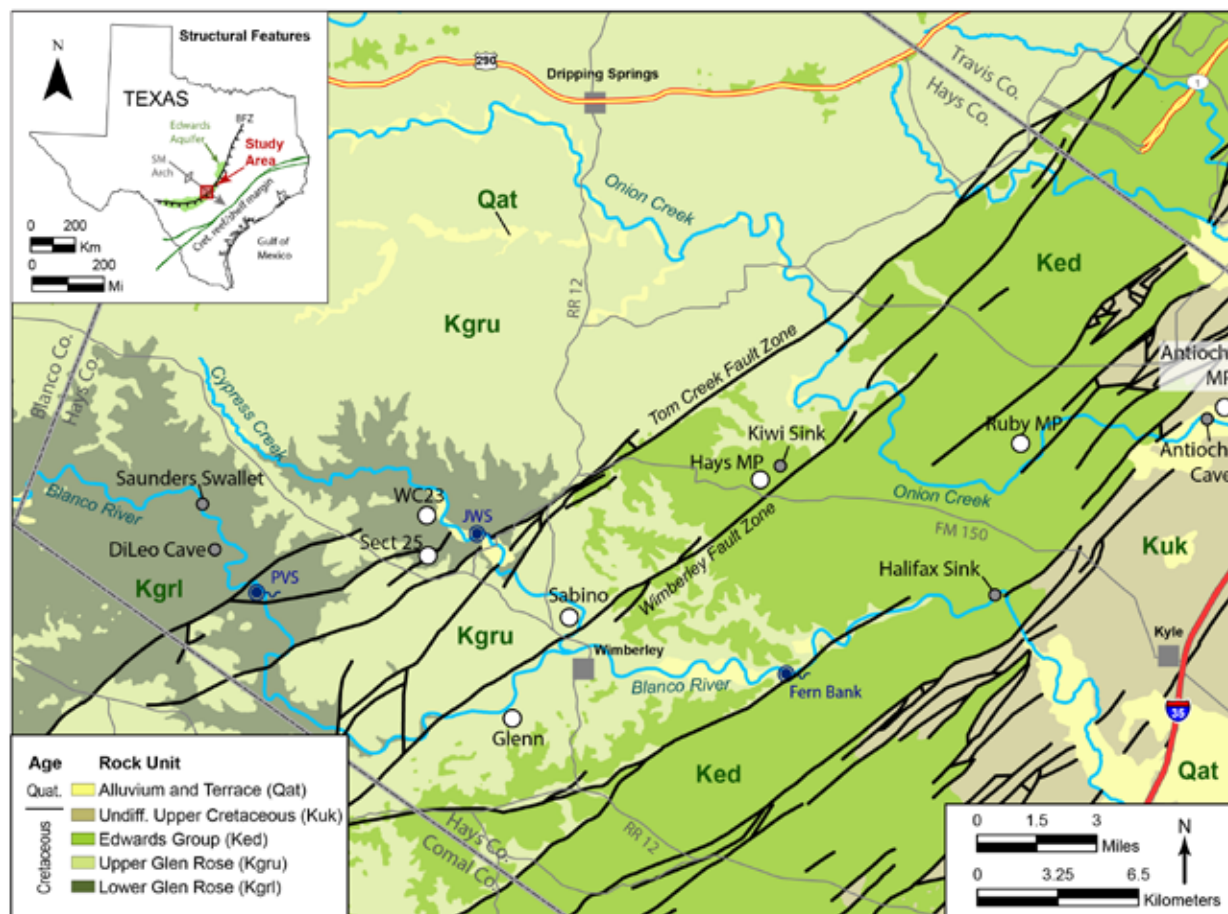


Figure 1. Simplified geologic map of the study area with key geographic and point feature locations referenced in the paper. Geologic Atlas of Texas digital basemap geology from (Stoeser et al., 2005). Inset map shows regional structures (after Ewing, 1991). SM Arch=San Marcos Arch, BFZ=Balcones Fault Zone. Detailed stratigraphic column is shown in Figure 2.

Hydrogeologic Setting

Geology

The rocks on the surface and subsurface across the study area are made up almost entirely of Cretaceous carbonate units. Figure 1 is a location and geologic map showing the general distribution of the geologic units and faults in the study area.

The eastern portion of the study area contains the Edwards Group. Stratigraphically beneath the Edwards Group is the Trinity Group that is exposed in the western portion of the study area. Figure 2 shows the litho- and hydrostratigraphy that is representative of much of Hays County.

In the western side of the study area, the outcrops are dominated by the Lower Glen Rose within the river valleys, with the Upper Glen Rose making up the hilltops. There are limited exposures of the Hensel Formation and the underlying Cow Creek Limestone along the Blanco River near Saunders Swallet (Figure 1).

The Upper Glen Rose Member is 108 m (355 ft) thick in the upper reaches of the Onion Creek watershed and thickens to about 137 m (450 ft) in the eastern portion of the study area. In outcrop, the Upper Glen Rose is subdivided into eight informal lithologic units, which correlate to the classic work of Stricklin et al. (1971). These units generally consist of stacked and alternating limestones, dolomites, mudstones, and marls.

The Lower Glen Rose, about 250 ft thick, is characterized by fossiliferous limestone units with well-developed rudistid reef mounds and biostromes often found near the top and base of the unit. The shaley, dolomitic Hensel, about 10 m (35 ft) thick, is also exposed in the incised river valleys and locally provides semi-confining aquifer properties. The Cow Creek is about 23 m (75 ft) thick. The upper portion of the Cow Creek, is a cross-bedded grainstone unit that is often limestone, but can also be dolomite. The lower portion of the Cow Creek becomes more dolomitic and silty with depth grading into the underlying Hammett Shale.

Structures

Structure is an important control on the location of recharge, flow paths, and spring discharge locations in carbonate aquifers (Sasowsky, 1999). The inset map in Figure 1 illustrates the complex intersection of regional structures in the study area that influenced Cretaceous

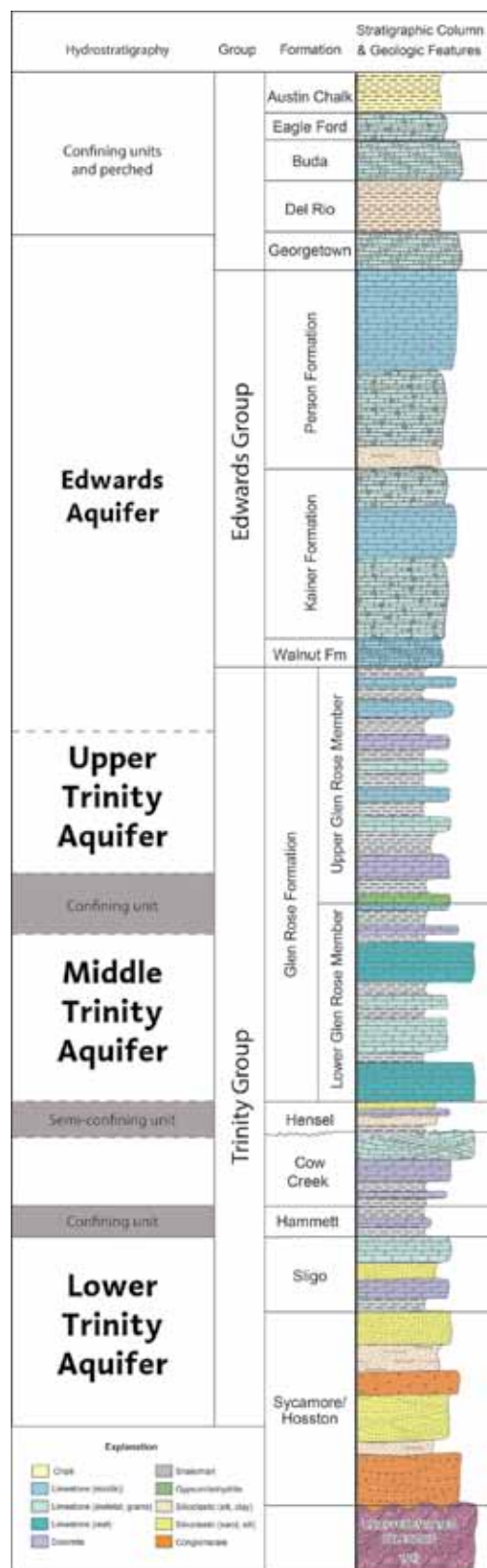


Figure 2. Stratigraphy and hydrogeology of the study area. The focus of this study is on the Upper and Middle Trinity Aquifers.

deposition and subsequent structures, such as the Miocene Balcones Fault Zone (BFZ). The BFZ is the most significant structural feature, which covers the southeastern portion of the study area and produces the prominent physiographic feature known as the Balcones Escarpment in central Texas. The BFZ is a fault system consisting of numerous normal faults with hanging walls generally down toward the Gulf of Mexico and with displacements ranging up to 245 m (800 ft). Faults are generally steeply dipping (45–85 degrees) to the southeast and strike to the northeast. The faults are described as “en echelon,” which indicates that they are closely spaced, overlapping and subparallel. The BFZ is characterized by structures including horsts, grabens, anticlines, monoclines, and relay ramps (Grimshaw and Woodruff 1986; Collins, 1995; Collins and Hovorka 1997; Collins, 2004; Ferrill et al. 2004; Hunt et al., 2015).

Figure 3 is a structure contour of the top of the Cow Creek Limestone. The figure illustrates the strong structural style influence of the BFZ on the Cow Creek moving from west to east into the BFZ. Within the BFZ significant deformation occurs due to the transfer of displacement from the Tom Creek/Mount Bonnell fault to the San Marcos fault to the southeast. The deformed geologic units form a large structural feature identified as a relay ramp, or transfer structure (Grimshaw and Woodruff, 1986; Collins and Hovorka 1997; Hunt et al., 2015). The influence of relay ramps on groundwater flow is such that where the amount of throw along a fault is significant, flow of groundwater may be impeded. Where the amount of throw is minimal, or non-existent, the flow of groundwater will be unimpeded.

The Tom Creek fault is of particular importance to this study (Figures 1 and 3). The fault extends northeast-

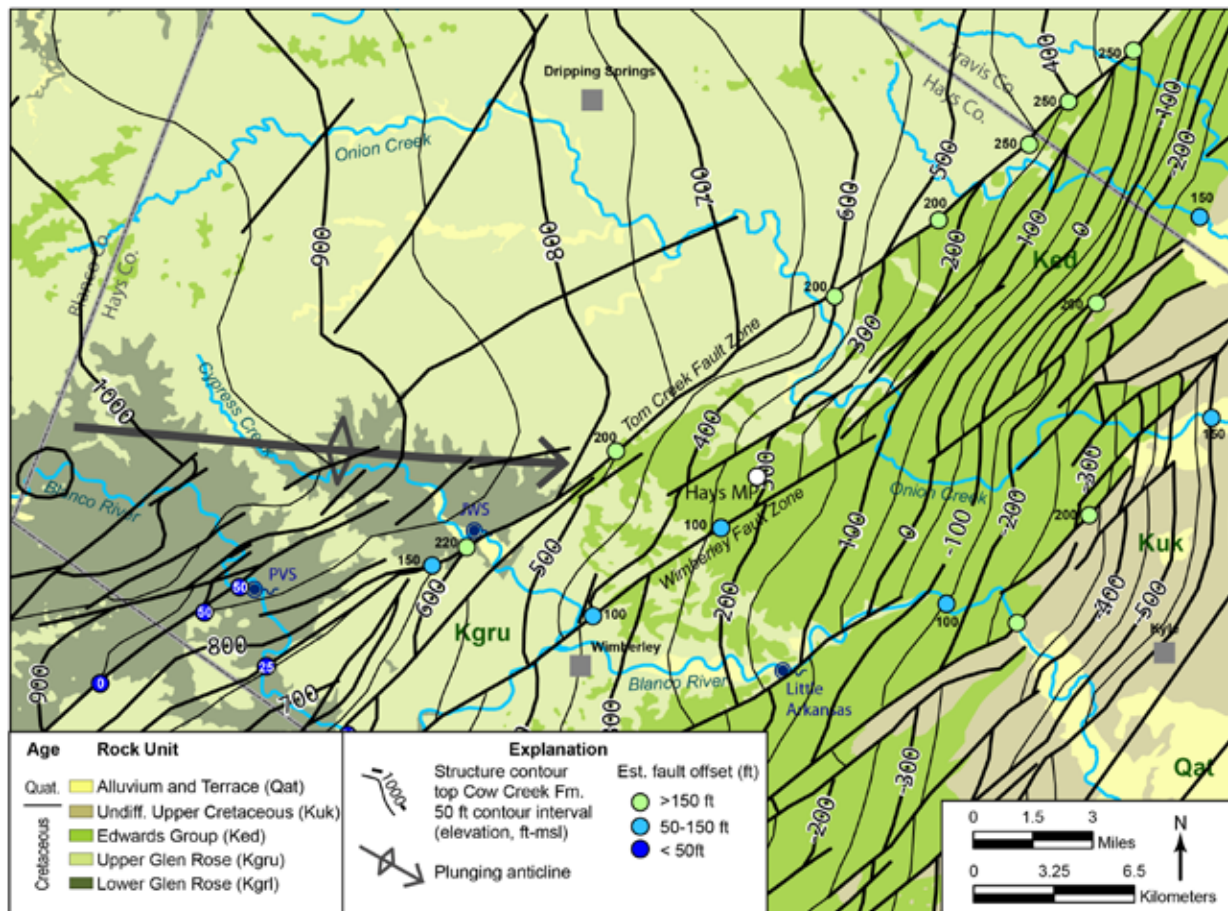


Figure 3. Structure and geologic map of the study area. Structure contours on the top of the Cow Creek show dip to the ENE to the north of the anticline. South of the anticline the structural style consists of highly faulted blocks between the Tom Creek and San Marcos Faults forming a relay ramp structure. Contours were hand drawn using more than 300 control points (most of which are geophysical logs) and faults modified from the Geologic Atlas of Texas (Al Broun, unpublished data).

southwest through Wimberley with throws of as much as 76 m (250 ft) to the east where the fault crosses into Travis County. Yet, about 3 km (2 mi) west of Wimberley, the Tom Creek fault has throws of about 15 m (50 ft), and close to zero meters another 3 km (2 mi) to the southwest. Northwest of Wimberley, a broad, eastward plunging anticline is delineated by structural contours drawn on the top of the Cow Creek Limestone. The nature of the varying offsets along the Tom Creek fault is similar to the relay ramp structures discussed above. Another significant structure is a horst block, which has allowed for uplift and exposure of the Cow Creek Limestone at the surface within the bed of the Blanco River (Figure 1, area around Saunders Swallet).

Hydrogeology

Recent studies have refined the hydrostratigraphy of the study area (Smith and Hunt, 2010; Smith et al., 2013; Wong et al., 2014). The principal conclusions that were drawn from these studies are outlined below and summarized in the hydrostratigraphic column in Figure 2.

The Trinity Group geologic units have historically been divided into three aquifers: the Upper Trinity (Upper Glen Rose Member), the Middle Trinity (Lower Glen Rose Member, Hensel, Cow Creek), and the Lower Trinity (Sligo and Hosston Formations) (DeCook, 1963; Ashworth, 1983; Barker et al., 1994; Barker and Ardis, 1996; Mace et al., 2000; Wierman et al., 2010). The Hammett Shale is a confining unit that separates the Middle and Lower Trinity Aquifers. Figure 2 demonstrates that the hydrogeologic units (or aquifers) do not necessarily correlate to lithostratigraphic units (Smith et al., 2013; Wong et al., 2014).

In the eastern part of the study area, the upper 45 m (150 ft) of the Upper Glen Rose Limestone are hydraulically connected to the overlying Edwards units. The lower 90 m (300 ft) of the Upper Glen Rose, and farther east, the upper portion of the Lower Glen Rose is best characterized as an aquitard. The units have intervals of evaporite minerals that occlude the porosity and permeability (Figure 4). Some of these intervals consist largely of interlocking evaporite nodules. While some of these intervals have evaporite nodules separated by a dolomitic matrix. These units are characterized as having low permeability and porosity, poor water quality, and water levels that change very little. Where these units are situated close to the surface, the evaporites have

been largely removed by dissolution from infiltration by meteoric water and replaced by calcite (Figure 5).

Based on a regional compilation of aquifer test data, average transmissivities of the Middle Trinity Aquifer 50 m²/d (535 ft²/d) are lower than the Edward Aquifer 890 m²/d (9,600 ft²/d). However, hydraulic conductivity of the Middle Trinity Aquifer is comparable to the Edwards Aquifer with average values of 3.4 m/d (11 ft/d) and 8.5 m/d (28 ft/d), respectively (Hunt et al., 2010). The Cow Creek is the most prolific water-producing hydrologic unit in the Middle Trinity.



Figure 4. Photograph of a side view of a borehole showing evaporite (gypsum) nodules developed in the Upper Glen Rose. The photograph was taken at a depth of 150 m (490 ft) in the Hays MP well (Figure 1).



Figure 5. Photograph of an outcrop of relict evaporite nodules within the lower-most Upper Glen Rose.

The Hensel is a water-bearing unit west of the study area, and is thought to be conducive to recharge directly from the surface or through overlying units. In the study area, the Hensel is a silty dolomite and behaves as a semi-confining unit on top of the Cow Creek, and is locally breached with fractures and solution features.

The Lower Glen Rose is also an important hydrologic unit within the Middle Trinity Aquifer with the best production occurring within the lower rudist reef facies, which has vertical and lateral heterogeneity. The Lower Glen Rose is also highly karstic with numerous mapped caves in the western portion of the study area (Delio Cave, Figure 1). Over much of the study area, particularly in the deeper sections, portions of the Lower Glen Rose and the Hensel provide confinement to the underlying Cow Creek Limestone.

Karst

The Middle Trinity Aquifer is a karstic and fractured aquifer (Wierman et al., 2010) with karst features found in the very shallow subsurface and at depths of more than 300 m (1,300 ft). In the western portion of the study area, numerous caves, swallets, and springs are found within the Lower Glen Rose and Cow Creek Limestone (Figure 1). One example of a recharge feature in the Cow Creek Limestone (Middle Trinity) is Saunders Swallet (Figures 1 and 6), which takes in water flowing in the Blanco River. The Cow Creek also provides substantial flow to the Blanco River with discharges from Jacob's Well Spring (JWS) and Pleasant Valley Springs (PVS), which are both artesian springs (Figure 1). JWS is a significant karst conduit in which scuba divers have mapped more than 3.5 km (2.2 mi) of passage in the Cow Creek Limestone (Figure 7). Prior to discharging from JWS, groundwater flows upward through the Hensel and out to the surface through an opening in the Lower Glen Rose. Although the Hensel is confining in the vicinity of Jacob's Well and Pleasant Springs, it is clearly permeable in some locations in the recharge zone to the west since the Cow Creek is recharged from an area much larger than the small window of exposed Cow Creek in the Blanco River (Hunt et al., 2017).

In the subsurface, and east of the recharge zone, there are numerous observations of voids that result from karst processes. Those features have been observed from driller, geophysical, and camera logs. Solutionally enlarged fractures have been observed in the Cow Creek



Figure 6. Photograph of Saunders Swallet. This recharge features is located in the Blanco River and developed within the Cow Creek Limestone. Water was flowing into the swallet, where the person is standing, when the photograph was taken in 2013.

in the Antioch multiport well (Antioch MP; Figure 1) just west of Buda, at depths of about 400 m (1,300 ft) (Figure 8). Despite the presence of karst features at depth, east of the major Middle Trinity springs the conduit development is not as mature and thus groundwater is not flowing as rapidly under natural conditions. The karst features at depth, however, do allow for locally very highly transmissive properties for wells. Test wells near the multiport monitor well Hays MP (Figure 1) can yield up to about 45 liters per second (700 gallons per minute) during pumping with reported average transmissivities of about 80 m²/d (870 ft²/d; WRGS, 2017).



Figure 7. Photograph of Jacob's Well Spring. The spring issues from a significant karst conduit in which scuba divers have mapped more than 3.5 km (2 miles) of passage in the Cow Creek Limestone. Photograph taken in 2011.

Recharge

Historically the Trinity Aquifer was not considered a karst aquifer and recharge was conceptualized to broadly absorb only 4% of rainfall as recharge (Ashworth, 1983). Conversely, recharge to the karstic Edwards Aquifer was known to be dominated by losing streams (Slade et al., 1986) with recharge of up to 30% of rainfall, typical of many karst aquifers (Hauwert and Sharp, 2014). Figure 1 shows the locations of some karst features within streams in the Edwards Aquifer recharge zone (Antioch Cave, Halifax Sink).

Recent studies (Smith et al., 2015; Hunt et al., 2017) indicate significant recharge to the Middle Trinity occurs from losing streams, such as the Blanco River, Cypress Creek, and Onion Creek (Figures 6 and 9). The losing reaches of the Blanco River and Cypress Creek sustain PVS and JWS, respectively. Any water in the Cow Creek that does not exit the aquifer at the springs probably provides flow to the deeper part of the Middle Trinity Aquifer. As discussed below, chemical analyses of groundwater from deep wells to the east indicate that the water in some of the wells has low conductivity and total dissolved solids. This suggests that there is a pathway for water from the shallow system to move deeper into the subsurface.

Another source of recharge to the Middle Trinity is vertical leakage from the overlying Upper Glen Rose (Jones et al., 2011). Recharge to the Balcones Fault Zone Middle Trinity Aquifer in the vicinity of the Hays MP well is primarily from lateral flows from the



Figure 8. Photograph of a solution-enlarged fracture and void within the Cow Creek Limestone in a borehole at a depth of 400 m (1,360 ft).

updip recharge area to the west (Smith et al., 2015; Wong et al., 2014). However, there is some indication of a hydrologic connection (vertical leakage) from the Upper Glen Rose into the Middle Trinity either due to significant head gradients from recharge in the Upper Glen Rose or drawdown from pumping from the Middle Trinity Aquifer (BSEACD, 2017). Much of the recharge to the Upper Trinity Aquifer is from direct precipitation and infiltration in areas where the Upper Trinity geologic units are exposed at the surface (Wierman et al., 2010). Some of this is diffuse infiltration through soils and some is through recharge features such as Kiwi Sink (Location shown in Figure 1). The entrance to Kiwi Sink is in a thin veneer of the base of the Edwards Group and the opening penetrates into the Upper Glen Rose. This sinkhole is within 300 m (1,000 ft) of the Hays MP multiport monitor well.

Potentiometric Surface Mapping

The network of monitor wells in the study area has expanded considerably in the past 10 years as access has been gained to many private wells, and instruments for recording water levels have been increasingly used. Figure 9 shows a regional Middle Trinity potentiometric map created during March 2009. These measurements show that regional flow of groundwater in the Middle Trinity generally follows the dip of the strata. However, flow is to the northeast and parallel to the Tom Creek/Mount Bonnell fault zone where offsets along the fault are greater than 250 ft and suggest a barrier to flow.

Another potentiometric map on Figure 9 is focused on an area west of Wimberley. Water-level data were collected from Middle Trinity wells in 2013 (Watson et al., 2014). Contours of this data set show a similar pattern to the 2009 data, but the greater density of data in the 2013 study shows several features, including: (1) a large potentiometric trough along Cypress Creek reflecting the highly permeable JWS conduit development, and (2) a steeper gradient of flow east of JWS near Wimberley that likely reflects a decrease in permeability, and (3) more widely spaced contours to the west of Wimberley indicating potentially higher permeability than the area to the east. Considerable offset of the Cow Creek along the Tom Creek fault provides some amount of restriction to lateral flow near Wimberley. To the west, where the amount of throw is less, or nonexistent, there is less restriction to flow through the Cow Creek due to structural influences such as relay ramps (Hunt et al., 2015).

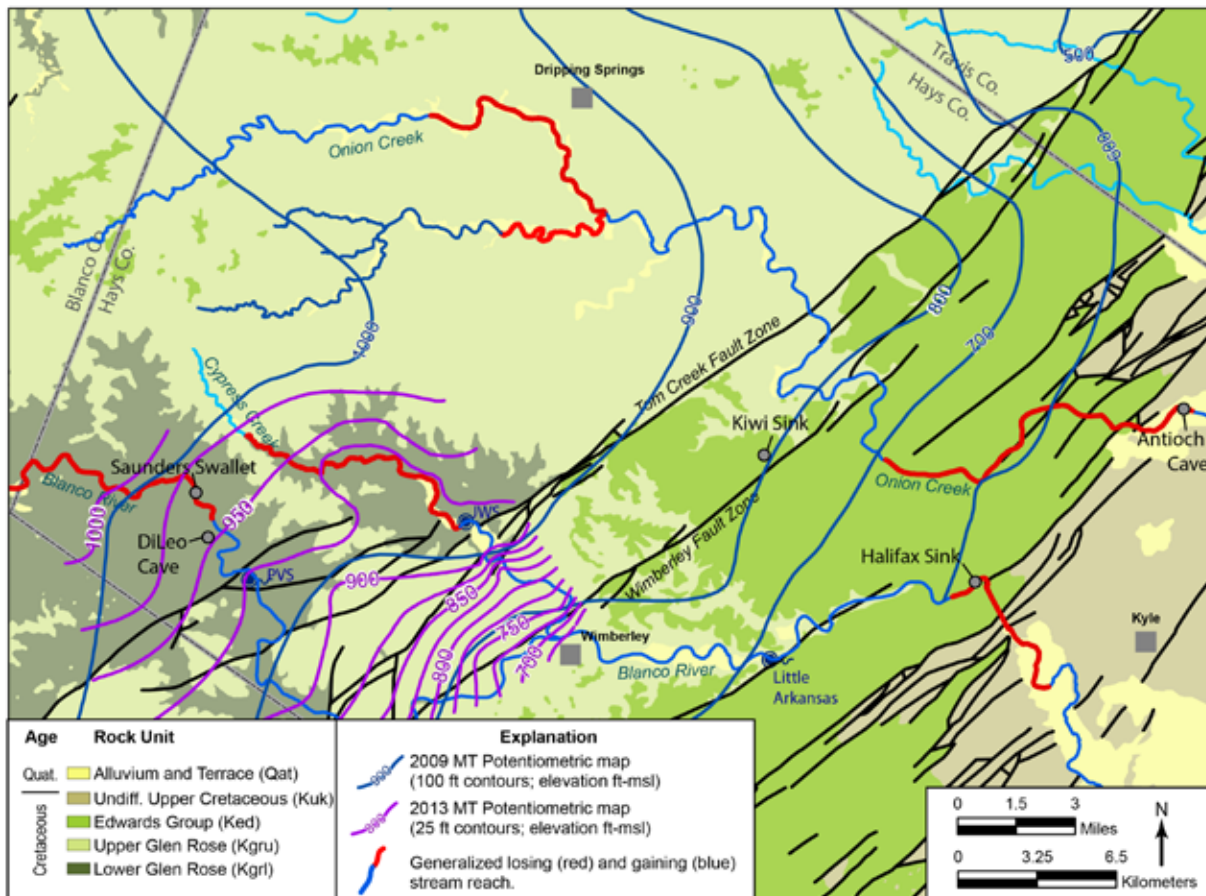


Figure 9. Regional (Hunt et al., 2010) and localized (Watson, et al., 2014) potentiometric maps of the Middle Trinity Aquifer with losing and gaining reaches of streams and karst features.

Continuous water-level measurements recorded over the past 10 years show significantly different water-level patterns between Middle Trinity wells on the upthrown side of the Tom Creek fault (WC23, HCP3, Graham) compared to Middle Trinity wells (Sabino and Glenn) on the downthrown side (Figure 10). Because of the moderating influence of JWS as it acts as a significant drain for the Middle Trinity Aquifer in this area, water levels approach a baseline during dry periods. Following major rain events, water levels in these wells spike, but quickly return to near base-flow conditions mimicking the response at JWS, thus indicating the influence of conduit (karst) flow on the upthrown side of the fault.

Middle Trinity wells on the downthrown side of the fault show as much as 45 m (150 ft) of head change between wet and dry periods with gradual rises and falls in water levels. On average, water levels on the downthrown side are about 50 m (165 ft) lower than water levels on the upthrown side of the fault. These data suggest

that the Tom Creek fault zone demarks a change in the permeability structure within the Middle Trinity Aquifer, and thus may partially restrict the northwest to southeast flow of groundwater.

Multiport Monitor Well

In February 2017, a multiport monitor well (Hays MP; Figure 1) was installed in the Rolling Oaks subdivision of central Hays County, Texas. This well was installed to better understand the horizontal and vertical relationships of the various hydrologic units of the Trinity Group. Initial head and geochemical results indicate a complex stratified aquifer system. In general the data support a deep karstic aquifer within the Cow Creek and Lower Glen Rose beneath a shallow karst aquifer developed in the uppermost Upper Glen Rose. The top of the Cow Creek is at about 230 m (750 ft) below ground surface with heads 232 m above mean sea level (760 ft-msl) and total dissolved solids (TDS) content of 1,550 mg/L. The Upper Glen Rose contains groundwater with about

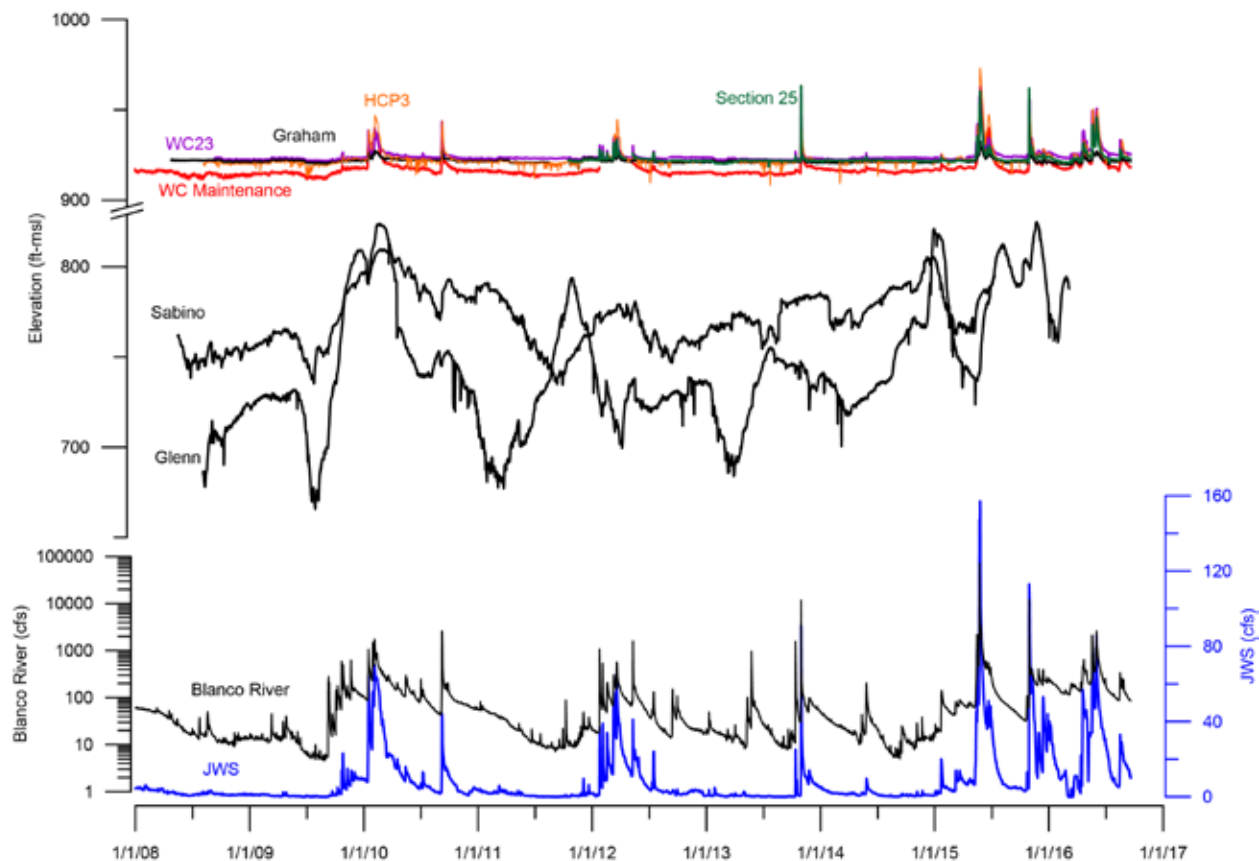


Figure 10. Hydrograph from wells, Jacob's Well Spring, and the Blanco River at Wimberley. Source data from the Hays-Trinity Groundwater Conservation District.

600 mg/L TDS to a depth of about 100 m (330 ft) below ground surface with heads at 265 m-msl (870 ft-msl; BSEACD, 2017). Several intermediate zones contain gypsum and have up to 3,180 mg/L TDS, with heads between the deep and shallow aquifers. These beds appear to correspond to gypsum-bearing aquitard units in other multiport wells described in Wong et al. (2014) and found in Figure 1 (Ruby MP, Antioch MP).

Geochemistry and Relative Groundwater Age

Major ion and isotope geochemistry can provide additional information about the source, recharge, and flow paths of groundwater. Figure 11 is a contour map showing the distribution of TDS in the Middle Trinity (Hunt et al., 2017) and results of carbon-14 isotopes (^{14}C) shown as percent modern carbon (pmC) (TWDB, 2017) in the Middle Trinity Aquifer.

The 500 mg/L contour helps to define where much of the recharge is actively occurring. The 1,000 mg/L TDS contour tends to extend irregularly from the recharge

areas, including to the east along a relay ramp and along the potentiometric gradient (Hunt et al., 2015 and 2017).

The spatial trends of carbon-14 and tritium values in the Middle Trinity are similar in the study area, with lower values present to the east of PVS and JWS. Samples of Middle Trinity groundwater collected from JWS and PVS ($n=9$) have relatively high average pmC (88%) and tritium (1.7 TU) indicating the water is relatively young to modern (less than 50 yrs old). Middle Trinity well-water samples have a range of carbon-14 values spanning 0–120% pmC ($n=61$) and tritium 0–2.3 TU ($n=60$) (TWDB, 2017). These data suggest a range of very old, greater than 10,000 years, to modern groundwater, less than 50 years old, respectively, depending on the proximity of the well to the recharge zone and influence by karst features. The good correlation of the radiogenic isotopes suggests some degree of mixing of modern water with older water, likely influenced by relatively rapid flow through karst features, but also supports the concept of much older groundwater east of the major springs and east of the Tom Creek fault.

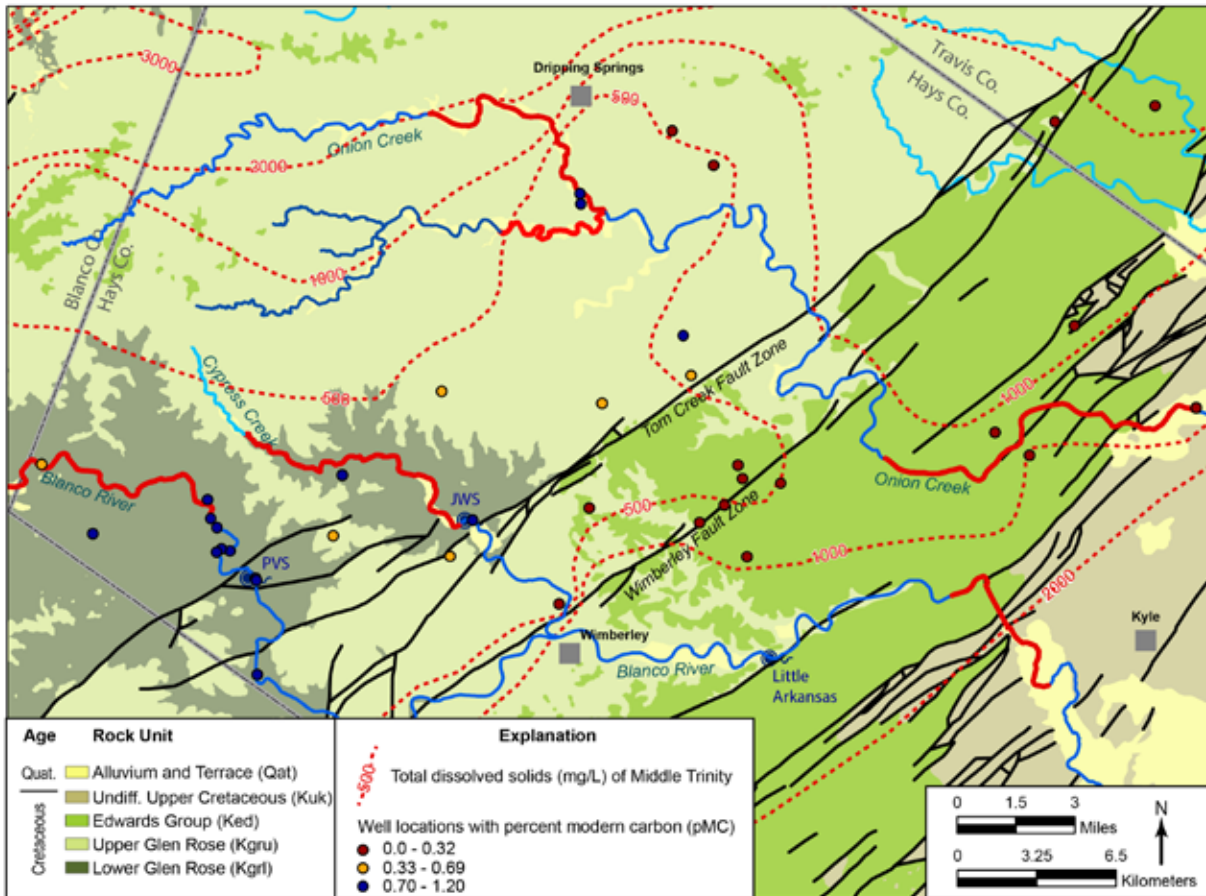


Figure 11. Total dissolved solids and carbon-14 map of the Middle Trinity Aquifer. Contours show fresh water (less than 500 mg/l) over the net losing portions of the Blanco River and Onion Creek. Carbon-14 samples are also shown with the relatively young water within the recharge zone of the Hill Country Trinity Aquifer and relatively older water within the BFZ Middle Trinity Aquifer east of the recharge zone.

Discussion

Data from the studies discussed above indicate a very complex system of stacked and juxtaposed karst aquifers across much of Hays County. Figure 12 is a summary diagram and conceptual model. This study focuses on the Middle Trinity Aquifer and its lateral changes from the Hill Country into the BFZ, generally expressed by the degree of karstification of the Cow Creek and Lower Glen Rose Limestone. In the Hill Country Middle Trinity Aquifer there is a shallow, generally unconfined, well-developed karst aquifer system. In the areas to the west where the Middle Trinity units crop out, there are sinkholes, swallets, and small solution features where recharge is observed. Major recharge features conduct water from the Blanco River and tributaries into the Middle Trinity Aquifer. From these areas of recharge, some of the water flows within conduits east to discharge at PVS and JWS. With a greater average discharge, PVS probably has a similar plumbing

system of conduits, but is not accessible by divers. The groundwater in this portion of the aquifer, with generally low TDS values, has a relatively young to modern age and is part of active surface-groundwater interactions.

To the east, these same units make up the BFZ Middle Trinity Aquifer and are found at depths of 245 m (800 ft) and greater. The aquifer is under confined conditions with fractures enlarged by dissolution. The conduit development is not as mature as the shallow system to the west, and thus groundwater is not flowing as rapidly under natural conditions. However, some high yielding deep wells have very good water quality with TDS values of less than 1,000 mg/L. The closest likely recharge area is about 11 km (6.9 mi) to the west along the Blanco River. Despite the low TDS water (less than 1,000 mg/L), the relatively old age suggests that the groundwater is on a less active pathway than in the recharge zone.

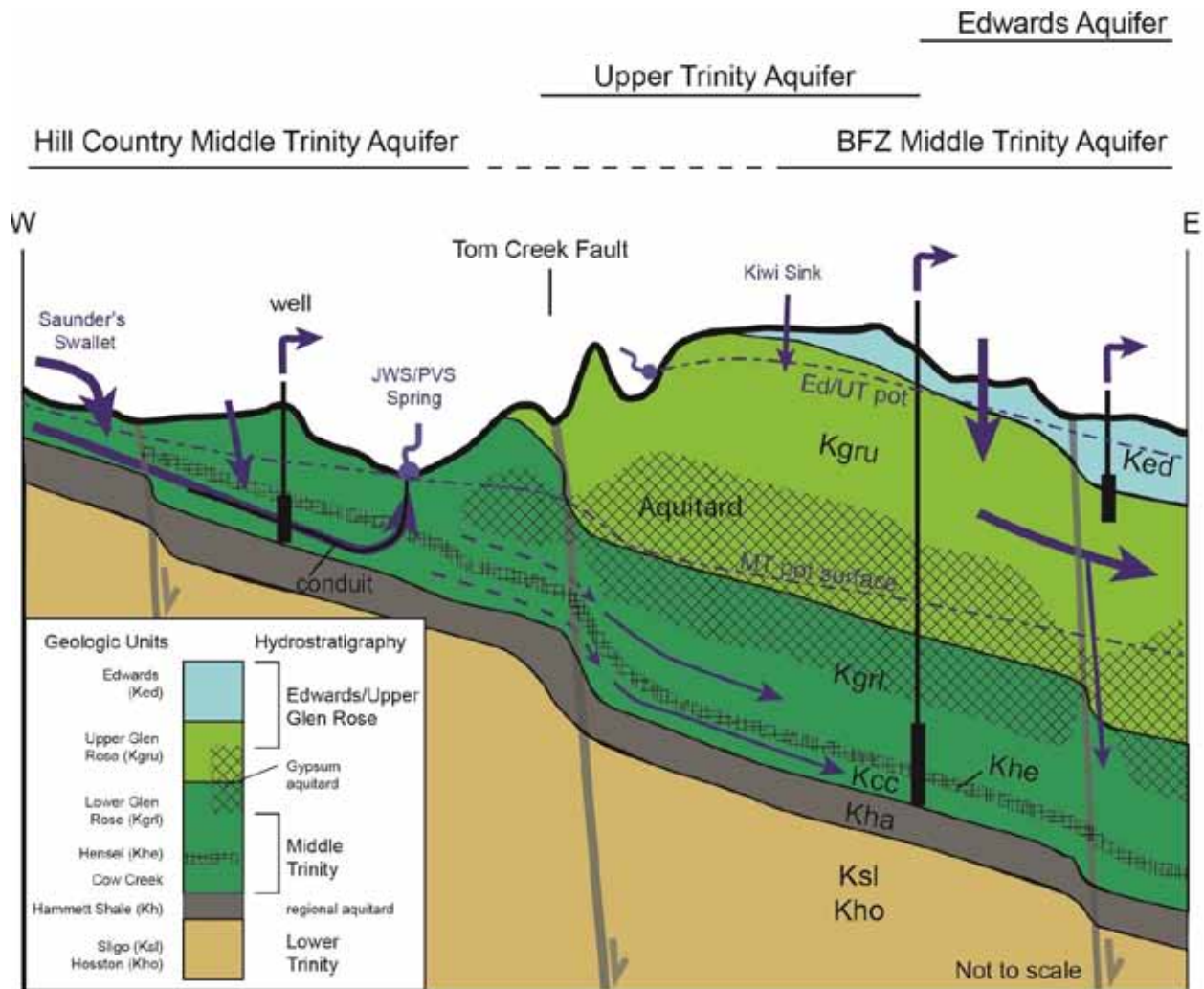


Figure 12. Schematic cross section and conceptual model.

The transition from the Hill Country Middle Trinity Aquifer into the BFZ Middle Trinity Aquifer occurs across a major fault zone (Tom Creek), with throws of up to 76 m (250 ft). Moving from northeast to southwest, the fault zone decreases in offset. In the north near Travis County the fault appears as a barrier to flow as demonstrated by the northeast direction of groundwater flow. Moving southwest into the JWS area potentiometric gradients turn to the southeast, but become much steeper indicating relatively lower permeability and likely restricted flow across the fault zone. Continuing southward toward PVS, the gradients become less steep, likely more permeable, and with flow to the east-southeast. The change in gradient is generally coincident with a relay-ramp structure that allows for continuity of the geologic units from the Hill Country Trinity Aquifer into the BFZ Trinity Aquifer.

Hydrographs and geochemistry indicate that the fault zone delineates a change in the permeability field, likely related to the degree of karst development.

Other studies have shown that in the BFZ, the uppermost Upper Glen Rose is in hydrologic communication with the overlying Edwards Group where the Edwards is saturated (Wong et al., 2014). The degree of vertical hydrogeologic connection between the Upper Trinity Aquifer and the underlying BFZ Middle Trinity aquifer is poorly understood. Recent aquifer test data indicate a local hydrologic connection depending upon climatic conditions or drawdown from pumping.

Conclusions

The Middle Trinity Aquifer meets the definition of a karst aquifer due to its conduit permeability within

soluble rocks. However, the same aquifer has contrasting properties that are separated by the complex Tom Creek Fault Zone. The westerly Hill Country Middle Trinity Aquifer is a shallow karst aquifer system influenced by rapid conduit flow and characterized by active surface and groundwater interactions. The Balcones Fault Zone Middle Trinity Aquifer, to the east, is a deeply confined karst aquifer system with more limited conduit development, with no direct surface-groundwater interactions, and slower groundwater flow.

The implications of this study will influence future hydrogeologic evaluations and modeling. Evaluations include the potential for impacts to existing domestic-supply wells by large-scale pumping of wells completed in the Balcones Fault Zone Middle Trinity Aquifer. Groundwater management districts in Texas are responsible for the protection of aquifers and the users of those aquifers. A better understanding of these complex systems will allow for policy decisions that will minimize the potential for unreasonable impacts from groundwater pumping on wells and springs.

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KARST, SCIENTIFIC UNCERTAINTY, AND THE LAW

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Abstract

Courts struggle to deal with evidence relating to the existence of karst terrain and the impact of human activities on karst terrain. Although courts often must hear cases involving complex scientific issues, karst seems to prove especially problematic, perhaps because of the lack of uniformity and the site-specific nature of the resource.

Helping Others Maintain Environmental Standards (HOME) v. Bos, 406 Ill.App.3d 669, 941 N.E.2d 347 (2010) (“*Bos*”), represents the most extreme example of a court struggling with evidence relating to karst matters. The court found against the plaintiffs, primarily because the expert witness admitted that additional testing *could* have been done, but was not, due in part to financial constraints. One legal treatise referred to the defense’s “relentless theme of studies not done” as “raging, fuming, “it’s-all-an-environmental-conspiracy” presentation (Rogers Environmental Law, 2d., Section 4:18). This case explicitly raises the questions that many others implicitly raise. How many studies are enough? Which studies are sufficient?

The *Bos* case and a variety of other published opinions involve courts analyzing expert testimony as to karst matters and determining whether such evidence is sufficient. Examination of these cases proves useful for future litigants and experts. The cases examined involve a variety of situations, including Environmental Impact Assessments and various citizen challenges to development. The review reveals that courts apply inconsistent standards and then use inconsistent analysis in the application. Some of the inconsistency can be explained by the context of the case, while others cannot.

Analysis of the court cases indicate that courts are generally ill-equipped to deal with expert testimony related to karst matters and that this testimony may prove to be more problematic than other technical, scientific evidence due to the nature of karst as a heterogeneous resource depending upon site-specific studies and examination. This circumstance further raises the issue of the cost of expert testimony relating to karst in court cases and whether karst investigations should instead be conducted by state or federal agencies. However, if these agencies should conduct the investigations, do the agencies have adequate resources to do so?

The paper recommends that the scientific karst community further educate lawyers, judges and citizens on the scientific aspects of karst, including the heterogeneous nature of karst. Ultimately, however, expert witnesses in karst matters will be forced to incorporate education of the court into their reports and testimony, to the extent that the court allows.

Introduction

Courts struggle to understand increasingly complex and technical expert testimony in a broad range of cases. However, nowhere is this struggle more evident than with respect to expert testimony related to karst. In 2010, a state court in Illinois decided a case that drew national attention for the court’s extraordinary comments on expert witness testimony on a karst issue. The context of the case raises a number of issues on expert testimony, including how courts should evaluate the testimony, who should pay for expert testimony and whether experts must conduct every test possible. Examination of this case, along with the handful of additional court cases in the United States that evaluate expert testimony on karst, yields some basic principles that should guide expert witnesses and litigants in karst matters.

The Nature of Expert Testimony

The Federal Rules of Evidence set forth the guidelines for qualification as an expert witness and for evaluation of expert witness testimony in federal courts. An expert qualifies by knowledge, skill, experience, training or education (Federal Rules of Evidence Rule 702). Opinions expressed must meet the following requirements: (1) the expert’s scientific, technical, or other specialized knowledge will help the trier of fact to understand the evidence or to determine a fact in issue; (2) the testimony is based on sufficient facts or data; (3) the testimony is the product of reliable principles and methods; and, (4) the expert has reliably applied the principles and methods to the facts of the case (Federal Rules of Evidence Rule 702). An expert may base their opinion on facts and data personally observed or facts and data the witness has been made aware of (Federal Rules of Evidence Rule 703).

Rules that apply in most state courts are either based on or similar to the Federal Rules. Judges have fairly broad discretion in applying the rules.

Another issue that proves important in understanding these issues involve the relationship between trial courts and appellate courts. Trial courts find the facts and then apply the law to the facts to make rulings. If a jury is seated, the jury finds the facts and the court instructs the jury on the law to apply. If no jury sits, the judge in the trial court finds the facts and applies the law. Appellate courts hear legal arguments and generally do not hear witnesses or admit additional evidence.

Therefore, appellate courts generally defer to the trial court, or the court that hears the testimony, on facts. Facts include judgements about expert testimony. The trial court is held to an “arbitrary and capricious” standard on factual issues. With respect to legal issues, the appellate court generally owes no deference to the trial court and may apply the law as the appellate court interprets the law.

An Illinois Case Creates Uncertainty for Expert Testimony

Introduction

In *Helping Others Maintain Environmental Standards v. Bos*, 406 Ill.App.3d 669, 941 N.E.2d 347 (2010) (“*Bos*”), a citizen group (HOMES) filed suit against the developer of a large dairy facility and the Illinois Department of Agriculture to prevent the construction of the dairy. The citizen’s group had an employee of the Illinois State Geological Survey, who was not paid by HOMES, testify as an expert witness on their behalf. The trial court ultimately ruled against HOMES. The case was appealed by HOMES. Most importantly for this analysis, the appellate court approved the trial court’s holding that HOMES did not meet the requirements to obtain a permanent injunction.

Specifically, HOMES needed to demonstrate a high probability of groundwater contamination from the dairy. HOMES has an employee of the Illinois State Geological Survey testify as to the high probability. *Bos*’ expert witnesses testified otherwise. The trial court found that HOMES failed to prove the high probability of groundwater contamination. The appellate court ruled that the trial court finding was reasonable and upheld the finding.

Facts of the Case

Bos proposed to build two large dairies, each of which would hold 6,850 animal units in the form of dairy cows and calves. One of the facilities would have three livestock waste holding ponds. To move forward, *Bos* needed approval from the Illinois Department of Agriculture. Eight siting requirements must be met to

receive approval under the Illinois Livestock Act. The requirements ask whether:

- (1) registration and livestock waste management plan certification requirements were met by the notice of intent to construct;
- (2) the design, location, or proposed operation would protect the environment by being consistent with the Livestock Act;
- (3) the location minimized incompatibility with the area’s character by being zoned for agriculture or complying with the Livestock Act’s setback requirements;
- (4) the facility was in a 100–year flood plain or an environmentally sensitive area and, if so, whether the proposed construction standards were consistent with protecting the area’s safety;
- (5) the owner or operator submitted plans to minimize the likelihood of environmental damage from spills, runoff, and leaching;
- (6) odor control plans were reasonable and incorporated odor reduction technologies;
- (7) traffic patterns minimized the effect on existing traffic flow; and
- (8) construction of the facility was consistent with community growth, tourism, recreation, or economic development through compliance with applicable zoning and setback requirements. (510 ILCS 77/ 12(d)).

Requirement (4), which provides for heightened construction standards in karst areas, formed the focus of the case and the expert testimony. “Environmentally sensitive area” includes a karst area or an area with aquifer material within five feet of the bottom of the waste facility. Much of the dispute focused on whether the proposed facility was in a “karst area”. The lawsuit alleged that the bedrock underlying the proposed facility and in the area of the facility consisted of Galena Group Carbonate Rock with karst features. These geologic conditions make the groundwater in the area highly susceptible to contamination according to the allegations. Specifically, the claims of HOMES centered on the issue of whether the waste containment pond liners were inadequately designed because the design failed to consider the karst terrain.

Karst Areas and Location of Livestock Waste Handling Facilities

The Illinois Livestock Act defines “karst area” as “an area with a land surface containing sinkholes, large springs, disrupted land drainage, and underground drainage systems associated with karstified carbonate bedrock and caves or a land surface without those features but containing a karstified carbonate bedrock unit generally overlain by less than 60 feet of unconsolidated materials” (510 ILCS 77/10.24). “Karstified carbonate bedrock” is defined as “a carbonate bedrock unit (limestone or dolomite) that has a pronounced conduit or secondary porosity due to dissolution of the rock along joints, fractures, or bedding plains” (510 ILCS 77/10.26).

Under administrative regulations, if the “proposed livestock waste handling facility is to be located within an area designated as ‘Sink hole areas’ on ‘Karst Terrains and Carbonate Rocks of Illinois’, IDNR–ISGS Illinois Map 8”², or if soil samples from within 20 feet of the livestock waste handling facility boundaries indicate that the waste handling facility is in a “karst area,” additional inspections and tests are required (35 Ill. Adm. Code §§ 506.302(b), (g)). If a livestock waste handling facility is in a karst area, the waste facility must be designed to prevent seepage of waste into groundwater (510 ILCS 77/13(b)(2); 35 Ill. Adm. Code § 506.312(a)) and is to be constructed using a rigid material such as concrete or steel (35 Ill. Adm. Code § 506.312(b)).

However, the facility’s owner or operator may receive the Department’s permission to “modify or exceed these standards in order to meet site specific objectives” (35 Ill. Adm. Code § 506.312(c)). In such a situation, the owner or operator must demonstrate that the modification is at least as protective of the groundwater, surface water, and structural integrity of the waste facility as are the regulation’s requirements (35 Ill. Adm. Code § 506.312(c)). No livestock waste facility may be constructed within 400 feet of a natural depression in a karst area (510 ILCS 77/13(b)(2); 35 Ill. Adm. Code § 506.302(g)(1)).

The Expert Testimony

The trial turned on the expert witnesses on each side. HOMES relied mainly on evidence presented by Samuel Panno. Panno is a senior scientist with the Illinois State Geological Survey. The state Attorney General’s Office originally asked Panno to get involved in the case, presumably on behalf of the state (*Bos*, 374). The Attorney General’s Office later changed their mind and decided that the state should not be involved (*Ibid*).

Panno testified that karstified carbonate bedrock was “a crucial component of [HOME’s] case” (*Bos*, 374). Panno admitted that he failed to make a site-specific investigation. He based his opinion on LiDAR imagery, examination of aerial photos and field investigations. The testimony indicated that Panno used LiDAR imagery to locate fractures in the carbonate rock. One lineament underlain a waste holding pond, but Panno admitted that lineaments are an interpretative tool to indicate where to look for further information. One photo appeared to show a spring, but Panno admitted that he could not definitely identify the feature as a spring. The testimony failed to tie his findings directly to the site of the waste holding ponds, with the information mainly coming from outside the site (*Ibid*).

Panno similarly testified that elevated levels of sodium chloride could indicate susceptibility of the karst aquifer, but admitted that similar levels had been found in non-karst areas. His investigation failed to include testing of wells near the dairy for bacteria. Panno admitted that such tests were a “good idea” to detect a connection between septic systems and the wells (*Ibid*).

Panno testified that *Bos* should have measured stream flow, performed groundwater chemistry evaluation, installed monitoring wells and conducted dye tracing, but he failed to take the same steps (*Bos*, 374). He admitted that a site-specific analysis would most appropriately determine the characteristics of the site. Panno also called into question the testimony of another expert who had suggested that the presence of weathered or highly weathered limestone in rock corings and borings indicated karstic bedrock. Panno stated that not all such bedrock is karstified carbonate bedrock.

The trial court also seemed to place great weight on Panno’s admission that a number of additional tests could have been conducted to provide more definitive indications of whether karst terrain underlain the proposed dairy site. Specifically, Panno did not evaluate groundwater chemistry, conduct well monitoring or use dye tracing. Panno failed to take these steps due to cost (*Ibid*). The State Geological Survey had few resources and so various tests were not done (*Bos*, 375). He did not ask HOMES to fund the studies because that is “not something we do” (*Ibid*). The state funding was so limited that staff would “drive 10 hours round trip and do 10 hours of fieldwork in one day because there was no money to stay overnight in a hotel!” (*Ibid*).

However, no rock corings from the site were examined and no bacterial well data from the area were sought.

These tests would not be prohibitively expensive (*Bos*, 374). The court characterized HOMES' evidence as "vague" as to specific contaminants, concentrations and release mechanisms (*Ibid*).

The court placed greater weight on the evidence presented by the expert witnesses for *Bos*. The court favorably cited the regional and site-specific investigations, including examination of rock corings and well data. The *Bos* experts concluded that the area was not karst and that facility design was sufficient to protect groundwater (*Ibid*). *Bos* also argued that certain information that Panno failed to disclose at the trial for the preliminary injunction entitled them to damages (*Ibid*).

Conclusions

Commentators reacted incredulously to the standard that the *Bos* case appeared to set. "The defense puts on a raging, fuming, 'it's-all-an-environmental-conspiracy' presentation, and the court sits there meekly, absorbing every word of it. The relentless theme of studies not done...is of course the stuff of routine cross-examination" (Rodgers and Burleson, Section 4.18). The fact that Panno, a civil servant, served as the expert witness for the citizen group also raises the issue of whether state or federal agencies should provide neutral expert testimony. In addition, the case raises the question of whether "the 'studies not done' should be assigned to the citizens or undertaken by the authorities themselves" (*Ibid*). However, if state or federal agencies should serve as experts for the courts, significant additional funding needs to be provided.

Other Karst Expert Testimony Cases **Introduction**

A handful of other published court opinions also address the standards for expert testimony in cases where karst plays an important role. These cases appear in a variety of contexts. Although none of the cases present holdings as dramatic or far-reaching as *Bos*, the opinions, cumulatively, present guidelines that expert witnesses and litigants should heed in future cases

***Terpstra v. Peterson* 1999 WL 289283 (Ct. App. Minn. 1999)**

Terpstra challenged the approval of a conditional use permit for a covered hog feedlot and alleged that the granting of the permit was arbitrary and capricious. (*Terpstra*, 1). *Terpstra* contended that an Environmental Assessment Worksheet should have been completed. However, the Rice County Board of Commissions determined that an EAW was not necessary and voted to approve the permit. *Terpstra* presented maps from the

Geological Atlas of Rice County that indicated that the proposed feedlot would be in an area with a moderate risk of karst. (*Terpstra*, 3).

The board questioned the accuracy of the information, noting that the conclusions were based only on topographical features and that no soil samples or wells samples were collected or analyzed (*Ibid*). The board concluded that "no evidence exists which suggests that Far-Gaze Farms' proposal would endanger the health, safety and welfare of the county's citizens." (*Terpstra*, 3).

The court found that while the evidence may not have significant probative value, the evidence "suggests" that karst exists in the area. (*Ibid*). Therefore, the proposal *may* endanger the health, safety and welfare of the county's citizens. However, the court upheld the approval of the permit. *Terpstra* failed to present evidence on the accuracy of the Geological Survey maps, the degree of danger presented by karst or how likely sinkhole formation is in a karst area (*Ibid*). No evidence on the record showing the relationship between a "karst problem" and public health and safety (*Ibid*).

***Olmsted County Concerned Citizens v. Minnesota Pollution Control Agency*, 2010 WL 4941663 (Ct. App. Minn. 2010) (unpublished)**

The *Minnesota Pollution Control Agency* (MPCA) decided not to require an Environmental Impact Statement (EIS) for a proposed ethanol facility. *Olmsted County Concerned Citizens* (OCCC) filed suit, claiming that the decision was arbitrary, capricious and not supported by the evidence. Public comments on the draft Environmental Assessment Worksheet included concerns about the karst geological features, data and modeling methodologies, and spills and emergency responses. (*Olmsted County Concerned Citizens*, 1).

After a public hearing before the MPCA Citizen's Board (the "Board"), the Board delayed its decision and asked the MPCA to prepare a set of findings that would require a limited-scope EIS on several issues including surface water and groundwater interactions in karst geological areas and the adequacy of a 30-day pump test to predict the quantity and quality of water in the karst geological areas (*Ibid*, 2). At a second hearing, after receiving further information, the MPCA Citizen's Board determined that the proposed ethanol plant did not have the potential for significant environmental effects and voted unanimously that an EIS was not required. OCCC filed suit.

With respect to dye tracing tests, the MPCA maintained that the tests were not needed because of the groundwater protection provided by the design of the plant. In addition, no open or free draining karst features exist on the property to allow the introduction of dyes. Furthermore, the “intensive site investigations and geophysics work” at the site vitiated the need for dye tracing (*Olmsted County Concerned Citizens*, 4). As for leaks and spills in light of karst geology, the court found that the record contained significant information indicating that the site contained few karst characteristics. If fractures or cavities in the bedrock were encountered in the excavation stage, plans were in place to address the issues (*Ibid*, 10). Based on the evidence, the decision was not arbitrary and capricious and was backed by substantial evidence.

Karst Environmental Education and Protection, Inc. v. Federal Highway Administration, 2011 WL 5301589 (U.S. Dist. Ct., W.D. Kentucky 2011)

Karst Environmental Education and Protection, Inc. (KEEP) challenged the adequacy of the geologic survey relied on by the *Federal Highway Administration* (FHWA) as “ cursory”. (*Karst Environmental Education and Protection*, 18). The group argued the National Environmental Policy Act (NEPA) requires an in-depth karst analysis, including dye tracing and computer modeling of groundwater (*Hoosier Env'tl. Council*, 1). The study here failed to discuss karst topography “as a whole”, focusing only on the largest caves and sinkholes. (*Karst Environmental Education and Protection*, 18). KEEP also faulted the method by which the Final Environmental Impact Statement (FEIS) tabulated the biological impact on the caves. The FEIS measured the distance from the Project area to the mouth of the cave. KEEP maintained that, given the speed by which groundwater could move, proximity to the cave opening is immaterial. The network of underground streams and passageways are much closer to the project.

The court rejected the arguments, citing the relative scale and impact of the project in this case and the project in *Hoosier Env'tl.* The project at issue creates a connector road 3.8 miles long, whereas *Hoosier Env'tl.* involved a highway of over 140 miles. (*Karst Environmental Education and Protection*, 19). While acknowledging that the agency “could have” done more, the court found that the FHWA took the required “hard look” at the karst issues, finding that the review was proportionate to the size of the action. (*Ibid*). “[P]racticability and reasonableness must be taken into account...to preserve the values and amenities of the natural environment” (*Env'tl. Defense Fund*, 468).

In re Louisiana Energy Services, LP, 2010 WL 3969642 (Ct. App. New Mexico 2010)

Citizens for Alternatives to Radioactive Dumping (CARD) objected to the granting of a groundwater discharge permit to *Louisiana Energy Services, LP* (Louisiana Energy). CARD appealed a ruling of the lower court that, among other things, found that CARD’s proffered expert witness did not qualify as an expert on the matter before the court.

The expert, Dr. Richard Phillips, testified that he had a Ph.D. in geomorphology and that CARD had retained him seventeen days earlier to investigate the ground water hydrology in the immediate vicinity of the site (*In re Louisiana Energy Services, LP*, 1). Phillips submitted a report about karst aquifers at the Waste Isolation Pilot Plant (WIPP) site, sixty to seventy miles from the Louisiana Energy site. Based on a field investigation he conducted north of the Louisiana Energy site, Phillips concluded that the Louisiana Energy site was in a karst region.

Phillips based his finding primarily on a structural depression that holds water ephemerally, and Baker Spring, which holds water perennially. Phillips testified that the depression and Baker Spring were “telltale features of a karst terrain.” His testimony indicated that the karstic formation would likely be affected by runoff from the site. Phillips admitted that he had spent only one day in the field to support his findings and that he failed to visit the Louisiana Energy site (*Ibid*).

Expert witnesses for Louisiana Energy contradicted Phillips’s testimony, asserting that the karst-like features observed by Phillips could have been caused by human activity. (*In re Louisiana Energy Services, LP*, 2) These witnesses concluded that no karst existed on the site, that Baker spring was not related to the site and evidence of karst on the site would not affect the viability of their operations on the site due to the hydrology in the area, and the practices and protections on the site.

The trial court concluded that Phillips failed to qualify as an expert witness in this case (*Ibid*, 5). The key findings to support this ruling included Phillips’s failure to visit the site and the fact that Phillips’s conclusions were based on karst features on an unrelated site and study of another site sixty miles from the Louisiana Energy Services site (*Ibid*). Citing New Mexico Rules of Evidence, similar to Rule 702 of the Federal Rules of Evidence, the New Mexico Court of Appeals affirmed this ruling, finding that the trial court’s ruling was not arbitrary and capricious (*In re Louisiana Energy Services, LP*, 4-5).

Conclusions

The four cases cited in this section involve karst expert testimony in a variety of contexts. However, the cases present consistent principles. As indicated by these cases, the courts generally defer to the administrative agency. To rebut the agency, evidence must be substantial and show serious error on behalf of the agency. Testimony should be based on a site-specific investigation, the findings should be specific, and the evidence should clearly link impacts to the existence of karst features.

The cases in this section do not extend as far as the *Bos* case in requiring expert witnesses to engage in any and all possible tests. However, *In re Louisiana Energy Services, LP* represents a significant ruling in that the court disqualifies the expert witness. Noting the case indicates that the expert's credentials fell short. Instead, the expert was disqualified due to basing the opinion on secondary sources instead of a site-specific investigation. A more accurate analysis of the court's opinion would classify the ruling as disqualifying the opinion, not the expert. If the expert would have done a site-specific investigation, he would likely have qualified.

Conclusions

The *Bos* case appears to impose extraordinary requirements on expert witnesses by discrediting expert testimony for, among other things, failing to use every possible test to characterize the site. The ruling remains unprecedented. However, examination of other cases involving expert witnesses, along with the pertinent Federal Rules of Evidence, on karst matters yields useful principles for expert witnesses and litigants. The Federal Rules of Evidence require that the expert possess the requisite expertise, the testimony is based on "sufficient facts and evidence" and "the product of reliable principles and methods", and that these principles and methods are applied to the facts of the case.

The *Bos* case illustrates how onerous the burden of proof may be on a party challenging an agency finding. That case suggests that the challenger may have to conduct "every possible study". On the other hand, *Karst Environmental Education and Protection* explicitly stated that the agency "could have" done more, but upheld the agency's investigation as adequate to meet the agency's duty to take a "hard look".

Court interpretations of the rules give greater weight to expert testimony that is (1) based on site-specific investigations and data; (2) includes specific and precise analysis; and (3) clearly links the data to specific impacts. The *Bos* case additionally suggests that the expert conduct every possible test that may aid in the

investigation, and may be interpreted to require costly, and even cost-prohibitive tests. However, no other court has gone that far.

The *Bos* case also raise troubling questions of whether the burden of providing expert testimony should be placed on private citizens, who will rarely be able to match corporate opponents, or whether state and federal agencies should be funded to give them the ability to provide unbiased evidence to courts. Obviously, the cost of retaining an expert witness may be an insurmountable burden to many citizen groups. To conduct "every possible study" would eliminate even more groups from participation in the judicial process.

Courts also appear to struggle to understand the complexities of expert testimony relating to karst issues. Expert witnesses and the litigants who employ them should keep these issues in mind. Judges and juries must be educated in order to comprehend and analyze expert witness testimony relating to karst.

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WHEN SINKHOLES BECOME LEGAL PROBLEMS

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Abstract

Sinkholes can cause property damage, injury to people and harm to the environment. It is therefore not surprising that myriad legal issues arise in the context of sinkholes and the actual and potential harms they present. This paper will focus on those legal issues and will include a discussion of potential causes of action (i.e., legal claims), both under statutory laws (e.g., state laws like in Pennsylvania under which sinkholes can be deemed a nuisance) and common law (i.e., claims derived from longstanding judicial precedent), and available damages (i.e., monetary compensation) and other remedies. Mining activities and water supply wells for industrial, commercial and residential uses, which pump groundwater in karst and other sinkhole prone areas, are often a direct cause of sinkholes. Yet most government agencies regulating mining and other related industries are ill-equipped, either technically or politically, to manage the potential, and in some cases, inevitable damage. Few, in fact, recognize the direct relationship between activities they typically permit, the formation of sinkholes, and the resulting harms.

This paper will also discuss both bringing a case for sinkhole remediation (direct lawsuits and mining permit appeals) and defending sinkhole-related claims. Because cases involving karst terrain and sinkholes tend to turn on the presentation of highly technical scientific principles, educating the court is critical, as is the experience and expertise of a top-notch expert witness. This paper will discuss the ways to effectively present such cases in court, including the presentation of technical witnesses/experts.

Two case studies will be examined. One case involves a school and a neighboring quarry, in which the court found that a quarry was the direct cause of sinkholes opening in the surrounding area. As a result, the court held that the quarry constituted a nuisance, and therefore denied a permit extension allowing further mining. Another case study will examine sinkholes opening near a major roadway in an area where no mining is known to have occurred.

Introduction

Sinkholes can lead to significant physical, economic, and environmental harm. A party impacted by sinkholes may have several viable causes of action against other parties and, in certain circumstances, legal recourse against government agencies. This paper is intended to provide a general overview of the legal landscape surrounding sinkhole litigation, including preventative measures, claims, defenses, and available remedies.

Overview of Common Legal Issues Implicated by Sinkholes

The common thread running through the wide range of legal issues that arise surrounding the threat and occurrence of collapse sinkholes can be boiled down to one word: causation. The question of who or what caused the sinkhole at issue is the lodestar of any claim, defense, or regulatory or enforcement action. Given the highly technical issues involved, and the fact that the conditions leading to the opening of a sinkhole are subterranean (and thus unobservable by a judge or jury), the responsibility of proving or disproving the alleged cause of a sinkhole falls to expert witnesses.

Bringing Legal Claims Related to Sinkholes

A party may bring a number of tort claims (i.e., claims based on some type of harm caused by another person or party) related to the occurrence of collapse sinkholes depending on the circumstances presented and the party's ultimate objective. These claims overwhelmingly arise under state law rather than federal law. This paper is not intended to describe in detail the law of any particular state, but rather to provide a general overview of the types of claims that are most commonly invoked in sinkhole cases. Fortunately, most state law claims are derived from the common law, and as a result, the causes of action are the same or very similar from state to state.

Negligence is one of the most common claims asserted by parties affected by sinkholes. In order to prevail on a negligence claim, a plaintiff must show that the defendant owed a duty to the plaintiff, that the defendant breached that duty, and that the breach caused an injury

to the plaintiff.¹ When it comes to sinkhole litigation, technical considerations can inform all elements of a negligence claim. For example, the landowner often has a duty to make the premises safe for other people who enter the property with the landowner's express or implied permission. The extent of the owner's obligation is usually dictated by the type of people who may foreseeably enter the land, the foreseeable uses of the land, and what the owner knew or should have known about his or her land. This duty generally includes "inspecting the premises to discover possible dangerous conditions of which the owner/occupier does not have actual knowledge, and taking reasonable precautions to protect invitees from dangers foreseeable from the arrangement or use of the premises."² This speaks to one of the most fundamental concepts underlying many of the legal issues addressed herein. Namely, that the law is concerned not only with what a party actually knew, but also with what a party *should have known* given the particular circumstances. In the context of sinkhole litigation, this legal concept, known as constructive knowledge, prevents landowners from simply hiding behind a veil of willful ignorance.

In the case of *Lore v. Suwanee Creek Homeowners Association*, a sinkhole opened in a "recreation area", and the plaintiff—after repeatedly informing the landowner about the sinkhole—was injured when the ground collapsed from underneath her as she was standing approximately four feet from the sinkhole.³ The appeals court held that the owner had a duty to inspect the sinkhole and the surrounding area to determine whether it posed a danger, and remanded the case to the trial court to determine whether the landowner breached that duty by failing to inspect and/or by failing to take reasonable steps to protect individuals from foreseeable dangers. Thus, technical knowledge and expertise can be critically important in determining not only when a duty arises, but what actions must be taken to satisfy that duty and mitigate the chance of harm. The same is true with respect to claims related to sinkholes occurring on adjacent land.

Failure to comply with guidelines or accepted procedures can serve as evidence of breach and causation. For instance, in *Widner v. King County*, defendant King County filed a motion for summary judgment (i.e., a motion arguing that there are no disputed factual questions and that the court can reach a legal conclusion and resolve the case without proceeding to trial) against plaintiffs' nuisance claims on the bases that (1) the plaintiff had no evidence that the County's construction of a temporary roadway caused sinkholes on plaintiffs' property, and (2) the County did not owe plaintiffs a

duty of care because the damage to the plaintiffs' upland property was not foreseeable.⁴ The trial court denied the motion and allowed the matter to proceed to trial on the basis of plaintiffs' expert report. In his report, the expert opined that had King County conducted a pre-construction analysis in accordance with the parameters set forth in the County's Guidelines for Bank Stabilization Projects, the damage to plaintiffs' property would likely have been both foreseeable and avoidable.⁵ The court denied the County's motion, ruling that the expert's opinion was sufficient to create questions of fact as to both causation and duty.

Plaintiffs also often rely on the tort of **trespass** to redress harm caused by sinkholes. Many jurisdictions recognize more specific causes of action derived from trespass that are directly applicable to sinkholes, including trespass by subsidence, trespass by water, and inadequate subjacent support. The elements of trespass by subsidence under Kansas law are representative of trespass-related causes of action. In order to prevail on a claim of trespass by subsidence under Kansas law, a landowner must show "(1) [that] the defendant committed an act that, (2) resulted in an intrusion upon the surface of the land, (3) which interfered with the surface owner's right to exclusive possession and enjoyment of the land."⁶ Here, too, there must be a causal connection between the defendant's act and the intrusion (i.e., the sinkholes). Although the family of trespass-based claims are viable in most jurisdictions, they are increasingly viewed as antiquated and disfavored.

Nuisance, which has two distinct yet often related dimensions, is another cause of action that is commonly invoked in sinkhole litigation.

Private nuisance is a non-trespassory invasion of another's interest in the private use and enjoyment of land. Liability for private nuisance arises where there is interference with a plaintiff's use or enjoyment of the land, and that interference is both unreasonable and substantial. Here, as with negligence, it must be shown that the defendant—or land or property that the defendant owned or controlled—caused the interference.⁷

Public nuisance arises where there is an unreasonable interference with a right (not necessarily the use and enjoyment of land) common to the general public. State and local governments are empowered to abate public nuisances. Most jurisdictions do, however, also permit private parties to bring claims seeking damages where a public nuisance injures their property, but only if the nuisance is "specially injurious" to that party, meaning that the nuisance affects that party differently and more

severely than the general public.⁸ Public nuisance is addressed at greater length in Case Study One, below.

In addition to tort claims, sinkholes can give rise to **contract claims** and liabilities. Thorough due diligence is critical, particularly in karst regions and other sinkhole-prone areas. This is true not only for buyers, who may ultimately be saddled with a sinkhole-laden property (and the liability that may accompany it), but also for sellers, to whom a comprehensive understanding of the site is invaluable when it comes to making representations and warranties in a land contract. The failure of a party (or a party's expert) to identify areas that are particularly prone to sinkholes can have significant consequences on the questions of who bears the liability for potential harm that may arise if sinkholes open and who is responsible for repairing any sinkholes that open. Case Study Two, below, addresses several contractual issues that can arise when sinkholes open.

Parties aggrieved by the occurrence of sinkholes may also have **statutory claims** and other forms of recourse, possibly through or against a state regulatory agency. This route is generally more effective when a party is seeking injunctive relief (i.e., an order to do something or stop doing something) as opposed to monetary damages. Various statutes and regulations may contain footholds that can be used to force agencies or private parties to take action to prevent future sinkholes. For example, state statutes commonly declare certain conditions to be public nuisances, and then impose a duty upon a state agency or agencies to mitigate or abate such nuisances. Pressure can be brought to bear upon those agencies, and, in many situations, parties may compel an agency to act by seeking a writ of mandamus (i.e., a court order requiring a government agency or official take a particular action) from a court with proper jurisdiction. Because many of the activities that commonly cause sinkholes are associated with industries that are subject to significant health, safety, and environmental regulation, and thus require various permits in order to operate, the permitting process can be an effective means to combat sinkholes. Permitting is a public process. Third-parties are afforded the opportunity to comment on proposed permits, and the permitting agency is required to consider those comments. If the permitting process itself does not bear fruit, an interested third-party may then challenge the permit in court or before some form of administrative tribunal. Case Study 1, below, illustrates the effective use of several of these tactics.

Defending Sinkhole-Related Claims

Issues of causation, knowledge, and the reasonableness of an action (or lack of action) under a particular set of circumstances also dominate the defense against sinkhole-based claims. Technical data and expert opinions are therefore also critically important when defending against sinkhole-based claims.

The expiration of the applicable statute of limitations (i.e., a set period of time after which a claim can no longer be brought) is one of the most common defenses against sinkhole-related tort and contract claims. Causation and other technical questions are often critical components of a statute of limitations defense. In general, a statute of limitations only begins to run at the moment that a claim can first be brought (this is known as the "accrual" of a claim), which is not always the same moment that the underlying act occurred. For example, with trespass to land, after the defendant commits the act that gives rise to the claim, that claim does not accrue until the subsidence or other intrusion occurs and interferes with the landowner's property rights. Where the cause of a sinkhole is reasonably ascertainable through investigation, the statute of limitations will not be tolled.⁹ Thus, causation is a critical question to both parties, as is the question of what is "reasonably ascertainable." Once a party knows or has reason to believe that a sinkhole was the result of another person's action, the statute of limitations "clock" begins to run.

Compliance with the law, including environmental laws and permitting requirements, *is not* a defense to most tort claims, including nuisance and negligence.¹⁰ However, compliance with the law does tend to show the lack of willful or malicious misconduct that is generally required to support an award of punitive damages (i.e., additional money awarded to punish a defendant for particularly egregious behavior).¹¹ In fact, courts have recognized that punitive damages are "improper where a defendant has adhered to environmental and safety regulations."¹²

Evidence of alternative or additional causes of sinkholes may also serve to negate a plaintiff's evidence related to causation. Such evidence is particularly useful when it suggests that the plaintiff herself may have caused, or contributed to the conditions that caused, the sinkhole. The impact of this type of evidence varies significantly depending on which state's laws govern in a particular case. At one end of the spectrum, certain states do not allow a plaintiff to recover *any* damages if he or she is found to be at all responsible for the harm underlying his or her claim. Other states will reduce the amount of a plaintiff's damages commensurate with the percentage of responsibility the plaintiff is found to bear. In other states,

the plaintiff's damages will be reduced commensurate with the plaintiff's responsibility, unless plaintiff is found to bear the majority of the responsibility for his or her own injury, in which case no damages may be recovered. Regardless of the jurisdiction, evidence of alternative or additional causes of sinkholes is critically important in sinkhole litigation.

It is worth noting that there is rarely (if ever) direct evidence (i.e., evidence that directly supports the truth of an assertion) of sinkhole causation. Such evidence is always circumstantial (i.e., evidence that supports the creation of an inference that in turn supports the truth of an assertion, for example, the presence of the victim's blood on the defendant's shirt), and the thoroughness, documentation, and credibility of experts is of critical importance, as is the manner in which experts present these highly technical theories of causation—particularly if there is a jury involved. It is important to address contributing factors or alternate theories of causation squarely and honestly. Although experts are retained by and testify on behalf of their clients, it is not their responsibility to openly advocate on their client's behalf. This is a fine line to walk. While it's important for an expert to approach his or her work with their client's interest at the forefront of his or her mind, and to present their opinions in the light most favorable to the client's position, an expert must also be careful not to wander too far into the realm of advocacy, lest they lose credibility in the eyes of the judge or jury.

Relief Available for Sinkhole-Related Claims

Courts generally have considerable discretion in crafting the relief awarded to plaintiffs that succeed in proving the various sinkhole-based claims. Damages may be awarded to compensate the plaintiff for personal injury, property damage, and the foreseeable consequences arising from the occurrence of sinkholes. However, in a disproportionate number of cases—particularly those involving successful nuisance claims—parties seek and courts award some form of injunctive relief. Courts generally have wide discretion to issue injunctions, which can be either affirmative (i.e., ordering a party to act) or negative (i.e., ordering a party to refrain from acting). Courts generally try to issue narrow injunctions targeted at the behavior or condition that is causing the harm.¹³ These forms of relief may also be available in regulatory and statutory cases.

Case Study One

This case study involves a private boarding school located in a rural area and a limestone quarry located directly next to the school. The school and the quarry are located in karst terrain.

Mining has been occurring on the quarry property since the 19th Century, but it wasn't until the 1960s that mining began at depth, which required the dewatering of the quarry pit. The state regulatory agency issued the quarry its first mining permit in the mid-1970s. Although the permit approves mining to a depth of -200' MSL, the agency has required the quarry to apply for separate "depth corrections" in order to mine progressively closer to that depth. In July 2011, the agency issued the quarry a depth correction allowing it to mine to a depth of -170' MSL; the previous depth correction, issued in 2007, allowed the quarry to mine to -120' MSL. Following the issuance of the most recent depth correction, the quarry was pumping 2-4 million gallons of water per day from the quarry pit.

In 1989, collapse sinkholes began to open on the school's campus. The sinkholes ranged from several feet across to nearly a quarter an acre, most exceeding 20 feet across. Between 1989 and 2014 at least 29 sinkholes opened on the school's campus, and at least 10 sinkholes opened on neighboring properties, the largest of which was 150 feet long, 75 feet wide, and 15-20 feet deep. Over the course of this time period, wells on the school's campus began to go dry. Deeper wells were drilled, only to dry up a few years later. In addition, the creek that historically ran across the campus and the quarry property ran dry; what little flow remained was sporadic and was drained by a swallet that formed on the quarry's property, not far from the school's property line.

The sinkholes presented an enormous danger to the safety of the students, faculty, staff, and visitors, and posed a potentially existential problem for the school. Around the time that the quarry applied for its most recent depth correction in 2008, the school retained two experts—a licensed professional engineer and a Ph.D. in geology—to investigate the potential cause or causes of the sinkholes, and to make recommendations as to how future sinkholes might be prevented. Based on the investigation of these experts, which revealed that the dewatering of the quarry pit was causing the sinkholes and that deepening the quarry pit would promote continued sinkholes on the campus, the school opposed issuance of the depth correction. The agency limited its review to the marginal impact of adding 50 feet to the quarry, as opposed to the continuing impact of the ongoing dewatering of the quarry (an approach

that was later held to be improper and unlawful). After concluding that the school failed to show that the depth correction would exacerbate the sinkhole problem, the agency issued the depth correction in 2011. The school appealed the depth correction to a state administrative court.

Not surprisingly, the issue of causation was at the heart of the school's appeal, which was ultimately resolved in the school's favor after a two-week trial, most of which was focused on conflicting expert testimony. The court ultimately concluded that—because the quarry's dewatering had substantially lowered the groundwater under the school, which, given the underlying karst features, resulted in the sinkholes—the quarry's dewatering of the quarry pit is the “overriding cause” of the sinkholes.¹⁴ At trial, the quarry and the agency's experts offered several alternate theories of sinkhole causation, including flooding caused by heavy precipitation and the school's development activities on its campus, which the court rejected. The court found that continued dewatering will further depress groundwater levels below the school, and—crediting the opinions of the school's expert witnesses—found that “dewatering of the quarry is directly resulting and will continue to result in the hazardous formation of collapse sinkholes.”¹⁵

The court anchored its legal conclusions on various provisions of the state's noncoal surface mining act and related regulations. Citing the stated purpose of the act, which includes “preventing and eliminating hazards to health and safety,”¹⁶ the court pointed to the requirement that no permit may be issued unless the applicant affirmatively demonstrates, among other things, “that it will ensure the protection of the quality and quantity of surface water and groundwater, both within the permit area and adjacent areas, as well as the rights of present users of surface water and groundwater.”¹⁷ Citing a number of statutory and regulatory provisions, the court affirmed that the agency not only has the authority to deny the depth correction “if continued mining is causing unavoidable and serious harm to health and safety,” but also the “duty to ensure that mining can be performed without undue risk to health, safety, and welfare.”¹⁸ The court ruled that by issuing the depth correction the agency acted unlawfully and unreasonably by enabling a serious hazard to continue unabated. The court also rejected the standard for reviewing the quarry's application, stating that “the question is not whether the limited subject of the revision can be safely accomplished,” but rather “whether the project as a whole, as revised, can be safely accomplished.”¹⁹ Invoking a statutory provision that declares “any condition that creates a risk of...subsidence, cave-in, or other unsafe, dangerous or

hazardous condition”²⁰ to be a public nuisance, the court ruled that the quarry is creating a public nuisance. The court also invoked the agency's statutory duty to abate and remove public nuisances.²¹

In the wake of the court's decision, the agency required the quarry to begin reclamation and to submit a reclamation plan and timeline that was driven by the time needed to restore the groundwater and abate the nuisance, rather than the time needed to extract the remaining mineable reserves. The quarry's failure to comply resulted in the issuance of an order that imposed various requirements and restrictions upon the quarry, most notably, a daily pumping limit of 500,000 gallons. That order was recently upheld by the court.

This case exemplifies the critical role that expert witnesses can play in sinkhole litigation. As the court wrote: “the School assembled a top-notch team of experts for evaluating the karst geology of the [basin] and the hydrogeologic connection between the quarry's dewatering and the sinkhole development on the School's campus, the key issues in the case.”²² This case also illustrates that statutes and regulations and the permitting process can be powerful tools that a party can use to combat sinkholes, even in cases where the government agency entrusted with enforcing those laws fails to do so.

Case Study Two

This case study pertains to an ongoing dispute arising out of a lease renewal agreement between a state roadway commission and a concessionaire for a rest area on the roadway. A number of years after the lease was executed, several sinkholes opened on the property, none of which damaged existing structures. Each party has taken the position that, under the lease, the other party is responsible for the costs associated with repairing the sinkholes. The parties are currently in the process of negotiating in hopes of avoiding litigation. The lease does not specifically address sinkholes, but there are several relevant provisions that have become the focus of the parties' negotiations. The issues include the question of what constitutes a pre-existing condition, and whether sinkholes are “environmental” in nature. Again, the question of causation and underlying conditions are front and center. Technical experts are critical to the analysis.

Conclusion

Sinkholes have the potential to create significant and wide-ranging legal liabilities. Thorough and thoughtful work performed by qualified technical experts is critically important to prevent, reduce, manage, prove, or disprove such liabilities.

Endnotes

- 1 See Restatement (Second) of Torts § 281 (1965).
- 2 Lore v. Suwanee Creek Homeowners Ass’n, Inc., 305 Ga.App. 165, 168 (Ga. Ct. App. 2010).
- 3 Lore v. Suwanee Creek Homeowners Ass’n, Inc., 305 Ga.App. 165, 168 (Ga. Ct. App. 2010).
- 4 Widner v. King County, No. C08-1170JLR, 2009 WL 2578979, *2 (W.D. Wash. Aug. 18, 2009).
- 5 Widner v. King County at *2.
- 6 See e.g., Kowalsky v. S & J Operating Co., 539 Fed. Appx. 908, 913 (10th Cir. 2013).
- 7 See generally City of Atlanta v. Hofrichter/Stiakakis, 663 S.E.2d 379, 383 (Ga. App. 2008).
- 8 See Hale v. Ward Co., 2014 ND 126 (N.D. 2014).
- 9 See e.g., Kowalsky, 539 Fed.Appx. at 915.
- 10 Stone Man, Inc. v. Green, 263 Ga. 470, 471-72 (1993).
- 11 Stone Man, Inc. v. Green at 471-72.
- 12 Stone Man, Inc. v. Green at 472.
- 13 See e.g., Stone Man, Inc. v. Green at 471-72.
- 14 Solebury School v. Commonwealth of Pennsylvania Dep’t of Env’tl. Prot. and New Hope Crushed Stone & Lime Co., No. 2011-136-L, 2014 WL 4087592, *14 (Environmental Hearing Board July 31, 2014) (hereinafter Solebury School v. DEP)
- 15 Solebury School v. DEP at *16.
- 16 Solebury School v. DEP at *21 (quoting 52 P.S. § 3302).
- 17 Solebury School v. DEP at *21 (citing 25 Pa. Code § 77.457(a)).
- 18 Solebury School v. DEP at *22.
- 19 Solebury School v. DEP at *24.
- 20 52 P.S. § 3311(b).
- 21 See 52 P.S. § 3311(b); 71 P.S. § 510-17(3).
- 22 Solebury School v. DEP at *28.

LITIGATION AND THE COMPLEXITIES OF SINKHOLE INSURANCE CLAIMS IN FLORIDA

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Abstract

The entirety of peninsular Florida is underlain by relatively young limestone bedrock and overlain by sands that easily ravel into voids and cavities within the limestone. Surficial expressions of karstic activity are immediately evident in its thousands of circular lakes, wetlands, and cypress heads. Additionally, Florida has had literally tens of thousands of subsidence-related insurance claims over the past two decades, far surpassing the entire history of property insurance before that. The peak came around 2011, the year that new legislation made it much harder for a homeowner to prove a claim. The issue was essentially ‘what is the definition of structural damage?’ as defined by Florida Statute related to property insurance and specifically sinkhole coverage. Prior to 2011, a clear definition of structural damage did not exist, consequently the attorneys maintained that the plain definition (structural damage is damage to a structure) held, in spite of many geotechnical and structural reports that defined structural damage as an engineer would deem – loss of load carrying capacity. Consequently, cosmetic damage that was not remotely “structural” was considered damage by the courts, and legal cases blossomed out of control.

In 2011, Florida Statutes redefined “structural damage” using five separate criteria. These criteria include, for example “interior floor displacement or deflection in excess of acceptable variances as defined in ACI 117-90 or the Florida Building Code, which results in settlement-related damage to the interior such that the interior building structure or members become unfit for service or represents a safety hazard as defined within the Florida Building Code...”. Other criteria have to do with foundation displacement; leaning or listing of the building; or ground movement that results in portions or all of the building likely to imminently collapse. Of course, there are additional criteria and exceptions. Overall, these statutory changes have resulted in significantly fewer sinkhole claims, in spite of the occasional sinkhole that enraptures the news media (for example, the March 2013 death of Mr. Jeffrey Bush as a result of sinkhole collapse below his bedroom). So while all property insurance companies in Florida still cover “catastrophic ground cover collapse” for all homes, there are far fewer of these claims to deal with as the law has become more sophisticated.

Introduction

Florida property insurance is more dynamic than most markets. Most property insurance claims are about fire or water damage, but Florida’s property insurance also has to cover hurricanes, which provide significant damage and repair costs. Additionally, a large portion of Florida is underlain by limestone that is relatively near the surface (with 30 meters) and subject to karst activity. The proximity to the surface, the relative thickness of sand versus clay overlying the limestone, the downward gradient of surface waters to the aquifer, and the propensity for dissolution increases sinkhole occurrence.

Because of this sinkhole activity, land improvements such as homes and other buildings located in karst regions had been damaged such that sinkhole insurance was added to the list of perils that were required to be covered by property insurance, under Florida law. The author is unsure when the property insurance requirement was initiated, but it was decades ago. Initially, there was no distinction among various types of damage, and prior to 2007 all sinkhole insurance was comprehensive. In 2004, a “Sinkhole Summit” occurred among the geologist community to convene experts in the field of Florida geology. Of the 26 participants, 13 were PhD geologists. The result of this meeting was the 2005 Special Publication 57 from the Florida Geological Survey, in which a consistent and rather comprehensive methodology was set forth to investigate sinkhole insurance claims - this included SPT borings, hand auger borings, test pits to expose the foundation, GPR and electrical resistivity surveys, as well as floor elevation surveys and photodocumentation. These were generally incorporated into changes to the Florida Statutes in 2007 regarding sinkhole insurance. Regulations were again clarified in 2011 to present day law. Here are some of the main parts of the law:

The current mandate for property insurance companies is the following:

“Every insurer authorized to transact property insurance in this state must provide coverage for a catastrophic ground cover collapse.” (CGCC)

In other words, all properties are insured for catastrophic sinkholes that are further defined below:

(a) “Catastrophic ground cover collapse” means geological activity that results in all the following:

1. The abrupt collapse of the ground cover;
2. A depression in the ground cover clearly visible to the naked eye;
3. Structural damage to the covered building, including the foundation; and
4. The insured structure being condemned and ordered to be vacated by the governmental agency authorized by law to issue such an order for that structure.

The conditions above must all be met, meaning that it is indeed a rare situation that would develop for these conditions. Most sinkhole activity in Florida is not sudden collapse sinkholes, but rather dissolution type sinkholes that are slower, occurring over days, weeks, and years and causing settlement damage that is small at first, but then progresses over time. This type of sinkhole activity can be covered, but is a rider on the insurance policy rather than part of the insurance coverage as it was in the past.

A further detail that is required is to define item 3 above, “structural damage”. Prior to 2011, this term was not further defined in the insurance regulations related to sinkhole coverage, Florida Statutes Chapter 627.706. Without a legal definition, attorneys argued that “structural damage” was plainly defined as “damage to a structure”, which is a very for a very broad definition that covers not only a) what a structural engineer would say was ‘structural damage’ but also b) cosmetic damage, which by definition is superficial and would not result in loss of load bearing capacity of structural elements.

The Five-Fold Test of Structural Damage

In 2011, these five tests for structural damage were added to the language as clarifications of the previous statutes.

“Structural damage” means a covered building, regardless of the date of its construction, has experienced the following:

1. Interior floor displacement or deflection in excess of acceptable variances as defined in ACI 117-90 or the Florida Building Code, which results in settlement-related damage to the interior such that the interior building structure or members become unfit for service or represents a safety hazard as defined within the Florida Building Code;

2. Foundation displacement or deflection in excess of acceptable variances as defined in ACI 318-95 or the Florida Building Code, which results in settlement-related damage to the primary structural members or primary structural systems that prevents those members or systems from supporting the loads and forces they were designed to support to the extent that stresses in those primary structural members or primary structural systems exceeds one and one-third the nominal strength allowed under the Florida Building Code for new buildings of similar structure, purpose, or location;

3. Damage that results in listing, leaning, or buckling of the exterior load-bearing walls or other vertical primary structural members to such an extent that a plumb line passing through the center of gravity does not fall inside the middle one-third of the base as defined within the Florida Building Code;

4. Damage that results in the building, or any portion of the building containing primary structural members or primary structural systems, being significantly likely to imminently collapse because of the movement or instability of the ground within the influence zone of the supporting ground within the sheer plane necessary for the purpose of supporting such building as defined within the Florida Building Code; or

5. Damage occurring on or after October 15, 2005, that qualifies as “substantial structural damage” as defined in the Florida Building Code.

The first four of these five definitions follow a logical course of progressively worsening conditions. When movement occurs in a building, it is fairly easy to have interior floor displacements; it takes a little more settlement to cause concentrated loads such that the primary structural load bearing elements exceed their design by 33%, and even more settlement to cause tilting in the walls sufficient that there is eccentric loading outside the ‘kernel’ or middle third of the base. The fourth definition is the longest and most difficult to properly ‘unpack’; but it basically says the building is in an imminent collapse mode. Naturally, geologists and engineers initially read this as the ‘collapse’ referred to the soil or rock beneath the structure, and not the structure itself. The fifth definition refers more to the timing of the damage, disqualifying damages prior to 2005, with “substantial structural damage” defined as a 20% or greater loss load carrying capacity.

The bottom line of the changes in regulations is that there must now be “structural damage” (as defined above) present that may be the result of sinkhole

activity. Structural Damage Assessments are completed with limited or no geotechnical evaluation first, and if there is sufficient structural damage present, a sinkhole investigation may proceed to determine if sinkhole activity is a cause of the damage. With these regulatory changes, a significant reduction in sinkhole claims has occurred, based on the number of sinkhole assignments our company (and many sinkhole experts) have received since 2012. Other recent and significant industry changes include the following:

The Managed Repair Program

Citizens Property Insurance Corporation, the largest residential property insurer in Florida, is a not-for-profit, tax exempt government entity created in 2002 to be an insurer 'of last resort' for high risk policies, such as hurricane prone areas and sinkhole prone areas of Florida. In response to rising numbers of sinkhole claims and in some cases fraud by contractors, Citizens created the Managed Repair Program which did two things to bring things under control: created a pre-approved Contractor Network of licensed and vetted specialty contractors to do sinkhole repair (grouting and underpinning of structures); providing multiple quotes for repairs to the homeowner; provided third-party monitoring services to assure the contractor's performance and conformance to the specifications; and provide a 3-year warranty to the homeowner. This program has significantly reduced the number of "fly-by-night", unqualified contractors from doing substandard repairs to homes.

The Neutral Evaluation Process

In the event that the homeowner disagreed with the engineer's determination of whether or not sinkhole activity was a cause of damage, or disagreed with the engineer on the repair program for the structure, a Neutral Evaluation program was established by the Office of Insurance Regulation. A Neutral Evaluator or N.E. (who was either a geotechnical engineer, a structural engineer or a professional geologist) was assigned to the case to provide a third-party opinion to help resolve the dispute. The NE determines for themselves a cause of loss by reviewing all previously completed investigations from the site and if necessary conducting his/her own investigation including additional testing. Neutral Evaluation is mandatory if requested by either the insured or the insurer, and must be allowed reasonable access to the interior and exterior of the property. The evaluation is non-binding, but the NE may be brought into the courts in case the claim cannot be settled after the Evaluation.

Litigation

As with most property insurance claims that are disputed using the legal system in the US, most are settled out of court. However, there are many sinkhole claims still in the court system, and some still outstanding from before the rule change of 2011. The insured homeowner's attorney hires an engineer who says that the damage is related to sinkhole activity, and the insurance company has their own expert who says the damage is due to other causes. These cases are most often settled by jury decisions, and all things being equal, appear to strongly favor homeowners over insurance companies. Further, instead of being solved by science and fact, court cases are often solved on emotions or less than full understanding of the scientific issues.

ENGINEERING ASSESSMENT OF KARST SINKHOLE CAUSATION AND PREDICTION IN LITIGATION

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Abstract

Sinkholes in karst environments can cause damage to facilities and structures and pose a health and safety risk. The occurrence of sinkholes is difficult to predict and poses liability to planners, designers, owners, and engineers who practice in these areas. Often times the occurrence of sinkholes leads to litigation over who is responsible and who should have anticipated and designed mitigation to prevent consequences of sinkholes. Where performance does not meet with expectations, individuals are put at risk, or where damage occurs, litigation frequently ensues. The critical components of the litigation often revolve around causation, predictability, and cost to remediate and/or prevent future sinkholes.

Causation is important to identify responsible parties. Since the number of factors that influence the frequency, severity, and locations of sinkholes are many and involve geology, geotechnical engineering, surface water hydrology, and groundwater hydrology, a multidisciplinary approach is needed. A logical and prioritized basis is best to assess the relative merits of various mechanisms and determination of the one or two primary factors that either caused a condition to develop, or exacerbated an existing condition, and those factors that could reasonably have been anticipated using the appropriate standard of care. From an engineering perspective, it is essential to understand the causative factors to develop and estimate the costs for mitigation and restoration. The presentation will address the factors important to this assessment and approach to prioritization to deduce the key causative factors for covered carbonate karst. The presentation will also address the measures to identify the certainties and address the uncertainties in karst conditions for litigation.

Consequences of Unanticipated Karst

Litigation issues related to sinkholes in karst focus on their unanticipated occurrence. The potential impacts of unanticipated karst features are manifold. These include the potential for delays, and cost overruns where they are discovered in construction, as well as failures after construction that can cause a variety of damages including: property damage, injury, loss of use,

environmental damage and loss of life. Sinkholes can result in groundwater contamination with sediment, or releases of chemicals, extending broadly and widely. A sinkhole almost anywhere can be a safety hazard for injury or loss of life even in open fields. A sinkhole in a parking lot can damage automobiles, injure individuals, damage utilities and impair use of the property. A sinkhole forming under a structure results in loss of support for the structure that can lead to building damage or collapse. Even when karst conditions are known, specific occurrences may be unanticipated where investigations, assessments, and mitigations are not sufficient.

Uncertainty in Karst

Risk analysis has been applied to subsidence risk in karst (Kaufmann, 2008; Doctor et al., 2008, Perlow, 2008, Zisman, 2008, etc). Most of this type of work has been focused on development risk and not on identifying the specific risk of karst features being present at any specific location, though similar approaches can be used, provided sufficient site-specific data is available. There are a number of categories of uncertainty associated with the investigation and design for a successful project outcome. These can be divided into site uncertainties, methodological uncertainty and temporal behavior uncertainty.

For the purposes of this discussion, the term site uncertainties is defined as those unknown conditions present in the subsurface of the site that will affect the potential for sinkholes to form. Site uncertainties would affect the type and distribution of subsidence and the number of sinkholes that could be expected at a site and the decisions made to mitigate risk of sinkhole formation. The site uncertainties include site geologic variability, formational structural variability (i.e. the occurrence of fractures, folds or other features), the degree of weathering and karstification, the maturity of the karst, the presence of infilling, caves, etc., as well as, the depth and condition of soil overburden and the geo-hydrologic conditions.

Geology

Geological uncertainty relates to the nature of the formation as defined in geologic terms. That is the type

of rock, rock material properties. This occurs where the nature of the geologic formation is either not known, or poorly defined.

An example of this would be the situation where a formation is mapped that consists of alternating beds of differing rock types, without a defined sequence or where bedrock mapping is incomplete. Bedrock mapping is often incomplete where it is overlain by a thick mantle, or where surface geomorphology is not residual, such as where the karst stratum is overlain by alluvium, glacial deposits, or other such regolith that would mask the presence and nature of the underlying bedrock. This can obscure contacts between formations. Another instance of geologic uncertainty would be where complex faulting or folding results in local disruption of the regional geology that may not be completely mapped.

Structure

Structural uncertainty refers to uncertainty related to the geologic structure. This includes location and condition of joints, faults, as well as, voids in the bedrock formation which comprise the secondary porosity of the formation. Structural geology informs the search for voids, since solution is typically more pronounced in areas of higher

transmissibility where rock is fractured or broken and along discontinuities such as unconforming geologic contacts. Resolving or reducing structural uncertainty probably has the greatest impact on assessing sinkhole risks for a site.

Hydrology

Hydrologic uncertainty arises from complexity of groundwater flow in karst. The impact of groundwater hydrology on the environmental risks is profound; even a small opening can carry much flow (Fig 1). Hydrology of the karst is also critical where below-grade construction may penetrate the water table, since karst conduits can make many dewatering methods impractical. Likewise, surface water hydrology also presents uncertainties, since infiltration pathways for surface water may not be well known and will influence karst processes.

Geomorphology

Geomorphology is the study of the processes, characteristics and configuration and evolution of rocks and landforms. It is important to know what stage of the geomorphologic process the formation is in. Karstification is a geomorphologic process involving many stages from the initial dissolution of rock



Figure 1. Isolated karst conduit in otherwise intact rock

minerals, and formation weathering, to the erosion and infilling of voids, to the ultimate decomposition of the rock matrix. Understanding this process in a particular formation is necessary to assess whether voids are active conduits, plugged paleo-karst, or something in between. An excellent discussion of karst conditions and their formation is included in Waltham et al. (2005) and White (1988).

Investigation Methodology

The application of different methodologies will result in differing degrees of certainty when interpreting the results. If the geology, structure and geomorphology are sufficiently understood, appropriate investigational tools may be selected to assure the required information is obtained to assess the sinkhole risk at a site. It is critical to understand the limitations of the methods being used to properly assess the level of uncertainty with respect to the presence or absence of features. It is important to recognize that no method, short of complete removal of soil (regolith) over the top of rock, could fully disclose all openings in the top of rock.

Forensic Assessment

When a sinkhole has formed, some degree of uncertainty is removed, since the sinkhole itself provides evidence of subsurface conditions. Forensic studies usually include the following assessments:

- A. Condition and consequences
- B. Mitigation/repair
- C. Potential for recurrence
- D. Causation Assessment
- E. Responsible Parties

Forensic assessments are subject to all of the same limitation as any other investigation, though there are several advantages. Forensic investigators have the knowledge that something has indeed occurred, eliminating the need for speculation on the potential for something to occur. In litigation, the forensic investigator has the advantage of seeing all of the evidence revealed by the discovery process, providing a more circumspect view having information that may not have been available to all of the parties to the case. This can provide an improved picture, but will not remove all of the uncertainties outlined in the foregoing section. Regardless, it is important that the investigation extend beyond the limits of the sinkhole feature itself in order to establish the context and to provide a basis to assess what caused the sinkhole to open where it did and when it did. Investigation should assess a broad range of factors related to sinkhole causation including a thorough characterization of the surface and subsurface

conditions at the site, as well as, historical review to establish context in the timeline of events.

Definition of responsibility is probably the most difficult of all tasks. This assessment requires understanding of the standard of care. When it comes to karst, the standard of care can vary significantly from region to region and among the various disciplines involved in investigation, evaluation, and design in karst environments. Geologists, engineers, geophysicists, and hydrogeologists all look at karst from different perspectives. Often the lines of responsibility become blurred where one professional is relying on the work of another; such as an engineer basing a design on the work of a geologist, who in part forms his recommendations based on the work of a geophysicist. It is important to fully understand the relationships and responsibilities of the parties from a legal perspective and to understand the communications among the parties, as improper sharing of information is often a factor in these cases.

Finding Certainty in Karst

Resolving conflicts involving sinkholes in karst requires that the actions or inactions of the various parties be evaluated in light of the consequences they cause. Even where it is given that all karst features cannot be defined in covered karst, there remain actions that are certain to increase or induce sinkhole formation. The timeframe in the life of the karst formation is important to understand. In carbonate rock, active dissolution of the rock is usually not a consideration; whereas, in most instances openings are present within the carbonate rock below the regolith (soil overburden). At some point in the process, voids form in the regolith as soil grains are eroded and transported into the underlying voids.

Accordingly, there are three basic conditions that must exist to cause soil migration leading to the formation of collapse sinkholes in covered karst. These are: 1) hydraulic gradient sufficient to erode and transport soil, 2) pathways in the rock through which soil is transported, 3) place for transported soil to go. If any one of the three is missing, collapse sinkhole formation is improbable at best.

The regolith is eroded and transported by water. Water cannot erode or transport soil unless it is under a gradient that induces flow. Hydraulic gradients are the result of different water levels within the formation, but may be induced by manmade means through irrigation, modifying surface drainage, or altering groundwater levels through dewatering, or water injection. The highest gradients exist where water is free to fall under gravity. Such conditions exist where the static ground

water level is well below the ground surface and below the top of rock, where seepage of infiltrating water encounters a free surface of an unsaturated void. This condition leads to erosion of the soil grains at the free surface that progressively enlarges the cavity in a process known as piping. If all else is equal at a site, changes that lead to increased gradients, particularly through lowering of the static groundwater below the top of rock may nearly always be considered causative.

The absence of openings in the rock that serve as pathways for transport of material will preclude the formation of collapse sinkholes in covered karst. Obstructed openings will have a similar effect, but these can be cleared or flushed to open a pathway that was previously closed. Such can happen when excavations or mining operations expose the lower end of a filled karst feature and water seepage, either over time, or due to a sudden inflow that flushes the opening. The infilling material provides hydraulic resistance flattening the gradient due to its permeability. If it is removed, the gradient increases and can activate soil movement to enhance sinkhole formation.

Even if there is a gradient and pathway, there must be openings of a size equal to, or greater than, the volume of regolith that must be eroded to cause a sinkhole. Thus, small closed openings will fill and stop the process before collapse can occur. A manmade condition, such as where mining, or excavation exposes a karst feature or conduit, can create a new location for discharge and deposition of sediments carried by water flowing through the karst features. Such situations can be an incipient cause of sinkholes.

Assessing Causality and Responsibility

The first step in evaluating responsibility begins with reviewing the site investigations. Recognizing the uncertainties in karst, the key is not in determining whether all features were identified, but rather, were the karst conditions identified and associated risks explained. The adequacy of the investigation is also a factor, but depends on many factors related to contracting and communication. Investigation should be adequate to identify conditions necessary to assess the site conditions, but may be limited where karst is unanticipated, or where the full extent and nature of the project evolves after the initial investigation. Having a geologic, or geotechnical report that makes no mention of karst in a known karst area, generally increases the potential for karst liability for consultants.

It must be recognized that a few borings, or lines of surface geophysics, cannot prove that there is no sinkhole

risk. Proper use of the tools and interpretation of the results is essential to limiting professional liability in karst sites. Language that minimizes the consequences of karst without sufficiently detailed evaluation can open the door to design, construction, and land uses that induce sinkholes.

The second step is to assess whether appropriate measures were taken to mitigate the identified risks, or whether the owner of the project elected to assume those risks without mitigation. Sometimes, the clarity with which the risks are communicated becomes a significant factor in these cases. A project designer who ignores the karst related issues may well be assuming additional liability.

Even when all of the work on a project is done correctly, third party actions may cause or enhance the formation of sinkholes in covered karst. Identifying a manmade cause is essentially sorting out the activities undertaken by the various parties and assessing them in light of how they affected the sinkhole formation process. Such activities as installing a ground water supply well, tunneling, excavating a deep roadway cut, quarrying, and mining can alter the groundwater.

Evaluating causation is a multipronged process. There are always multiple factors that must work in concert for conditions to produce a sinkhole collapse. In some instances, comparison of conditions at one location to a similar site elsewhere may be considered to demonstrate either how an action either does or does not influence sinkhole occurrence. Extreme caution should be used when considering such an approach. While a site may look similar on the surface, many factors will make it differ. Karst in any location is unique. Differing factors may include:

- history of land use
- history of groundwater withdrawal
- stratigraphy
- faulting, fracturing, and bedding
- surface hydrology
- vegetation
- topography
- degree of karstification
- geochemistry
- groundwater hydrology

Any of these factors in itself or in combination with other factors can make a significant difference in the potential for sinkhole occurrence. All of the factors should be assessed before accepting another site as comparable.

A logical step-by-step approach is needed to assess cause and effect and to evaluate relative impacts. Time can be a measure of proof, where it can be shown that a sinkhole event is closely timed to a particular action, however, it

is also necessary to define the causative link in technical terms. It is extremely difficult to isolate one sinkhole occurrence and identify unique causation for it where multiple sinkholes have occurred in the surrounding area over time, independent of a specific cause. However, if sinkholes begin to form after an event that changes conditions to enhance sinkhole formation, there will be a better case to establish causation. A legal basis can be made where it can be shown, that but for a specific event, such as groundwater level depression or surface water diversion, sinkholes either would not have occurred, or would have been far less likely.

Standard of Care

The value of a prediction depends on the skill and care exercised in preparing the prediction. When the predicted behavior does not occur, negligence of the professional may be the basis of a litigation. The basis for establishing negligence in a tort case is based on a failure to exercise the care and skill that is ordinarily exercised by other members of the engineering profession in performing professional engineering services under similar circumstances (Dal Pino 2014). This is often referred to as the standard of care.

Establishing the standard of care in karst conditions can be challenging, since geologists and engineers often have different perspectives and some practitioners in karst have widely differing views on assessing and mitigating karst conditions. This interdisciplinary nature of karst makes the establishment of a single standard difficult.

Local practices differ from state to state and region to region based on local experience. Some geotechnical consultants involved in a karst project may have limited experience and may not have the depth of knowledge necessary to properly assess conditions, while others may have extensive depth of experience and capability. Despite following the standard of care they would normally use for other projects, different outcomes may be achieved. This raises the question as to when specialty services are required. The complexity, which can be much greater than typical sites, and the level of knowledge of geology and hydrogeology, require an understanding and application of fundamental soil mechanics at a higher level than would be typical of common practice. Specialists and experts are held to a different standard that is based on the performance of reasonable experts rather than common practice.

The fundamental question regarding the standard of care relates to the requirement that the comparison be made for “similar circumstances”. The high variability within karst automatically makes it different from most other

geologies and makes it difficult to assess what comprises care and skill that are ordinarily practiced. The standard of care is assessed state by state in rules, regulations and legal precedents and is not uniform nationwide.

Assessing a case with regard to compliance with the standard of care is especially challenging and requires special evaluation to establish the appropriate standard of care. It is important to define the role of the consultant(s) and review local and regional practices, as well as state requirements. Once these have been established, a comparison can be made for initial assessment. Detailed evaluation of contracts, correspondence, reports, and other communications is necessary to shed light on the roles played by the parties to a case and to improve the initial assessment.

A further complication in assessing negligence, is that the project facts and sequence of events can affect the roles of the parties as the project progressed. Predictions and decisions that appear reasonable at the time they were made, may be changed by new conditions disclosed at a later time. Seemingly simple changes to a site plan, such as relocating stormwater structures, can greatly affect the risk of sinkhole occurrence in a way not anticipated by the geotechnical engineer and unknown to the civil designer. Such situations can lead to defective performance even though both parties performed within their respective standard of care. Such instances illuminate the need for good communications of the nature of the risks throughout a design team that can be thwarted by the compartmentalized design and construction processes used on many projects.

Specialties in Conflict

Even given the same circumstances, geologists and engineers will often come to different conclusions. Geologists are scientists and base their recommendations on their experience and scientific judgement. Engineers work in applied science and base their recommendations on engineering design principals. While the two approaches may lead to consistent recommendations in some cases, but in others, they may not. Engineers are knowledgeable in geotechnical, structural, and construction aspects of the work that geologists are not. On the other hand, geologists may have specific knowledge about geologic structure, geomorphology, and hydrogeology that many engineers may not. In truth, neither can know the whole picture without input from the other.

Often, owners and developers will select the recommendation that leads to the outcome they desire and will tend, when given a choice, to select the

consultant that tells them what they want to hear. This is especially important where the recommendation will cost a lot of money.

Roger Brucker is a noted cave explorer and karst cave expert. In a 2014 article in *GeoStrata* magazine (Brucker, 2014), he cites a case where an expert warned of an underground karst cave and recommended routing a roadway around the area of thin roof rock. The developer ignored that recommendation, and constructed the road over the cavity that subsequently collapsed. At the conclusion of the article Mr. Brucker eschews mitigation measures and recommends avoiding development on karst altogether, while clearly that was not the recommendation of the developer's consultant. If one expert's recommendation is avoidance and another expert's recommendation is mitigation, or even normal practices with no special measures, the client is left to choose who to believe.

A team approach can resolve this. In karst work that the author has performed, both a karst geologist and a geotechnical engineer are typically included as a team. This approach gives the best of both disciplines and is essential to get a complete picture. Defining the cause of a sinkhole is dependent on understanding the geology and engineering measures taken in the process to determine who or what may be at fault.

Conclusion

Evaluating karst requires special knowledge and attention to detail to identify and characterize the mechanisms at work at a given site. It is not necessary to eliminate all uncertainties in the site conditions for a forensic assessment of causation in karst. It is only necessary to characterize conditions sufficiently to identify key factors that affect hydraulic gradients, pathways, and discharge of sediment. Establishing a traceable link from a specific action to changes in these factors is the primary basis to establish a causal relationships to that action. The causative action can be anything such as relocating a stream, actively withdrawing ground water, mining, site development, etc. Identification of the effects of the action, either directly or indirectly, and relating them to the key factors in sinkhole formation, can be the basis to establish causation, or demonstrate the irrelevance of an action. A team including an engineer and geologist can provide the best approach to investigation and evaluation of sinkhole occurrence and causation.

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USING STABLE ISOTOPES TO DISTINGUISH SINKHOLE AND DIFFUSE STORM INFILTRATION IN TWO ADJACENT SPRINGS

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Abstract

Two karst springs, Tippery Spring and Near Tippery Spring, have similar discharges ($\sim 0.1 \text{ m}^3/\text{s}$, 5 cfs) and are only 30 meters apart, yet they show unique behaviors in terms of water chemistry and discharge response to storms. Near Tippery has higher Mg/Ca ratio and Tippery Spring has more variable temperature response to storm events. This contrast was further extended to differences in recharge pathways based on stable isotope analysis (δD & $\delta^{18}\text{O}$) of spring water samples collected using ISCO automated samplers during a May (3 cm, 1 inch) storm and June (8 cm, 3 inch) storm in 2017.

Increased spring discharge preceded the arrival of storm water as conduits were purged of pre-storm water, indicated by no change in isotopic composition on the rising limb. The isotopic signature then became progressively more enriched at both springs, indicating storm water recharge. At Tippery, this enrichment began around peak flow, sooner than at Near Tippery where enrichment began during the descending limb. Thus, isotopes indicated a stronger surface connection at Tippery. Storm water recharge at both springs then progressed to a greater relative fraction of total discharge before recovering to pre-storm values within 24–36 hours. Storm intensity also affected the relative contribution of recharging water reaching both springs, with the June storm producing a larger recharge signature compared to the May storm. At Tippery, for a short time the majority of emerging water is storm water, with the absolute pre-storm contribution falling below its baseflow value. This reduction in pre-storm water may indicate a reversal in water exchange between the conduits and the surrounding matrix, an important consideration in karst contaminant transport.

While both springs can be traced to sinks, their isotopic signatures reflect how storm water infiltrates and travels within each spring's recharge area. Tippery is fed by a perennial sinking stream and more developed conduit network, while Near Tippery has a more diffuse recharge area with mixing of different surface inputs. As stable isotopes are unaffected by redox or dissolution processes, they can provide a conservative tracer with which to characterize how other parameters, such as temperature, alkalinity, and turbidity, are reflected in different spring recharge behaviors.

Introduction

Background

Water emerging from a karst spring is a mixture of different sourced waters within its recharge area and along the flow path (Ford & Williams, 1989). When surface connections are strong and travel times are short, spring water composition will be variable in response to recharge events. Since recharging water interacts with the surrounding rock as it travels along conduits, temperature can be used as a reactive tracer providing information about karst structure and recharge characteristics (Covington et al., 2011; Luhmann et al., 2011). Different thermal patterns develop as a result of the effectiveness of heat exchange between water and rock between a spring and its recharge area. When the surface temperature signature is preserved at the spring mouth, heat exchange is thermally ineffective, indicating rapid recharge, short flow paths, or large conduits. In contrast, springs with constant temperatures show thermally effective heat exchange, indicating more diffuse recharge, slow groundwater flow, and longer flow paths.

When stable isotope compositions of the recharge and waters along the flow path are distinctly different, then a hydrograph separation can be performed through an end-member mixing analysis. In the simplest two end-member scenario, spring water can be divided into pre-storm water and storm water (Lakey & Krothe, 1996; Fredrickson and Criss, 1999). As real systems may be a mix of more than two sources, such as perched epikarst water (Perrin et al., 2003; Aquilina et al., 2005), three and four component scenarios have also been explored (Lee & Krothe, 2001). Thus, both geochemical and thermal signatures of water at a spring reveal information about recharge sources and the travel path.

This study aims to contribute to the growing body of karst isotope hydrology through a comparison of isotopic storm responses between two adjacent springs. Because the adjacent springs receive recharge of the same isotopic composition, the resulting differences in isotope hydrographs are used to contrast recharge and flow paths. Not only can the flow paths feeding the springs be compared, but also contrasted from storm to storm due to antecedent moisture and rainfall intensity differences. Furthermore, the timing of the surface water component based on isotopes relative to other constituents (dissolved ions, sediment) provides insights into flow path length and mixing.

Study Site

Tipperry Spring and Near Tipperry Spring emanate from folded Ordovician dolomite (Berg, 1980). Due to topography and folding, several formations are exposed within each spring's estimated recharge area, transitioning uphill to limestone, shale, and then sandstone. Four local sinkholes occur near the contact between the shale and limestone, roughly half a mile to the northwest of the springs. Three of the sinkholes have been traced to Tipperry Spring, while the remaining sinkhole has been traced to Near Tipperry Spring (Hull, 1980). The two springs are at an elevation of 270 m (900 feet) MSL, and the sinkhole elevations are from 304–324 m (1000–1030 feet) MSL, with total relief of 400 m (1300 feet) within the springs' estimated recharge areas.

Of the three sinkholes traced to Tipperry Spring, one is fed by a perennial stream which completely submerges at the sink, referred to here as Tipperry Sink. The sinkhole traced to Near Tipperry Spring does not have an associated perennial stream. Based on the dye traces,

no crossover flow was apparent between each spring's delineated recharge area as each sinkhole traces to just one spring or the other. Although both springs emerge from the dolomite, the flow path between Tipperry Spring and its three associated sinkholes is largely within the limestone unit, while Near Tipperry Spring's flow path is within both the limestone and the dolomite (Figure 1).

Tipperry Spring and Near Tipperry Spring are less than 30 meters apart and emerge at similar baseflow discharge ($\sim 0.1 \text{ m}^3/\text{s}$; 5 cfs), but show historical differences in seasonal water chemistry, such as slightly greater seasonal variation in temperature at Tipperry Spring (Figure 2) and a higher Mg/Ca ratio in Near Tipperry Spring (Shuster & White, 1971). More recent research with high-resolution discharge monitoring has further explained these behavioral differences (Herman et al., 2009).

Expanding on the observed seasonal temperature behavior of the two springs is more recently observed behavioral differences in temperature response after a storm (Figure 3). Tipperry Spring tends to have a flashier thermal response, while Near Tipperry Spring's response

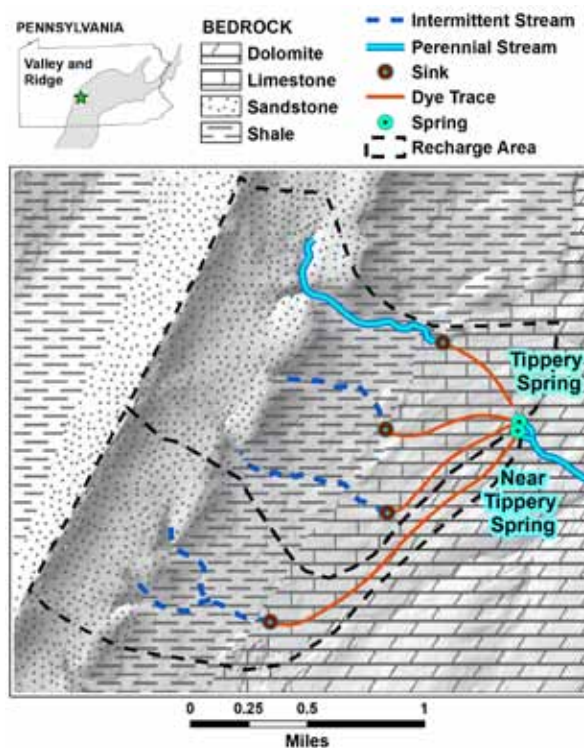


Figure 1. Location of Tipperry Spring and Near Tipperry Spring. Geology and hydrography data from Pennsylvania Spatial Data Access (PASDA).

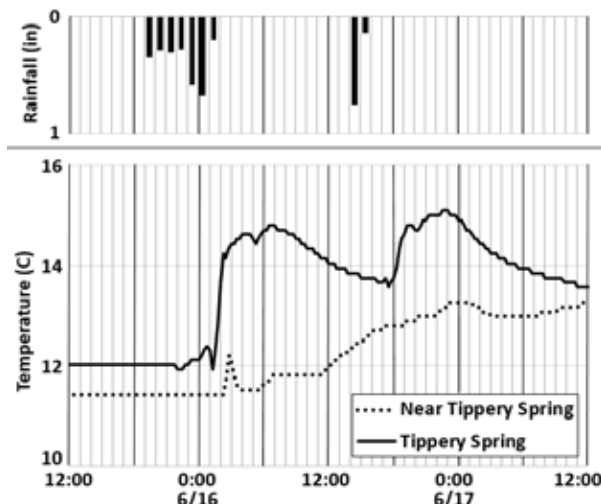


Figure 2. Seasonal temperature patterns from bi-weekly sampling for Tippery Spring and Near Tippery Spring, after Shuster & White (1971). While both springs show seasonal variation, indicating surface influence, Tippery Spring more closely follows seasonal extremes, indicating a greater degree of surface influence.

is more delayed and buffered. As Tippery Spring and Near Tippery Spring's recharge areas receive rainfall simultaneously from the same events, these thermal variations can be attributed to differences in the springs' surface connectivity and conduit geometry. For Tippery Spring, this suggests a stronger surface connection and a well-developed conduit network between surface and spring. For Near Tippery Spring, this suggests a dampened surface connection and greater water-rock interaction due to the greater degree of thermal diffusion.

These behavioral differences provide an opportunity to further assess the use of stable isotope variations for karst springs. While temperature variations suggest differences in recharge behavior between the two springs, variations in isotopic composition can further quantify these differences as they act as conservative tracers to study the timing and contribution of the isotopically distinct water sources. For Tippery Spring, this would be represented with a more dominant storm water signal. For Near Tippery Spring, this would be represented with a more buffered storm water signal.

Methods

Water samples were collected as grab samples during field visits and with ISCO 3700 auto-samplers triggered from rising spring water level in response to storms. The ISCO auto-samplers fill 24, 1-liter, acid-washed

bottles over the course of 24 hours, beginning with a high sampling frequency (every half hour) followed by decreasing frequency (every 2 hours). Bottles were retrieved within 12 hours after the storm ended, filtered with 0.45 μm nitrocellulose paper, and refrigerated in headspace-free bottles.

Spring water level and temperature were recorded with Onset HOBO pressure loggers at 15-minute intervals. Pressure was converted to water depth and corrected for logger placement, resulting in water depth of the pool at the mouth of each spring. Local precipitation data was recorded using a HOBO rain gauge data logger. pH was recorded using Manta2 data loggers at 15-minute intervals and during field visits with an IQ Scientific Instruments IQ150 meter with a Thermo Scientific Orion 9106BNWP pH electrode.

Samples were analyzed for $^{18}\text{O}/^{16}\text{O}$ and D/H isotope ratios using a Laser Water Isotope Analyzer V2 (Los Gatos Research, Inc., Mountain View, CA, USA at the UC Davis isotope laboratory) and reported relative to Vienna Standard Mean Ocean Water (VSMOW). These values are reported in delta (δ) notation in parts per thousand (permil) such that

$$\delta(^{18}\text{O}, \text{D}) = \left(\frac{R_M - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right) \times 1000 \quad \text{Eq. 1}$$

where R_M is the ratio of $^{18}\text{O}/^{16}\text{O}$ or D/H in the water sample R_{VSMOW} is the ratio of $^{18}\text{O}/^{16}\text{O}$ or D/H in the VSMOW standard.

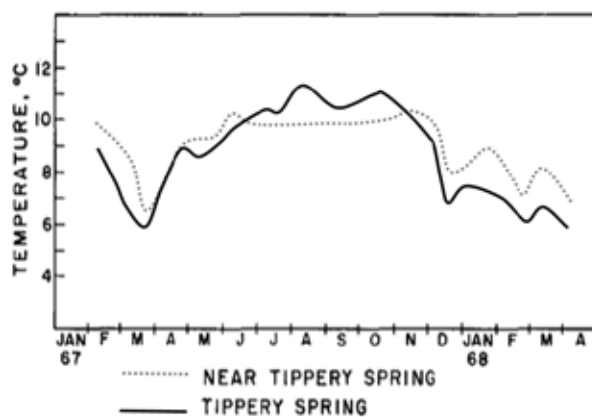


Figure 3. Temperature response at Tippery Spring and Near Tippery Spring in response to a June 2017 storm as part of this study. Vertical grid has a one-hour minor interval and six-hour major interval. Note the flashier response of Tippery Spring relative to Near Tippery Spring, indicative of a stronger surface connection.

Stable isotope data for rainwater were available for 2009–2011 from the nearby Shale Hills Critical Zone Observatory approximately 25 km from the springs (Duffy and Thomas, 2011). Precipitation was collected from the ridge top in the SHCZO using an event triggered sampler and analyzed at Penn State University.

Additional parameters, such as turbidity, total dissolved solids (TDS), and alkalinity were also measured to interpret the arrival of storm pulses. Turbidity was estimated using digital photometry as samples stored in transparent bottles showed visible turbidity pulses in response to the storms. Sample bottles were photographed while the sediment was suspended, converted to grayscale images, and the relative luminosity was measured digitally (Figure 4). TDS was calculated from ion concentrations measured with a Thermo Scientific iCAP 7200 inductively coupled plasma optical emission spectrometry (ICP-OES) analyzer and a Dionex ion chromatography (IC) analyzer and checked against specific conductance measured with an Exttech Instruments 407313 conductivity meter. Alkalinity was measured with a Hanna Instruments HI 775 alkalinity colorimeter.

Sampled Storm Events

1-inch Storm (May 4–7, 2017)

A 1-inch storm lasting 7 hours fell on the study site on May 4, 2017 (Figure 5). Preceding this storm, water level was 27 cm at Tippery Spring and 21 cm at Near Tippery Spring, slightly elevated compared to their annual average values of 18 cm and 15 cm, respectively. Two days prior, the site experienced a slight drizzle (1 cm, <0.5 inch). Slightly wet antecedent conditions prevailed, resulting in the initially elevated flow conditions, although water level was essentially stable at the time.



Figure 4. Visual turbidity change in Tippery Spring water samples capturing the storm pulse as it reached the spring. Increased turbidity resulted in darker bottles and therefore a lower pixel luminosity. Shown: May storm samples from 5/5/17 6:00–20:00.

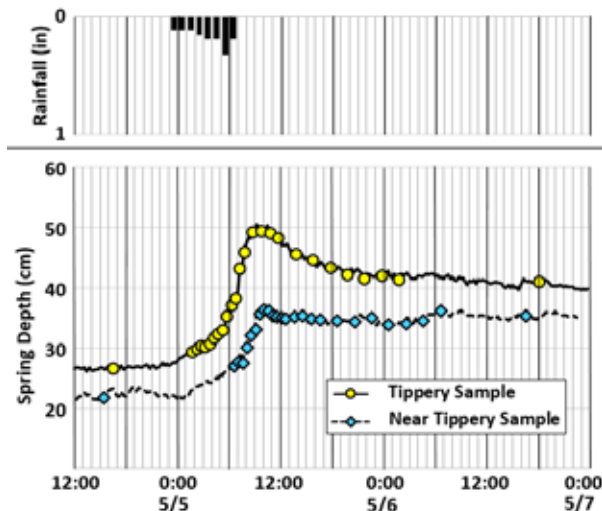


Figure 5. Rainfall, storm hydrograph, and sampling times for Tippery Spring and Near Tippery Spring, May 4–7, 2017. Vertical grid has a one-hour minor interval and six-hour major interval.

Grab samples were collected from both springs and the Tippery Sink 9 hours before the start of rainfall on May 4, 2017. The ISCO auto-samplers were activated at Tippery Spring and Near Tippery Spring 3 and 7 hours after the start of rainfall, respectively. Both ISCOs collected 24 samples across the rising limb, peak, and falling limb (Figure 5). Follow-up grab samples were collected at the springs about 12 hours after the end of the 24-hour ISCO sampling period.

3-inch Storm (June 14–17, 2017)

A 3-inch storm began to fall on the study site on June 14, 2017. This rainfall was divided in two pulses; the initial rainfall on June 14, which totaled two inches over 7 hours, and a second, smaller 1-inch pulse on June 15, which lasted for 2 hours. Both rainfall pulses resulted in distinct water level responses at both springs. Preceding rainfall, water level was 20 cm at Tippery Spring and 15 cm at Near Tippery Spring. These levels were similar to their average annual values of 18 cm and 15 cm, respectively. No rainfall events had occurred within two weeks prior. Dry antecedent conditions prevailed, resulting in the initially low flow conditions.

Grab samples were collected at each spring and Tippery Sink both 9 and 11 days before rainfall. The ISCO auto-samplers were activated at Tippery Spring and Near Tippery Spring 4 hours and 6 hours after the start of rainfall, respectively. Both auto-samplers collected a

total of 24 samples across the rising limbs, peaks, and descending limbs of both storm pulses (Figure 6).

Results

Samples vs. Local Meteoric Water Line

From 2008–2012, local springtime precipitation isotopic composition varied from -100‰ to 7‰ δD with a volume-weighted mean of -26.1‰ δD , and $\delta^{18}\text{O}$ varied from -11‰ to 1‰ $\delta^{18}\text{O}$ with a volume-weighted mean of -4.5‰ $\delta^{18}\text{O}$. Pre-storm (baseflow) isotopic values, determined from pre-storm influence samples, were similar between both springs and for both storms, at $-54.61 \pm 1.22\text{‰}$ δD and $-8.62 \pm 0.36\text{‰}$ $\delta^{18}\text{O}$, which were similar to the volume-weighted annual means of precipitation values of -57.35‰ δD and -8.71‰ $\delta^{18}\text{O}$ at the Shale Hills CZO (Figure 7). In response to the May storm, Tippery and Near Tippery's isotopic compositions were temporarily perturbed to maximum values of -49.54‰ δD & -7.64‰ $\delta^{18}\text{O}$, and -49.19‰ δD & -7.98‰ $\delta^{18}\text{O}$, respectively, before returning to baseflow values. Following the June storm, Tippery and Near Tippery's compositions were temporarily perturbed to maximum values of -36.52‰ δD & -6.52‰ $\delta^{18}\text{O}$, and -39.87‰ δD & -6.72‰ $\delta^{18}\text{O}$, respectively. All spring samples from the storm events plotted near the weighted Local Mean Water Line (Figure 7). Since the isotopic compositions of pre-storm and storm water differed but followed a mixing line, a binary mixing analysis, along with spring depth, allowed for characterization of the

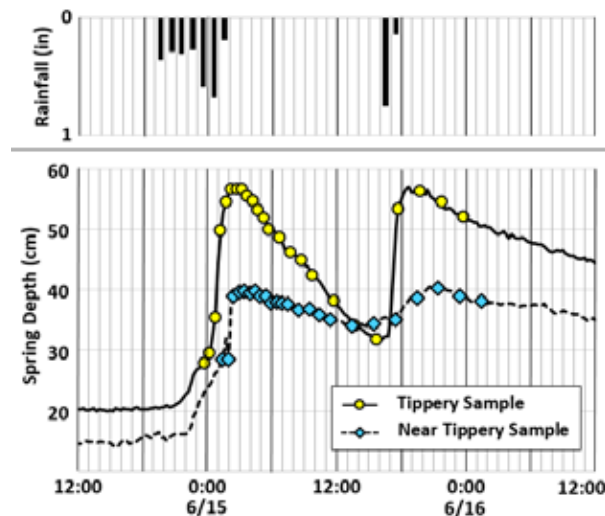


Figure 6. Rainfall, storm hydrograph and sampling times for Tippery Spring and Near Tippery Spring, June 14–17, 2017. Vertical grid has a one-hour minor interval and six-hour major interval.

timing and relative contribution of each component emerging from the springs.

Hydrograph Separation

Assuming a two end-member mixing model, storm water in the pre-storm water components can be separated as a binary mixing model

$$Q_R = Q_M \frac{(\delta_M - \delta_{PS})}{(\delta_R - \delta_{PS})} \quad \text{Eq. 2}$$

where Q_R is the fraction of discharge which is storm water, Q_M is the discharge at the time of sample, δ_M is the measured isotopic composition of spring water, δ_{PS} is the isotopic composition of pre-storm spring water, and δ_R is the isotopic composition of the storm water. Pre-storm spring water (δ_{PS}) values were determined from baseflow samples prior to storm response. Storm water values (δ_R) were based on average values for spring precipitation (Duffy and Thomas, 2011). A summary of isotopic values is provided in Table 1.

Applying Equation (2) to the measured isotopic composition and spring depth for each sample results in a storm hydrograph, showing the relative contributions of pre-storm water and storm water throughout the hydrograph. As direct discharge values were not

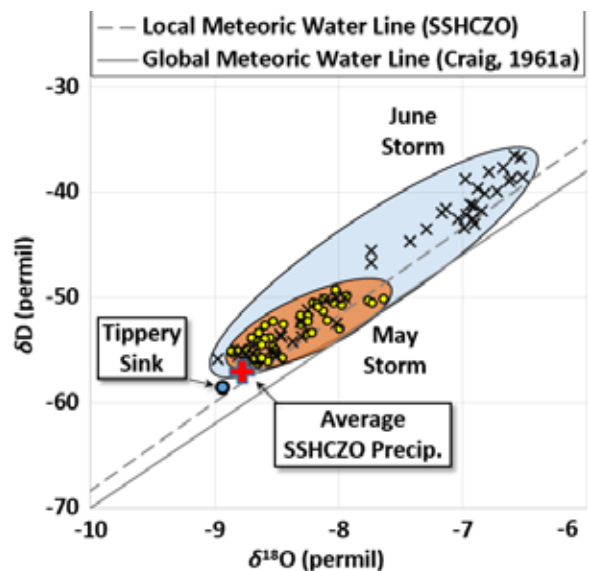


Figure 7. Storm sample isotopic composition. May (1-inch) storm values (yellow circles) highlighted overall by the orange oval. June (3-inch) storm values (black X's) highlighted by the blue oval. Unique symbols for each spring were not plotted due to the strong overlap in values.

Source	Parameter	$\delta D\text{‰}$	$\delta^{18}O\text{‰}$
SHCZO (2008-2012)	Mean Spring Precipitation (δ_R)	-26.10	-5.50
May 2017 Storm (1-inch)	Tipperry Spring, pre-storm (δ_{PS})	-55.00	-8.80
	Tipperry Spring, maximum response	-49.54	-7.64
	Near Tipperry Spring, pre-storm (δ_{PS})	-55.00	-8.54
June 2017 Storm (3-inch)	Near Tipperry Spring, maximum response	-49.19	-7.98
	Tipperry Spring, pre-storm (δ_{PS})	-55.00	-8.80
	Tipperry Spring, maximum response	-36.52	-6.52
	Near Tipperry Spring, pre-storm (δ_{PS})	-53.50	-8.55
	Near Tipperry Spring, maximum response	-39.88	-6.72

Table 1. Summary of isotopic values.

obtained for each spring, water level at the spring mouth was used instead. Given that an average storm isotope composition was used, rather than actual storm values, there is some uncertainty in the calculations. The range in seasonal isotopic composition suggests about 5% uncertainty for the May storm and 10% for the June storm due to a higher storm water component.

May (1-inch) Storm Hydrographs

Tipperry Spring's water level began to rise 2 hours after the start of rainfall, from 27 cm to 50 cm over the course of 9 hours (Figure 8). Isotopic composition of spring water showed no significant change throughout the rising limb, with the first indication of storm water arriving just before peak flow. Relative contribution of storm water increased during the descending limb, reaching a maximum component of 20%. This component then decreased, returning to 0% 24–32 hours after sampling began and 26 hours after the start of rainfall. This isotopic recovery occurred despite the lack of water level recovery to pre-storm levels.

Near Tipperry Spring's water level started to rise 3 hours after rainfall began (Figure 9). Water level rose gradually from 21 cm to 35 cm over the course of 9 hours. Spring water isotopic composition first showed indications of mixing just after peak flow and lasting for several hours. Spring water at this time was more depleted in δD and $\delta^{18}O$ relative to pre-storm water, despite the storm water being more enriched. Spring water composition eventually shifted towards enrichment 6 hours after peak flow, indicating the arrival of storm water, which increased progressively to a relative component of 10% around 12 hours after peak flow. The storm water component then decreased to near pre-storm levels by the collection of the grab sample 10 hours after the last ISCO sample was collected. Despite the isotopic composition returning to near pre-storm values during

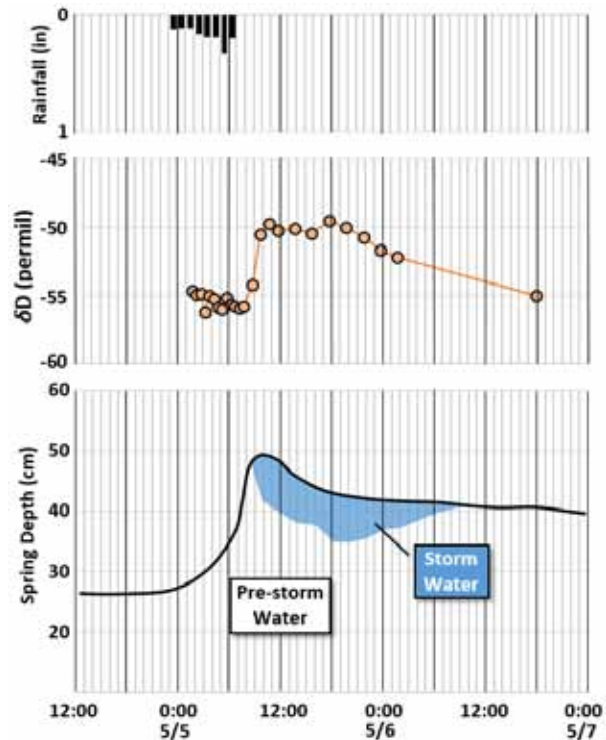


Figure 8. Tipperry Spring, May (1-inch) Storm, rainfall, δD values, and spring hydrograph with pre-storm and storm water separation. Vertical grid has a one-hour minor interval and six-hour major interval.

the May storm at Tipperry Spring, spring water level did not return to pre-storm levels, which was the case for both springs during both storms.

June (3-inch) Storm Hydrographs

Tipperry Spring's water level began to rise 2 hours after rainfall began, rising sharply from 20 cm to 57 cm over the course of 6 hours (Figure 10). Similar to the May storm, spring water showed no significant isotopic change throughout the rising limb, with the first indication of storm water arriving just before peak flow. Relative contribution of storm water then increased during the descending limb, reaching a maximum relative component of over 60% halfway through the descending limb. Before water level and isotopic composition could recover to pre-storm levels, the second storm pulse arrived, raising water level and again increasing the relative contribution of storm water. Full recovery was not observed before the end of the 24-hour water sampling period.

Near Tipperry Spring's water level began to rise 4 hours after the start of rainfall. Water level rose from 14 cm

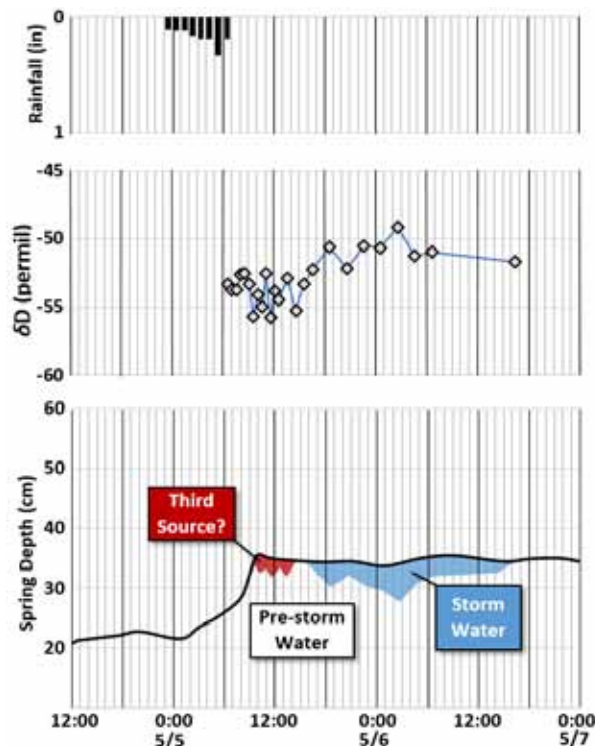


Figure 9. Near Tipperary Spring, May (1-inch) Storm, rainfall, δD values, and spring hydrograph with pre-storm and storm water separation. Vertical grid has a one-hour minor interval and six-hour major interval.

to 40 cm over the course of 8 hours (Figure 11). Spring water isotopic composition first indicated mixing with a depleted isotope signal which lasted for 2–3 hours during peak flow before returning to an unmixed signal. This short-lived mixing signature shared a similar timing as the May storm, although it showed an isotopic depletion during the May storm and isotopic enrichment during the June storm.

As spring water level began dropping, the storm water signal appeared, increasing gradually to a 53% relative component 14 hours after peak flow. Around this time, the second rainfall pulse occurred and, although this raised the water level again (from 34 cm to 40 cm), there was no change in isotopic composition for the remainder of sampling. Neither water level nor isotopic composition recovered by the end of the 24-hour sampling period.

Additional Parameters

In addition to stable isotopes, water samples were also analyzed for TDS and alkalinity along with visual turbidity changes. Although each spring showed notable changes to these parameters in response to storms, the

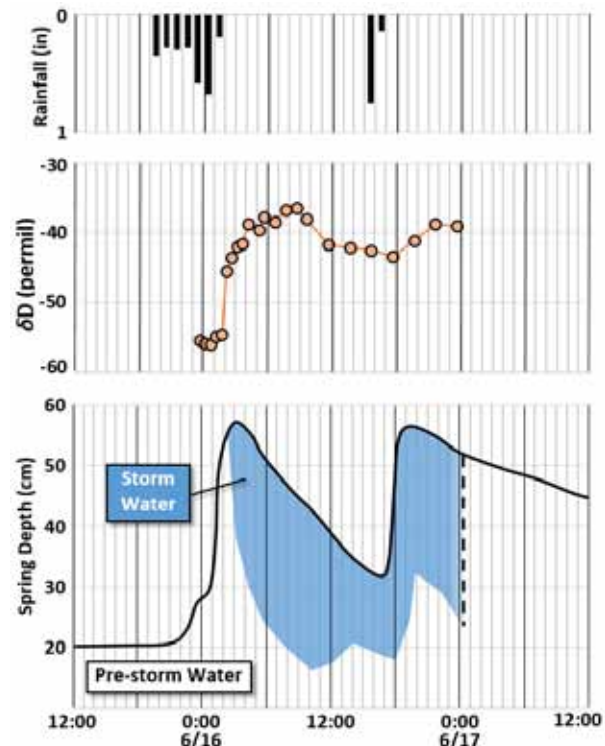


Figure 10. Tipperary Spring, June (3-inch) Storm, rainfall, δD values, and spring hydrograph with pre-storm and storm water separation. Vertical dashed line indicates end of sampling. Vertical grid has a one-hour minor interval and six-hour major interval.

timing and scale of these changes reflected the distinct behavior of the two springs and the two storm events.

May (1-inch) Storm Ions and Turbidity

Tipperary Spring's ion chemistry and turbidity reflect the influence of storm recharge in relation to water level (Figure 12). TDS and alkalinity showed a similar trend. Initially during the rising limb, little change was seen in TDS. Just before peak flow, a spike in values occurred followed by a rapid decrease in concentration, and a plateau at a lower concentration over the falling limb of the hydrograph. This spike occurred at the onset of storm water as indicated by the stable isotopes.

Turbidity also responded to the arrival of surface water, but with a slower recovery than TDS and alkalinity. No turbidity change was observed during the rising limb, with the first increase occurring at the onset of the storm water signal near peak flow. Turbidity then rose sharply, reaching peak turbidity 3 hours after peak flow before gradually returning to baseflow turbidity by the end of sampling.

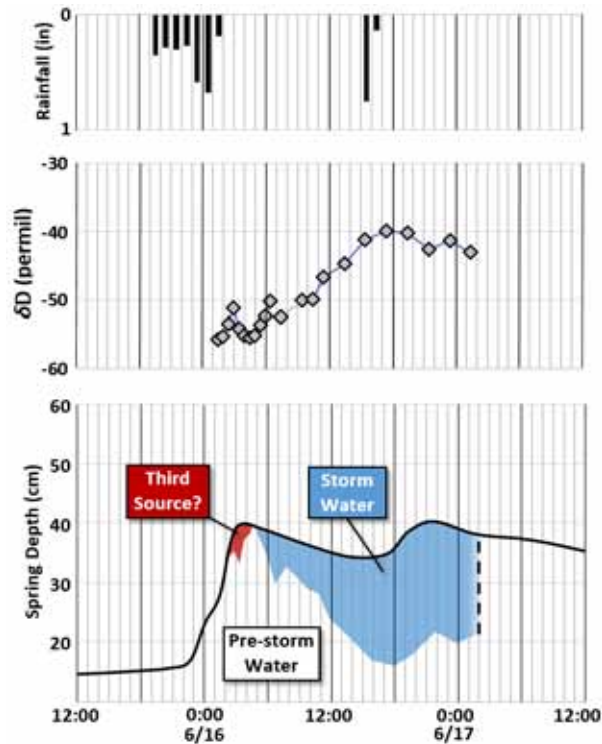


Figure 11. Near Tippery Spring, June (3-inch) Storm, rainfall, δD values, and spring hydrograph with pre-storm and storm water separation. Vertical dashed line indicates end of sampling. Vertical grid has a one-hour minor interval and six-hour major interval.

Near Tippery Spring's ion chemistry and turbidity response to the May storm highlights differences between how these two springs behave, most notably the initial response and the relation of values to peak flow. Similar to Tippery Spring, Near Tippery Spring showed little change during the gradual rising limb. The first changes occurred around peak flow and the onset of a mixed water source as indicated from the isotopes (Figure 13). Unlike Tippery Spring, this first mixed water source corresponded to a decrease in TDS, alkalinity, and turbidity, which lasted for several hours. As this source then gave way to the storm water signal, TDS and alkalinity values not only recovered, but increased beyond pre-storm values, reaching peak concentration 6 hours after peak flow. Turbidity also recovered and increased beyond pre-storm values, reaching peak turbidity nearly 12 hours after peak flow. TDS, alkalinity, and turbidity then gradually recovered to pre-storm values by the end of sampling.

June (3-inch) Storm Ions and Turbidity

Tippery Spring's response to the June storm showed a similar behavior to the May storm; an initial

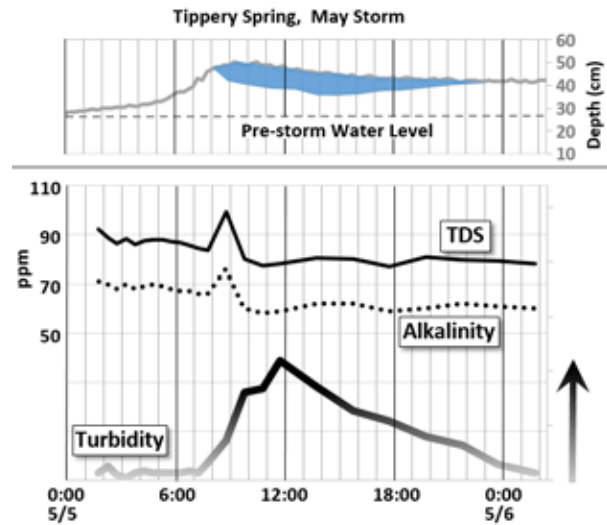


Figure 12. Tippery Spring, May (1-inch) Storm parameters in addition to separated hydrograph: Total dissolved solids (TDS), alkalinity, and turbidity. Turbidity values were determined semi-quantitatively from photographic black and white luminosity values of bottles (Figure 4), with darker bottles having a lower luminosity and higher turbidity as shown by increase in intensity along the graphed line. Vertical grid has a one-hour minor interval and six-hour major interval.

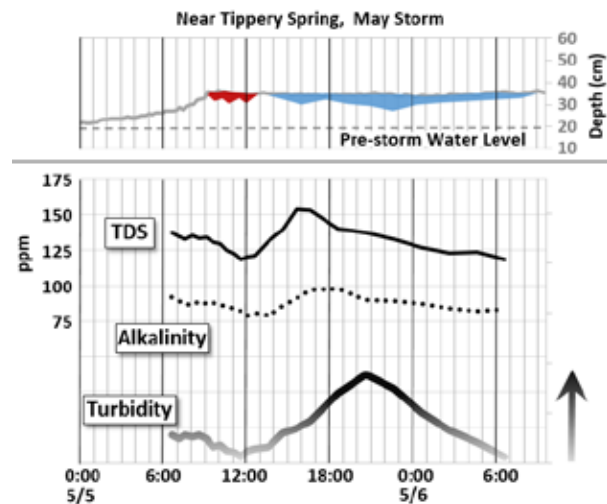


Figure 13. Near Tippery Spring, May (1-inch) Storm additional parameters in relation to rainfall and spring water level: TDS, alkalinity, and turbidity. Vertical grid has a one-hour minor interval and six-hour major interval.

spike, followed by a decrease in TDS and alkalinity corresponding to the onset of storm water around peak flow (Figure 14). The increase in turbidity again lagged behind the TDS peak. This pattern repeated during the second storm pulse during the June storm, indicating the behavior occurs irrespective of antecedent conditions.

Although the second storm pulse produced a similar rise in water level compared to the first pulse, it did not produce an equivalent change in TDS, alkalinity, and turbidity. These additional parameters did not return to pre-storm levels by the end of sampling.

Near Tippery Spring's TDS response to the June storm was more complex than the response for the May storm. TDS values fluctuated ± 50 ppm, while alkalinity values were steady until 5–6 hours after the first indication of storm water. At this point, alkalinity concentration gradually dropped by 60 ppm over 6 hours before returning to pre-storm levels (Figure 15). Although the second storm pulse produced a subsequent water level rise, it did not produce an apparent change in TDS and alkalinity.

Near Tippery Spring's turbidity response during the June storm was also more variable, with several peaks occurring throughout the sampling period. Turbidity initially rose sharply during the rising limb, but then dropped after the onset of the potential third source

around peak flow. Turbidity then rose again at the onset of storm water, and gradually decreased throughout the rest of the sampling period. TDS, alkalinity, and turbidity all returned to values similar to the pre-storm values by the end of sampling.

Discussion

Water level change, stable isotope chemistry, ion chemistry, and turbidity were all affected by storm intensity. Antecedent conditions prior to each storm also affected initial concentrations and water levels. The recharge style of each spring, first noted from prior research, was further described through high-resolution water sampling.

Effect of Antecedent Conditions, Storm Intensity, and Spring Recharge Style on Spring Response ***Antecedent Conditions***

For the May storm, antecedent conditions at both springs were marked by elevated water levels and decreased ion and alkalinity concentrations due to the recent rainfall a few days before sampling. For the June storm, antecedent conditions at both springs were marked by lower water levels and increased ion and alkalinity concentrations due to the lack of recent rainfall. Despite the greater rainfall and greater increase in water level during the June storm, water level response began later than for the May storm. This lag was likely due to the soil moisture deficit from dryer antecedent conditions.

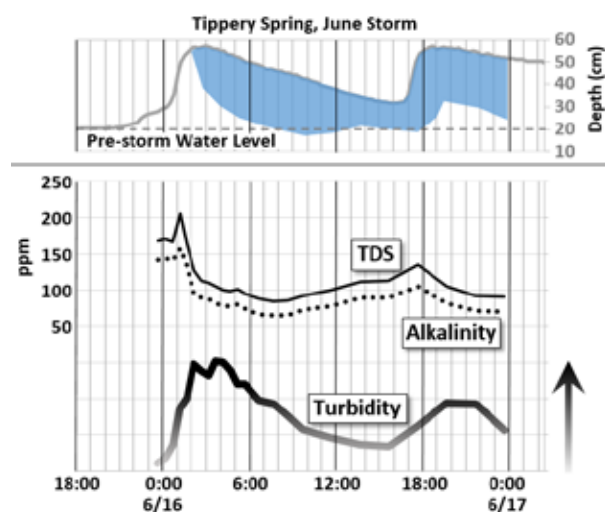


Figure 14. Tippiery Spring, June (3-inch) Storm additional parameters in relation to spring hydrograph: TDS, alkalinity, and turbidity. Vertical grid has a one-hour minor interval and six-hour major interval.

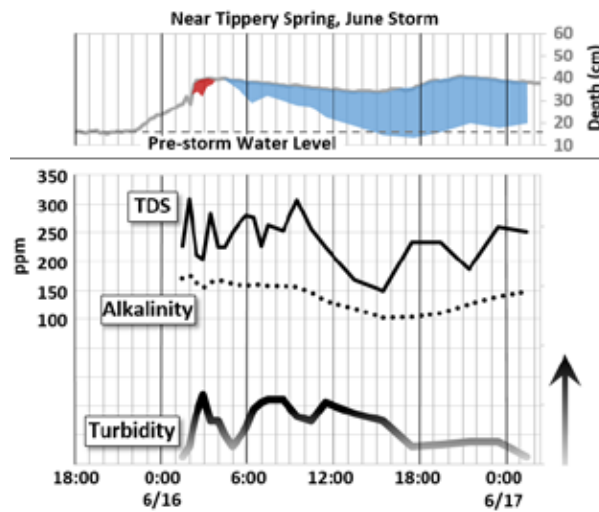


Figure 15. Near Tippiery Spring, June (3-inch) Storm additional parameters in relation to rainfall and spring water level: TDS, alkalinity, and turbidity. Vertical grid has a one-hour minor interval and six-hour major interval.

The ion concentrations also showed variation in response to antecedent conditions. Tippery Spring showed an elevated TDS spike on the rising limb. This spike was higher under the dry initial conditions of the June storm. The higher initial concentration may have occurred because there was less flushing of the system prior to the June storm. The concentrations were more variable at Near Tippery Spring, which may indicate flushing of different sources. The isotope data suggest that the sources varied from the “unknown” third source to dominantly storm water, but the portion of storm water was not as high as observed at Tippery. Thus, the isotope data indicated that the lower contribution of storm water seems to lead to varied TDS at Near Tippery Spring.

Initial stable isotope chemistry did not vary significantly between the two storms for both springs. The similar initial conditions indicated that, despite recent rainfall or lack thereof beforehand, average isotopic composition storm water values prevailed at the springs prior to the storms. This result is not surprising given the samples were collected a month apart, i.e., in the same season.

Storm Intensity

In response to intensity, the 1-inch May storm produced a smaller water level rise at Tippery Spring and Near Tippery Spring (23 cm and 14 cm, respectively), while the 3-inch June storm produced a greater water level rise at the two springs (37 and 26 cm, respectively). This greater overall water level response at both springs from the June storm occurred despite the drier antecedent conditions and moisture deficit, further emphasizing the influence of focused recharge driving fast flow.

The alkalinity and TDS variation decreased with the input of storm water (as indicated by the isotope hydrograph). The decrease is greater when the isotopes indicated a larger portion of storm water. The isotopic mixing indicated a greater storm water component during the June storm and a greater drop in TDS. At Near Tippery Spring, the portion of pre-storm water was lower and the TDS and alkalinity data were more variable.

In general, concentration decreases were also accompanied by an increase in turbidity, signaling the arrival of storm water with high suspended sediment flushed in at sinks. However, the turbidity lagged behind the TDS response. The response lag was shorter by several hours for the high intensity June storm compared

to the May storm. The isotopes indicated that the portion of storm water rose faster for the June storm as well, which may explain the more rapid sediment input.

Spring Recharge Style

Before intensive isotopic analysis of these springs, notable chemical and thermal behavior differences had been observed. Tippery Spring showed lower overall ion concentrations and a flashier water level and temperature response to storms. These characteristics for Tippery were attributed to a more direct connection to surface recharge. For Near Tippery Spring higher overall ion concentrations and a buffered water level and temperature response to storms were observed and attributed to a more diffuse recharge. These springs' behaviors and conceptual models were further described and quantified here through high resolution sampling for stable isotopes and additional parameters and the subsequent hydrograph separation. Due to their close proximity, storm response contrasts between the springs can be attributed to the nature of recharge and flow within each springs capture area, rather than to the timing of the storm itself. Measuring spring responses during storms of different intensities further highlighted these recharge behaviors. Tippery Spring's isotope data supported a conceptual model of a recharge area with a stronger surface connection and well-developed conduit network, while Near Tippery Spring's responses supported a conceptual model with a more diffuse surface connection and less developed conduit network.

Third Source at Near Tippery Spring

While the assumption of a binary mixing model worked well for Tippery Spring, this was not the case for Near Tippery Spring. A possible third mixing source was hinted at with the variable storm response of some parameters, such as alkalinity and turbidity, and became more apparent during analysis of stable isotope mixing.

At peak flow during both storms, and continuing for several hours past peak flow, isotopic values indicated mixing of a new source before briefly returning to baseflow isotopic values preceding the arrival of the storm water signal. During the May storm, this period had isotopic values which were more depleted (around -56.0‰ δD) than baseflow (-53.5‰ δD). As the storm isotopic value was more enriched than baseflow, this period of mixing with a depleted isotopic source during the May storm could not have been explained as mixing

of baseflow water with the enriched storm water. Considering the wet antecedent conditions preceding the May storm, it is possible that this third source was perched epikarst water from a colder precipitation event which was then flushed into the flow network in response to recharge from above.

This short-duration mixing signal variation also occurred during the June storm, although isotopic composition showed enrichment instead of depletion. As such, this appeared to be binary mixing of baseflow water with storm water. Considering the observation during the May storm, however, it is still possible that this was also a third source mixing which had a similar isotopic signal to storm water rather than a depleted soil water signal due to dry antecedent conditions.

Conclusions

High-resolution sampling of stable water isotopes and additional parameters provided evidence to understanding the recharge and flow behavior for two karst springs, Tippery Spring and Near Tippery Spring. As these two springs are adjacent to each other, they experience recharge from the same storm events, and thus have similar pre-storm baseflow isotopic compositions. In response to individual storms, though, their isotopic signatures vary based on storm intensity, but also due to their unique recharge behaviors.

For Tippery Spring, a more rapid recharge through well-defined surface inputs, such as sinks and sinkholes, with rapid transit through a more developed conduit network was supported. For Near Tippery Spring, a more diffuse, buffered recharge behavior through soil and epikarst, with a delayed transit through a less defined conduit network was supported. These behaviors appeared respective of storm intensity, which only varied the degree of response. Comparing the timing of storm water to additional parameters, such as TDS, alkalinity, and turbidity, further supported these conceptual models.

High-resolution monitoring of spring isotopic signatures in response to storms can elucidate how storm water infiltrates and moves within a recharge area. For these two springs, their close proximity further contrasted their unique recharge behaviors. These comparisons produced useful hydrologic information which is important for designing appropriate monitoring programs to provide source water protection in karst.

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THE HYDRO-CHEMICAL CHARACTERISTICS OF A KARST FAULTED BASIN: CASE STUDY OF THE BAIYI BASIN, KUNMING, CHINA

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Abstract

A fault-controlled karst basin is a special type of karst landform. It is defined as a basin-like topography surrounded by mountains, which is fully or partly karstified. Fault-controlled karst basins play a great role on urbanization and economic development of Yunnan Province which is located in a mountainous region. Baiyi Basin is a sub-basin of the Kunming faulted Basin with typical hydrogeological characteristics for a fault-controlled karst basin. It is also one of the most important drinking water source protection zones of Kunming City. In order to better understand the hydrogeological nature of this fault-controlled karst basin and to better protect the valuable groundwater resources, a pilot study focusing on the hydrochemical characteristics of fault-controlled karst basin springs was carried out in Baiyi Basin. A total of 10 springs in the basin are selected in this study. Water Temperature, Electric Conductivity (EC), and pH value were measured *in situ*. Water samples from these 10 springs were analyzed for Ca^{2+} , HCO_3^- , F^- , Cl^- , NO_3^- , Br^- , DOC, DIC contents and stable isotopic ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$). Results show that (1) the hydrochemical characteristics of fault-controlled karst basin are more complex than for a normal basin owing to the intense tectonic activities. Within the Baiyi fault-controlled karst basin, there are not only epikarst springs, shallow karst springs, and confined karst springs, but also non-karst springs. Even deep groundwater may be involved in the water cycle. (2) Water isotopic data reveal that Qinglongtan (QLT) Springs (QLT1 to QLT4) and a Heilongtan Spring (HeiLT1) share a common recharge water source. (3) Among 9 of 10 studied springs, nitrate concentrations slightly exceed of the drinking water standard (10mg/l).

Introduction

A fault-controlled karst basin is a special type of karst landform. It is defined as a basin-like topography that

surrounded by mountains, which is fully or partly karstified. Due to the unique geographical location, there are more than 1440 faulted basins and most of them are fault-controlled karst basin in Yunnan Province, China. They play a great role in economic development and urbanization in Yunnan Province. Nearly all major cities are located in faulted basins.

Every fault-controlled karst basin has its own evolutionary history, lithological units, and hydrogeological characteristics. Hydrologically, the karst basins can be divided into two types. One type formed its own “central radiating flow system” on the basin level. Karst water from mountainous recharge areas emerges at the edge of the basin where it meets Quaternary sediments and forms a series of karst springs in the basin. Another type is designated as a “through water system”, where water influx from karstic mountains, mostly flows through underground conduits to other water systems instead of flowing to the bottom of the basin (Wang et al., 2003). In general, fault-controlled karst basins are located in the watershed areas of the tributaries of Yangtze River, Pearl River, or Honghe River in Yunnan Province. The water in the basin is an important water source for the municipal water supply, agriculture irrigation, and industry. With the rapid urbanization and economic development of Yunnan Province, especially under global climate change, the water shortage issue has limited economic development and the urbanization process.

Baiyi Basin is a sub-basin of the Kunming faulted Basin. There are many big springs developed along the edge of the basin, and the water flows into a catchment, named Lake Songhuaba, the main drinking water source of Kunming City. The basin has been designated as the drinking water source protection zone of Kunming City in 1981. A comprehensive investigation was carried out in the entire water source protection area in 1988

(Kunming EPA report, 1988). However, very little research work focused on the faulted basin, especially the overall hydrogeological processes in faulted karst basin, has been conducted.

In order to better understand the hydrogeological processes of the fault-controlled karst basin and to better protect the important groundwater resources, a pilot study focusing on the hydrochemical characteristics of fault-controlled karst springs has been carried out in Baiyi Basin.

Study Area and Methods

Baiyi Basin is a typical fault-controlled karst basin, about 40 km north of downtown Kunming, the capital city of Yunnan Province. It extends along the main south to north tectonic strike (Figure 1). The host rocks of the karst aquifers are Paleozoic carbonates, which are widely distributed in the north, south and southwest of the basin. Lithologically, the Permian and Carboniferous carbonate formations are limestones, and the Silurian and Devonian rocks are dolomitic limestone. The groundwater catchment of the basin is consistent with the surface watershed, except for the north, where middle Devonian dolomitic limestone (D_2h^{1-1}) exists as the boundary.

This area belongs to the low latitude plateau monsoon climate. The annual temperature is 13.8°C , and precipitation is 1030.5 mm. It could be divided into two seasons, May to October is the wet season with 89% of total rainfall. November to April belongs to the dry season, with 11% of annual precipitation.

In north, south, and southwest mountainous area of the basin, karst features such as depressions, dolines, and shafts are extensively developed. The northern part belongs to the Liangwangshan karst highland, and “temporary” sinkholes are well developed because of soil collapse. All of those landforms indicate that precipitation could rapidly infiltrate into the underground aquifer. As a consequence, local residents can only rely on rainwater harvest systems and intermittent epikarst springs to resolve drinking water problems. No surface water flows into the basin, therefore all the water must come from rainfall.

Along the edge of Baiyi Basin, there are many springs formed. Among them, the Qinglongtan groups of springs

(QLT), Heilongtan Spring (HeiLT), Huanglongtan Spring (HLT) could be the most noted for their significant discharges.

The QLT group of springs, with more than 4 springs concentrated in a small area located at the northern edge of the basin, contribute the source water of Panlongjiang River, which has been named as the mother river of Dianchi Lake, the largest lake (water surface) in Yunnan. During summer, almost one third of discharge of the Panlongjiang River comes from the QLT springs. Near the main outlet of the QLT Springs, Lengshuidong Cave extends from south to north with a length of 300 meters and ends in a sump in the northern end. It is dry in the dry season and flooded in wet season with a discharge over $2 \text{ m}^3/\text{s}$. The elevations of the QLT springs are relatively higher than the cave but the springs have water permanently except for extreme droughts.

HeiLT is located on the eastern edge of the basin, with a discharge about $0.4 \text{ m}^3/\text{s}$. Personal communications with villagers indicate that the spring water becomes muddy

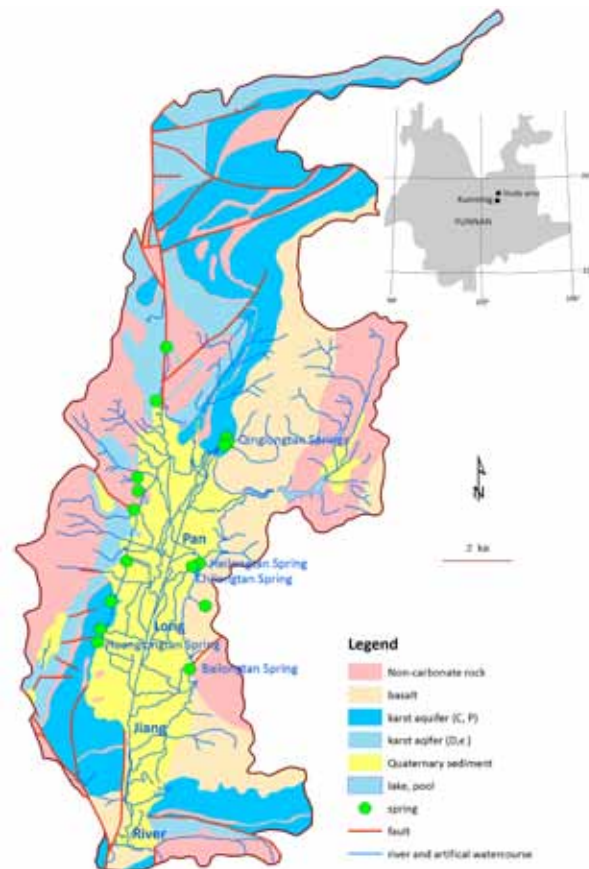


Figure 1. Hydrogeological map of the Baiyi Basin.

with high turbidity for a few days after the first heavy rain at the start of wet season. Two meters away from the main outlet of the spring, there is a small spring with a flow rate less than 0.5 l/s. Chilongtan Spring (CHLT), 30 meters west of HeiLT, is a small spring, and the discharge is approximately 8 to 10 l/s. The temperature of CHLT is usually 4 to 5°C, higher than that of HeiLT.

HLT appears at the western edge of the basin, and the ratio of discharges in wet season and in dry season is greater than 5. There are several small springs near HLT and the largest one has a discharge of 1 l/s.

Bailongtan Spring (BLT) is a relative small spring with a discharge about 5 to 7 l/s. The water infiltrates from nearby hills.

In addition to the springs described above, there are a few more springs but most of them have been used as the local drinking water sources or hardly to identify from the wet land around them. All these springs have been sampled during this study.

Five springs were sampled as part of a Chinese-Slovene project in June 2006 and several physical and chemical parameters were analyzed. Water temperature (T), pH, and electrical conductivity (EC) were measured *in situ* with WTW MultiLine P4. Total hardness (Ca + Mg) and calcium content (Ca) were determined using the standard titrimetric method (Greenberg et al., 1992). In November 2007, 3 springs were sampled for oxygen isotope analysis in the isotope lab, Institute of Geology and Geophysics, Chinese Academy of Sciences.

Watersamples from 10 springs were collected in December 2016 to analyze concentrations of Ca^{2+} , HCO_3^- , F^- , Cl^- , NO_3^- , Br^- , DOC, DIC and stable isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$). T, EC, and pH parameters were measured *in situ* by using a Hach HQ40d multi-parameter water quality mater. Ca^{2+} and HCO_3^- were determined by using MColortest calcium test and alkalinity test box respectively in the field. F^- , Cl^- , NO_3^- , Br^- were analyzed by DIONEX ICS-1100 Ion Chromatography System. DOC, DIC were determined by using the Analytik Jena Multi N/C 3100 instrument and stable isotope (^{18}O and ^2H) were analyzed using a Laser Absorption Spectroscopy (LAS) performed on the TIWA-45EP analyzer (Los Gatos Research) in Karst Lab of International Joint Research Center for Karstology, Yunnan University. Isotope measurements

were performed against three laboratory standards covering ranges from -51‰ to -123.6‰ (VSMOW) for $\delta^2\text{H}$ and from -7.69‰ to -16.14‰ (VSMOW) for $\delta^{18}\text{O}$ with precisions better than 0.1‰ for oxygen isotope and better than 0.5‰ for hydrogen isotope.

Results and Discussion

Measured temperature, conductivity (EC) and the ratio of calcium to magnesium (Ca/Mg) of the 5 springs in June 2006 are illustrated in Figure 2a.

Temperature varies from 15.1°C to 20.5°C. EC varies from 247 to 383 $\mu\text{S}/\text{cm}$ and Ca/Mg varies from 1.9 to 3.4. With respect to temperature, EC and Ca/Mg, they were 15.1 °C, 20.5 °C, 15.9 °C, 15.1 °C and 17.1 °C; 247, 284, 263, 251, and 383 $\mu\text{S}/\text{cm}$, 3.3, 2.4, 3.4, 2.2 and 1.9 for QLT1, CHLT, HeiLT1, HLT2, and HLT1, respectively (Figure 2a). The EC value of springs was much lower than the value of karst springs in other places. The EC of Qinglongdong Spring (28 km northeast of Kunming) oscillated between 404 and 483 $\mu\text{S}/\text{cm}$ during the same time period for instance. These results indicate that water from the springs might be contributed from different sources.

Ten springs were sampled and measured in November 2016 (Figure 2b). The temperature of spring water ranged from 13.9°C to 18.4°C, clearly 1 to 2°C lower than that of June 2006 because of the cooler air temperature. On the contrary, the EC of spring samples somewhat increased, except for the EC of CHLT remained the same. The concentrations of HCO_3^- and Ca^{2+} were unanimous for most springs falling into the range of 2.8 meq/l to 3.1 meq/l for HCO_3^- and 57 mg/l to 68 mg/l for Ca^{2+} except for BLT and HLT1, which were 0.7 meq/l and 17 mg/l for BLT and 4.3 meq/l and 102 mg/l for HLT1 respectively. BLT is not a karst spring. The DOC and DIC values among springs fell in the range of 2.94 mg/l to 4.53 mg/l and 28.79 mg/l to 33.27 mg/l except for BLT and HLT1, which were 1.05 mg/l and 0.79 mg/l for BLT and 5.5 mg/l and 49.36 mg/l for HLT1 respectively.

The concentration of F^- was 0.21 mg/l in HLT1 and undetectable in the other 9 springs. The concentration of Cl^- was between 0 to 2.43 mg/l. Cl^- concentrations for 8 of 10 springs were below 0.84 mg/l. Cl^- concentrations of HLT1 and HLT2 were 2.43 mg/l and 1.93 mg/l respectively.

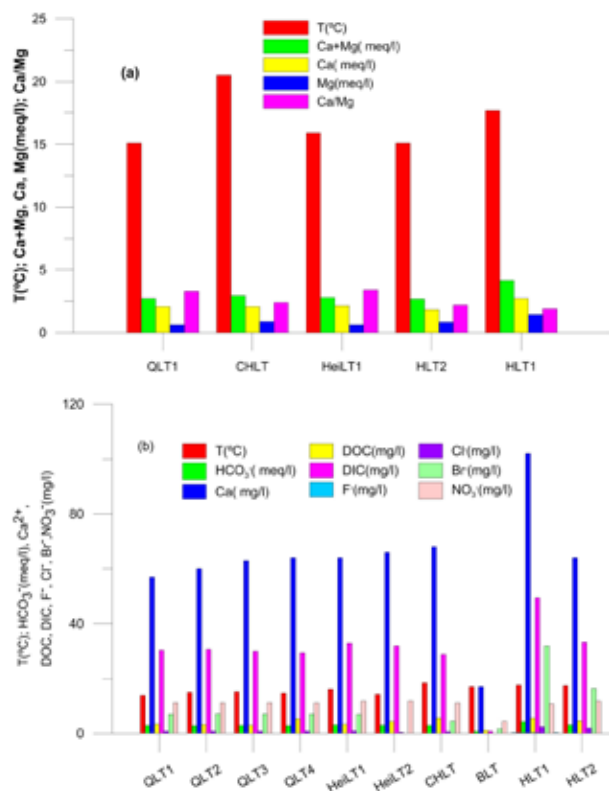


Figure 2. Hydrochemical parameters of samples: a, from QLT1, CHLT, HeiLT1, HLT2 and HLT1 springs in- June 2006 (upper panel); b, from QLT1, QLT2, QLT3, QLT4, HeiLT1, HeiLT2, CHLT, BLT, HLT1 and HLT2 springs in November 2016 (lower panel).

Br^- concentrations varied widely, from undetectable in HeiLT2, to 31.81 mg/l in HLT1. Br^- is mainly come from specific host rocks. In other words, the difference of Br^- concentrations enabled an initial distinction of groundwater flow path or host rock. For QLT1 to QLT4 and HeiLT1, the value of Br^- concentration was coincident in a range of 6.84 mg/l to 7.04 mg/l, but 4.45 mg/l in CHLT and 1.73 mg/l in BLT. The highest value was found in HLT1, 31.81 mg/l and the second highest in HLT2, 16.32 mg/l.

Nitrate concentration was 4.33 mg NO_3^-/l for BLT. Nitrate concentrations (10.76 mg/l to 11.77 mg/l) for the other 9 springs were slightly higher than the drinking standard, 10 mg/l. The nitrate concentration exhibits an increasing trend in the last 10 years, from 4 mg/l (Šebela et al, 2006) to about 10 mg/l in QLT1.

Results of three ^{18}O isotopic water samples from November 2007 showed that the QLT1 and HeiLT1

shared the same $\delta^{18}\text{O}$ value of -12.28‰ , which is slightly heavier than that of CHLT, -12.60‰ . This suggested that QLT1 and HeiLT1 might have same water source.

In December 2016, water samples for isotopic analysis were taken from 10 springs. Results are shown in Figure 3. The distinct lighter water stable isotopic values of BLT ($\delta^2\text{H} -93.31\text{‰}$ and $\delta^{18}\text{O} -12.68\text{‰}$) indicates that it has a different water source from other springs. CHLT (-12.70‰ for $\delta^{18}\text{O}$ and -90.95‰ for $\delta^2\text{H}$) may also have its own source water. Isotopic values of QLT1 ($\delta^2\text{H} -87.67\text{‰}$, $\delta^{18}\text{O} -12.53\text{‰}$), QLT2 ($\delta^2\text{H} -87.57\text{‰}$, $\delta^{18}\text{O} -12.48\text{‰}$), QLT3 ($\delta^2\text{H} -88.26\text{‰}$, $\delta^{18}\text{O} -12.47\text{‰}$), QLT4 ($\delta^2\text{H} -88.16\text{‰}$, $\delta^{18}\text{O} -12.41\text{‰}$), HeiLT1 ($\delta^2\text{H} -87.84\text{‰}$, $\delta^{18}\text{O} -12.44\text{‰}$) cluster together and indicate that they might have a common recharge water source. HeiLT2 ($\delta^2\text{H} -86.84\text{‰}$, $\delta^{18}\text{O} -11.72\text{‰}$), HLT1 ($\delta^2\text{H} -85.21\text{‰}$, $\delta^{18}\text{O} -11.89\text{‰}$) and HLT2 ($\delta^2\text{H} -84.93\text{‰}$ and $\delta^{18}\text{O} -11.48\text{‰}$) have heavier isotopic values and scattered away from each other.

Taking all hydrochemical characteristics of the water samples and field investigation into consideration, spring water in Baiyi Basin could be divided into five groups (Table 1).

Group 1, BLT. The spring has distinctive stable isotope values, limited discharge, and electrical conductivity and bicarbonate concentration are very low. It is formed by rainwater percolating through non-carbonate rock or sediments. This is a non-karst water spring.

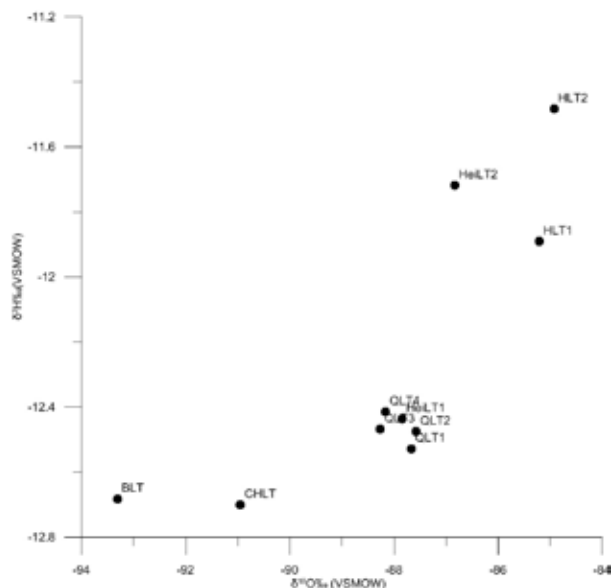


Figure 3. Isotopic analysis results of samples from December 2016.

Group#	Springs	Hydrochemical characteristics
1	BLT	distinctive stable isotope values; very Low EC and bicarbonate concentrations.
2	CHLT	distinctive stable isotope values; higher water temperature and constant discharge.
3	QLT1, QLT2, QLT3, QLT4, HeiLT1	similar hydrochemical characteristics and stable isotope values; relatively stable discharge; weak confined water
4	HeiLT2, HLT1	water temperature sensitive to air temperature; limited discharge (<5l/s); fracture-controlled infiltration.
5	HLT2	spring discharge and hydrochemical parameters oscillate greatly during dry and wet seasons; downstream has karst window in contact with open air and subterranean river

Table 1. Five groups of springs and their major hydrochemical characteristics in the Baiyi Basin.

Group 2, CHLT. The spring has distinctive stable isotope values. The water temperature is 2 to 4°C higher than surrounding springs. Discharge and EC are relatively constant. It might be the mixture of deep groundwater and karst water.

Group 3, QLT1, QLT2, QLT3, QLT4, HeiLT1. These 5 springs have similar hydrochemical characteristics and stable isotope values. Groundwater flows from mountainous recharge areas and emerges after intercepting Quaternary sediments at the edge of the basin. Spring water is weakly confined.

Group 4, HeiLT2 and HLT1. These 2 springs have limited discharge (<5l/s) and water temperature is influenced by air temperature. They might be impacted by human activities with relative higher Cl⁻ concentrations. The infiltration is controlled by fractures.

Group 5, HLT2. The spring discharge and hydrochemical parameters oscillate greatly during dry and wet seasons. Near the outlet of the spring, there is a karst window with open air along the groundwater flow path. This is a typical shallow karst spring.

Conclusions

The hydrochemical characteristic of the fault-controlled karst basin is highly complex as a consequence of intense tectonic activities. Within the fault-controlled Baiyi Basin, five groups of springs are identified. There are not only epikarst springs, shallow karst springs, and

confined karst springs, but also a non-karst spring. In some cases, deep groundwater might be involved in the water cycle in the fault-controlled karst basin.

The water isotope data shows that QLT Springs (QLT1 to QLT4) and HeiLT1 share a common recharge water source.

Nitrate concentrations for 9 out of 10 springs during the study period exceeded the drinking water standard of 10 mg/l.

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SURFACE TO CAVE DYE TRACING: LESSONS LEARNED FROM THE BELGIAN KARST

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Abstract

The vadose zone (unsaturated) of karst aquifers is critical for several reasons. (1) It is the main pathway for karst groundwater recharge from the surface to the phreatic zone (saturated), (2) it forms the transition zone between surface human activities (potential contamination) and the groundwater resource, and (3) it gives a support for karst fauna and flora through its hydrogeological dynamic. The hydrogeological functions of the vadose zone are of growing interest for these reasons but, also, because this highly heterogeneous media is still poorly understood by hydrogeologists and karst researchers.

In order to more fully apprehend the function of this zone, surface to cave dye tracing was performed above the Rochefort Cave in south Belgium. The goal was to explore the hydrological processes of the 30-meters

vadose zone between the surface and the cave by mean of dyes and drip-water monitoring. These methods enable us to discover information about groundwater dynamic. A maximum velocity of around 10 meters/hour was calculated in absence of rainfall and without significant flush during the injection of the dye. A multimodal breakthrough curve was recorded in the percolation water, the tracer being remobilized by every rainfall event during more than 120 days. The dye tracked the reaction of the percolation to rainfall events at the surface. Separation and analysis of the different peaks and their related rainfall events revealed a clear trend. The higher the rainfall intensity, the faster the reaction of the percolation. The effect of the rainfall gives infiltration velocities from 10 to 55 m/h for the higher rainfall intensities. Additionally, the dye tracing allowed us to compare the effect of snowmelt and

rainfall on the infiltration efficiency. Snowmelt has a higher remobilization effect on the dye, thus a higher infiltration potential compared to rainfall events. The effect of rainfall intensity on infiltration velocity and the difference between snowmelt and rainfall when considering infiltration efficiency seems of primary importance in a context of global climate changes. These results emphasize the importance of evaluating vadose processes in karst terrain.

Introduction

The karstic vadose zone is a highly heterogeneous media located between the ground surface and the phreatic zone of karst aquifers. The hydrogeological functions of this zone are difficult to assess given its spatial heterogeneity and the variety of processes occurring in its different parts: soil, epikarst and transmission zone (Bakalowicz, 1995; Williams, 2008). The pathway and effects of precipitation (rainfall and snowmelt) on recharge of the karst aquifer through the vadose zone is uncertain. For example, the following is not understood: water transit, pressure transfers, temporary storage, horizontal dispersion, mixing between recently infiltrated water and “old” water. Many of these processes may occur in this part of the aquifer.

While the vadose zone is an important part of the karst aquifer given its location, it remains poorly studied by karst scientists. It is important to study and understand the karst vadose zone for many reasons. For example, the vadose zone collects and drives autogenic recharge from the surface to the water table. This recharge is crucial for karst aquifers that are extensively exploited for human activities around the world. What are the processes and factors influencing this recharge inside the vadose zone? Are they subject to changes? Also, due to its position between the surface and the groundwater resource, the vadose zone is often the only protective layer between surface activities and potential contamination. Knowledge of vadose hydrogeological processes will assist in evaluating the vulnerability of groundwater and implement sustainable protection programs. In addition, the vadose zone is the main support for the fauna and flora of karst ecosystems. Vegetation will be able to grow and subterranean life is dependent of vadose water to live.

The hydrogeological dynamic of the karst vadose zone can be explored by in-cave experimentations and

monitoring. In particular, cave percolations (stalactite, fissures) may be studied to measure this dynamic. In this study, a cave percolation under a 30-meter thick vadose zone was used to perform a surface to cave dye trace with fluorescein and a compact field fluorometer. The aim was to highlight the infiltration behavior, groundwater velocity and residence time in vadose zone. In addition, the percolation was monitored for discharge, temperature, and electrical conductivity.

Study Site

The percolation monitoring and dye trace were conducted in the vadose zone of the Rochefort Cave, being one of the main karst network in Belgium (Figure 1). The cave is located in Givetian limestones, which are highly

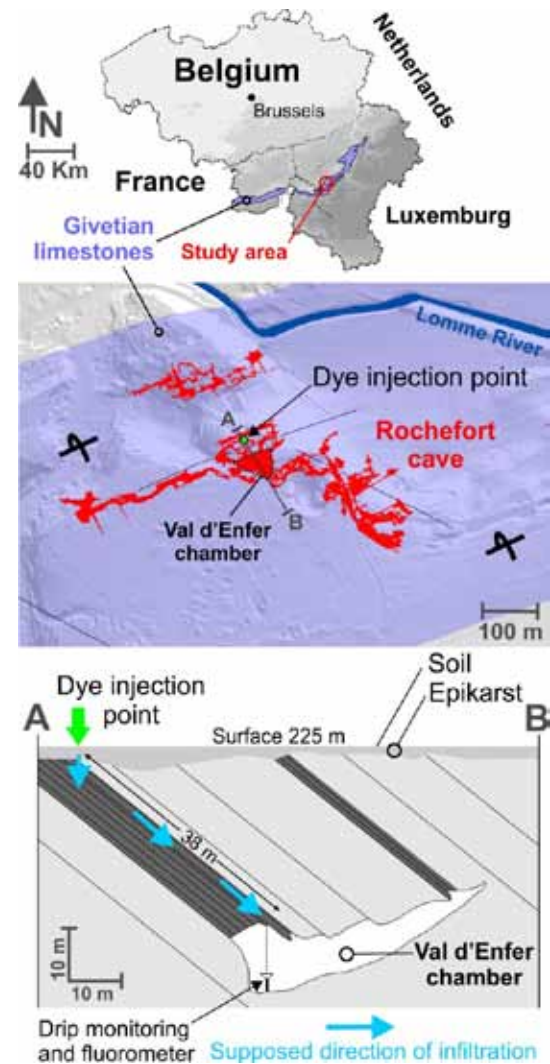


Figure 1. Location of the study site in south Belgium with the dye injection point at the surface and monitoring station in the Rochefort Cave.

fractured with a 45° south dipping strata. The vadose zone at this location is composed by a 30-meter thick layer of biostomal limestones with clayed beds. The percolation is located in the *Val d'Enfer* chamber. It is a perennial percolation from a fracture in clayey limestone.

Methodology

The dye trace was performed in March 2016. 500 grams of fluorescein was used. The dye was diluted with 40 liters of water and injected directly on the ground with a PVC-pipe in order to simulate a single point injection (Figure 2). The soil was not removed and the dye was injected with a limited flush in order to approximate natural conditions of infiltration (Kogovsek, 2010; Poulain et al., 2015). Rainfall, snow levels and air temperature were sampled above the cave (1 minute sampling). A Campbell T10 with a 0.03°C resolution and 0.03°C precision was used for the air temperature, while rainfall and snow were measured with a Lufft rain gauge with a 0.1 mm resolution. Inside the cave, the drip discharge was made with an auto-siphoning gauge (Kaufmann et al., 2016) which can accommodate a high range of discharge. Fluorescein monitoring was performed every 5 minutes with a Fluo-Green compact fluorometer (Poulain, 2017; Poulain et al., 2017) that was installed above the drip gauge (Figure 2). Additional measurement of temperature and electrical conductivity were made on the drip water. The measurement was made in a small bath (5 liters) so the buffer effect was considered negligible due to the high percolation discharge.

Results

Figure 3 shows the results of the vadose dye tracing and monitoring for 3 months between March and June 2016, as recorded in the percolation water. The first appearance of the fluorescein was 3h45 after the injection for a minimal straight line distance of 38 meters. The maximum infiltration velocity is 10.25 meter/hour. The breakthrough curve exhibits a multimodal behavior with a restitution time longer than 120 days.

The fluorescein concentration shows a slow increase during the first 15 hours of restitution and then a sharp peak up to 225 ppb. This peak is associated with a rainfall event at the surface and a discharge increase. The duration of this increase is short (15 to 20 hours) but such rainfall-associated peaks are visible 16 times on the breakthrough curve. The maximum dye concentration of

the peaks decreases as the restitution goes on, indicating a defined amount of dye that is slowly remobilized. The dye recovery was calculated based on the drip



Figure 2. Injection of fluorescein above the cave with a PVC-pipe and a 40-liters flush of water. The monitoring is made of a Fluo-Green fluorometer above a drip water gauge.

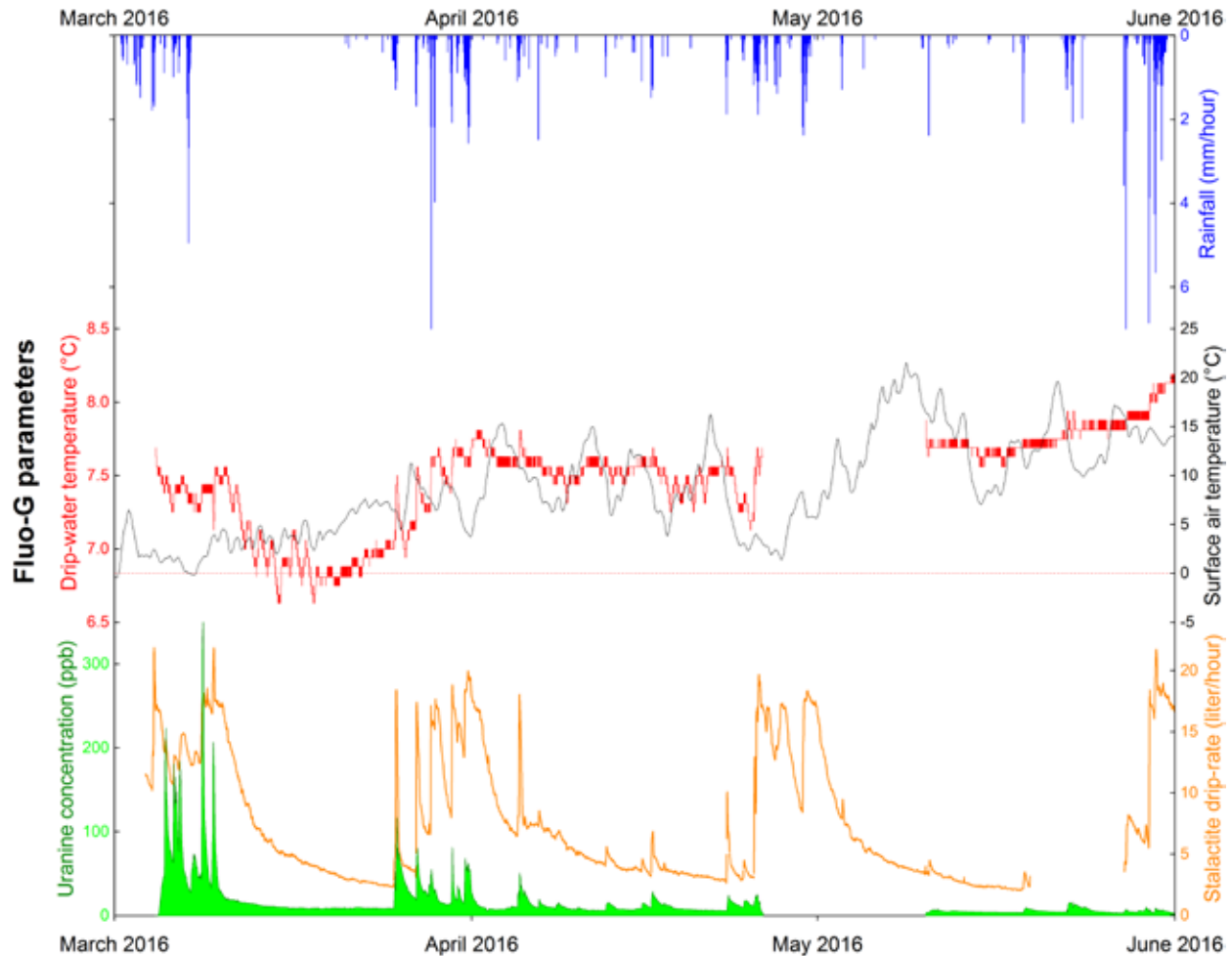


Figure 3. Surface and percolation monitoring results during the surface to cave dye trace.

discharge that range from 4 to 20 liters/hour. 0.345 g of fluorescein was recovered, giving a restitution rate of 0.07%.

The secondary breakthrough curve triggered by rainfall events further demonstrates the infiltration dynamic through the vadose zone. When normalized on a 0 to 1 scale for concentration, the breakthrough curves exhibit similar characteristics in terms of first arrival, peak time and total restitution time (Figure 4). It is possible to calculate the average behavior showing the characteristics of infiltration transit in this vadose zone during a rainfall event. Mean first arrival is 1h30 (maximum velocity of 25.7 meter/hour), mean peak time is 4.2h (modal velocity of 9 m/h). Nevertheless, it was not possible to control the migration of the dye and any change in the remobilization travel distance that might influence the velocity. Although this effect might

exist, it was considered non-significant since the calculated velocities did not increase with time for similar rainfalls conditions.

Plotting the reaction time of the percolation versus the rainfall event (appearance of the secondary restitution peak) against the rainfall intensity shows a negative dependency (Figure 5). Higher rainfall intensities result in faster reactions of the percolation and higher infiltration velocities up to 55 m/h.

Finally, two secondary peaks of the breakthrough curve where triggered by snow cover melting (Figure 6). While it is risky to draw conclusions based on only two occurrences, one may clearly see that the concentration of those peaks is higher than those triggered by rainfall. This may indicate that snowmelt has a different behavior than rainfall when infiltrating through vadose zone.

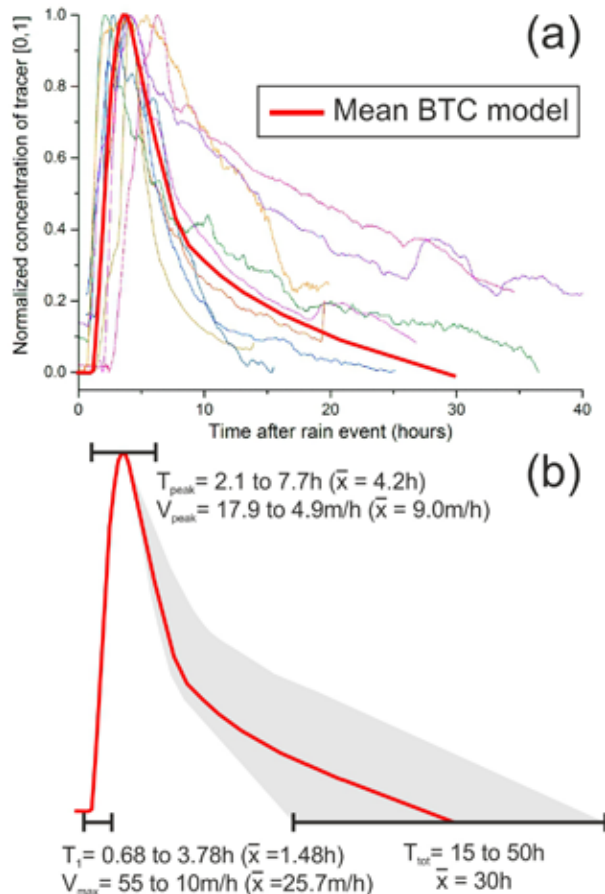


Figure 4. (a) Individual breakthrough curves for the 16 rainfall-associated peaks of dye, (b) mean behavior of the infiltration due to rainfall.

Discussion

The dye trace conducted in the vadose zone of the Rochefort Cave gives us quantitative information about hydrological dynamic in this part of the aquifer.

Diffuse infiltration through the karst vadose zone is a very quick process. Even without clear infiltration points such as a sinkhole or swallet, the process is efficient and shows velocities ranging from 10 to 55 meter/hour. If surface contamination were present, groundwater would quickly be threatened and the contaminant may spread over large distances. In terms of such vulnerability, the karst vadose zone is not an effective protection media. It is a place where quick and concentrated flow take place, with limited attenuation.

Even with this quick flow component, the heterogeneity of the vadose zone and the diversity of the hydrologic processes there result in prolonged storage of

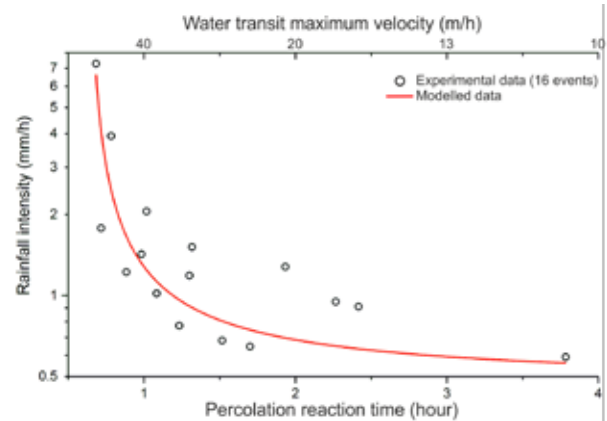


Figure 5. Relationship between rainfall intensity and the reaction time of the percolation to the rainfall event. The top X-axis gives the maximum transit velocity in the vadose zone.

groundwater. The infiltration spreads horizontally and may be temporary stored during several months. For this reason, contamination may have long term consequences. The restitution rate of this experiment clearly shows the large spreading and dilution of infiltration which might be catastrophic in case of contamination.

The dye trace highlights the importance of two factors in the vadose infiltration process. First, the intensity of the rainfall event affects the effectiveness of the infiltration. More intense rainfalls trigger faster infiltration processes and thus a more efficient recharge. In this case, the infiltration velocity is up to 5 times higher for the most intense rainfalls. Secondly, the type of precipitation input (snowmelt of rainfall) may have an effect on the infiltration efficiency but requires further data to be quantified precisely.

Conclusion

In a context of climate changes and global modifications of the water cycle, it is important to understand the

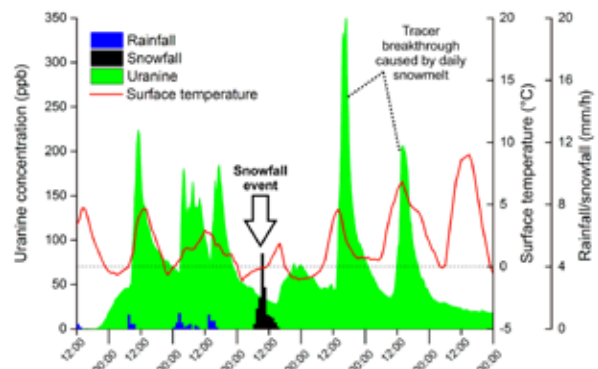


Figure 6. Secondary restitution peaks caused by snow melting.

reaction of karst aquifer to extreme weather events, as is reported in many recent studies (Murakami et al., 2017; Thompson et al., 2017; Wang et al., 2017), together with modifications of atmospheric temperature and thus precipitation type. Our field results indicate that these factors may be determinant for the recharge process of karst aquifers. Thus, it is expected that both quality and quantity of karst groundwater resource will be affected by those changes. In addition, the growing pressure of surface anthropogenic activities is a threat for the groundwater resource and future water supply. Our results emphasize the need for adapted protection solutions to limit the impacts of potential contaminants on the groundwater, especially in karst regions. Further experimentation and monitoring in the vadose zone seems necessary to tackle this specific issue by providing reliable field data.

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PHOTOLINEARS, FRACTURES, AND FALLACIES: A POST HOC STUDY OF PHOTOLINEAMENTS, HILLSBOROUGH COUNTY, FLORIDA

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Abstract

There is a misconception by some in the geologic and non-geologic communities of Florida that photolineaments and vertical bedrock fractures are one and the same. The main objectives of this paper are (1) to document a case study where a comprehensive geophysical and geotechnical exploration program was undertaken to verify a high-quality photolinear analysis; and, based on the case study, (2) evaluate the validity of photolinears as indicators of vertical bedrock fractures in the covered karst terrain of west-central Florida. The case study, an investigation by Upchurch et al. (1999), was an analysis of photolineaments at a 445-ha site intended for construction of an above-grade reservoir in west-central Florida. The photolineaments were ground truthed using ground penetrating radar (GPR), refraction and reflection seismic profiling, standard penetration testing (SPT), and cone penetrometer testing (CPT; Dobecki and Upchurch 2010).

The *post hoc* review, based on the comprehensive site geophysical and geotechnical testing and resulting data, determined that fifty-eight percent of the photolinears do not correspond to vertical fractures in the limestone bedrock. This review demonstrates the fallacies of assuming all photolinears represent vertical bedrock fractures in the covered karst terrain of west-central Florida. Based on this case study and the *post hoc* review, it is our belief that in the covered karst terrains of Florida, all photolinear evaluations should have some form of field verification in order to equate them to vertical bedrock fractures or karst features.

Introduction

Regional and local photolineament analyses are valuable as a first approximation of the possible presence of bedrock structures such as vertical fractures in covered karst (Lattman 1958; Lattman and Matzke 1961;

Lattman and Parizek 1964; and Littlefield et al. 1984). However, like any other tool, there is a potential for misuse of photolineament analyses, which can lead to potential errors and misinterpretations of actual geologic conditions (Wheeler 1983). In other karst regions of the world where the carbonate bedrock is thinly covered (less than 3 meters) by regolith or is bare, there is a higher correlation between photolinears and vertical bedrock fractures. However, this degree of correlation does not exist in the sinkhole prone, covered karst terrain of west-central Florida, where cover thicknesses are upwards of 15 or more meters.

Work completed by Littlefield et al. (1984) has indicated that sinkholes tend to preferentially occur on fracture traces (verified photolineaments) and at fracture trace intersections in Florida. The problem with many photolineament analyses completed in Florida is that verification testing is rarely completed or minimally done to prove that the photolineaments correlate with true vertical fractures in the bedrock. Furthermore, verification testing is rarely completed or minimally done to prove differences in the surrounding area in lithology, structure, hydraulic conductivity, or some other geologic property that suggests a vertical linear feature in the bedrock. The authors are only aware of one large-scale photolineament analysis in Florida wherein all of the photolinears were specifically and comprehensively ground truthed via geophysics and geotechnical testing.

A Case Study of a “Ground Truthed” Photolineament Assessment Study

Upchurch et al. (1999) was a comprehensive analysis of photolineaments at the then proposed C.W. Bill Young (Tampa Bay Regional) Reservoir site (Figure 1) in Hillsborough County, Florida. The proposed reservoir site was specifically located in an area of a relatively thick sequence of clay-rich Miocene strata, which

forms the aquitard between the surficial aquifer and Floridan aquifer. This location was thought to minimize risks associated with potential sinkhole formation and excessive reservoir leakage. A generalized stratigraphic column with representative unit thickness is presented on Figure 2.

A number of sinkhole studies, which were based on topographic analysis to identify areas with closed drainage, were conducted in the area and indicated numerous sinkholes to the northwest of the project site (Littlefield et al. 1984; Upchurch and Littlefield 1987 1988). Based on this knowledge and knowing that sinkholes tend to preferentially occur on fracture traces and at fracture trace intersections in Florida, it was decided during the planning and design phase of the project that a comprehensive karst geologic investigation, including photolinear interpretation, should be completed to provide reasonable assurances that the reservoir footprint was not in an area of elevated sinkhole risk or having the potential for excessive leakage.

Regional Geologic Setting

The study site is located within the Polk Upland Physiographic Province of Florida (Puri and Vernon, 1964). Land surface elevations range from approximately 21 to 30 meters above sea level (m ASL). The land surface is flat to gently sloping.

Three major geologic units occur at or near the land surface. They are, in order of youngest to oldest, undifferentiated Plio-Pleistocene marine terrace deposits, the Miocene Peace River Formation and the Miocene Arcadia Formation (Hawthorn Group; Scott 1988 and Scott et al. 2001). A generalized stratigraphic column with representative unit thickness is presented on Figure 2.

The Plio-Pleistocene marine terrace deposits consist of approximately 1 to 9 m of fine to medium, well sorted sand. Scattered, small lenses of clay are present, and the sand mantle is thickest in buried, relict sinkholes.

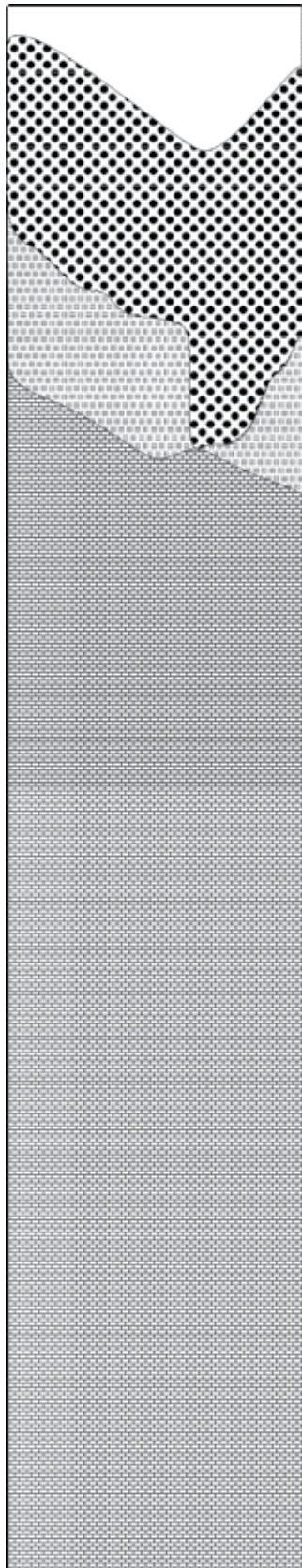
The Miocene Hawthorn Group (Figure 2) includes the Peace River Formation (Scott 1988). The Peace River includes an upper member, the Bone Valley Member, that generally consists of sand-sized and larger phosphorite grains set in a matrix of poorly consolidated sand, silt, and/or clay. The lithology of the unit is highly variable, and lateral and vertical facies changes can be abrupt. The remainder of the underlying Peace River Formation is a mixed clastic-carbonate unit composed of interbedded quartz sand, clay and dolostone. The quartz sand is clayey, fine to medium grained, and poorly consolidated.



Figure 1. C.W. Bill Young (Tampa Bay Regional) Reservoir site, Hillsborough County, Florida. Aerial photograph from Google Earth (2017).

The clay in the Peace River Formation may be sandy, silty, calcareous, or dolomitic, and poorly to moderately consolidated. The dolostone is typically sandy, clayey, micro to fine crystalline (dolosilt), and poorly to moderately indurated. Peace River sediments range from approximately 15 to 30 m in thickness and overlie older Miocene deposits that are typically less than 100m thick.

The Arcadia Formation underlies the Peace River Formation throughout the region (Scott 1988 and Scott et al. 2001). The upper, undifferentiated Peace River Formation consists of interbedded sand, clay, and carbonate strata. In contrast to the Peace River Formation, the Arcadia is more carbonate rich, with widespread dolostone and limestone layers and lenses. The base of the Arcadia includes a sandy, sometimes phosphatic limestone known as the Tampa Member of the Arcadia Formation. The Tampa Member is typically limestone that is moderately sandy, clayey, and locally may contain lenses of green and gray clayey sand, sandy



Pleistocene marine terrace deposit, Fine sand with minor clay
(1-9 m; median thickness = 5 m)

Plio-Pleistocene paleosol. Sand with clay to sandy clay, minor phosphate, and common aluminum phosphate minerals; informally known as the “leached zone” in the Central Florida Phosphate Mining District
(0-12 m; median thickness = 4 m)

Miocene Hawthorn Group. Complex mixture of limestone, dolostone, clay, and sand lithofacies; sparse to abundant phosphate
(100+ m thick)

See Figure 13 for the pattern of lithofacies interfingering

Figure 2. Generalized stratigraphic column showing stratigraphy and relative unit thicknesses at the C.W. Bill Young (Tampa Bay Regional) Reservoir site, Hillsborough County, Florida.

clay and chert. Near the site, the Tampa Member is found at depths greater than 61 m below land surface (BLS).

After deposition of the Miocene strata, a major unconformity formed that is characterized by a well-developed paleosol locally known as the “leached zone” (Figure 2). The leached zone is characterized by relict stream channels, in-filled, Mio-Pliocene-aged sinkholes, and an irregular surface, all of which are at least partly masked by the overlying Plio-Pleistocene marine terrace deposits.

Photolinear Analysis and Comprehensive Geophysical and Geotechnical Investigation

Figure 3 depicts a pre-construction aerial photograph of the reservoir site with an overlay of interpreted photolinear features by Upchurch et al. (1999). Photolinears were tentatively identified on USDA aerial photographs from six different years. The colors of lines on Figure 3 reflect confidence ranking of the photolinear.

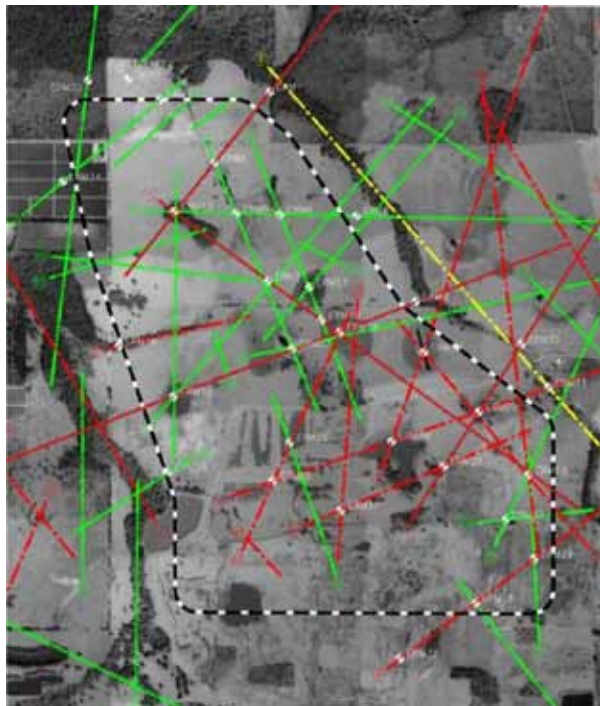


Figure 3. Pre-development aerial photograph of the C.W. Bill Young Reservoir site near Tampa, Hillsborough County, Florida showing photolineaments ranked by confidence. Dashed line is the center line of the proposed 91 m wide reservoir berm. Red lines represent highest confidence, while yellow reflects lowest.

Red lines represent highest confidence, while yellow reflects lowest.

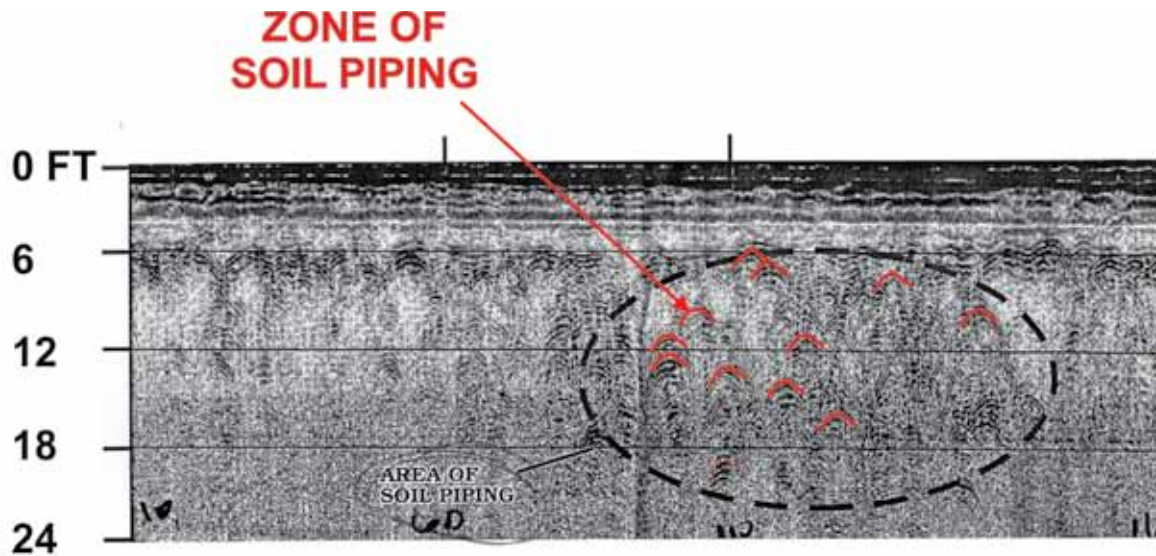
Areas for geological testing within the reservoir footprint were selected based on the photolinear analysis. Photolinear intersections, high and medium confidence photolinears, and apparent sinkhole features were subjected to geophysical testing. In addition, the proposed location of the berm surrounding the reservoir was subjected to extensive geophysical exploration.

Acquisition of GPR data covering large areas of the reservoir project, including traverses along the centerline of the entire embankment plus parallel lines approximately 30 m to each side of the centerline, were collected. Gridded (areal) coverage over areas of interest defined by the analysis of the photolinears was also acquired. In total, approximately 47.6 km of GPR profiling was acquired across the property (Figure 4). An example of an identified site GPR anomaly is presented on Figure 5.

Prior geologic investigations by the authors had identified the presence of a cemented sand layer at a depth of approximately 9 to 12 m BLS, which is over twice as deep as the GPR signal could reach. This



Figure 4. Location of ground penetrating radar survey lines (Upchurch et al. 1999).



ANOMALOUS GPR PROFILE

Figure 5. Example GPR profile showing shallow anomaly zone (Upchurch et al. 1999).

layer, which is a hard layer within the leached zone and below the water table, offered the potential of providing a surface that could reflect potential down warping, raveling, or sinkhole development. Seismic refraction was selected as the test method to track this layer, as it is an effective tool for mapping interfaces where a harder layer underlies a softer layer. Seismic shear (S) waves were selected over the compression (P) wave technique, because of the level of contrast between the shallower/softer soils and the cemented layer. All major GPR anomalies were tested using refraction profiling.

Preliminary testing of P versus S wave refraction showed that the P wave velocity of the cemented layer was approximately 15 to 20 percent higher than the loose soils above. The S wave velocity contrast, however, was nearly 300 percent higher in the cemented layer than in the looser shallow soils. This is to be expected below the water table where the P wave velocity of all layers jumps due to water saturation. The shear wave velocity has almost no response to full water saturation, as it expresses contrast between the matrix of the soils and the degree of cementation. The high contrast using S waves led to more precise interpretations of the resulting refraction data. All major GPR anomalies were tested using refraction profiling. The entire berm length was also surveyed using S wave refraction because material strength and continuity beneath the berm is such an important factor. In total, approximately 21.9 km of shear wave seismic refraction profiling was acquired across the site (Figure 6).



Figure 6. Location of seismic refraction lines (Upchurch et al. 1999).

Figures 7a and 7b are plots of a raw shot record – 24 channels, SH geophones/SH hammer source with a 3 m geophone spacing. The raw data show three clear velocity arrivals. Figures 8a and 8b depict an interpreted

seismic refraction profile in an area where the deepest (cemented) layer exhibits an approximately 6 m depression. The typical layer parameters are:

- Layer 1; $V_s = 107$ m/sec; surficial (disturbed) soil;
- Layer 2; $V_s = 271$ m/sec; compacted sands and clays; and
- Layer 3; $V_s = 736$ m/sec; cemented layer.

Such anomalies were tracked and mapped and then they were scheduled for more detailed analysis using high-

resolution seismic reflection, geotechnical borings, or both.

Areas that were characterized by photolinears, GPR anomalies, and refraction depression anomalies were deemed to be potential karst or fracture features that required deeper and more detailed investigation. These types of anomaly combinations were surveyed using high-resolution seismic reflection surveying. Testing consisted of a 24-channel seismograph, 12-fold acquisition procedures with 1.5 m shot and geophone spacing, and an 8-gauge Betsy Seisgun source fired

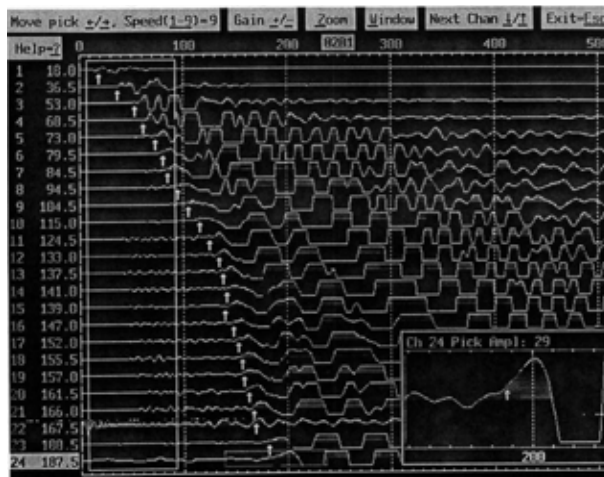


Figure 7a. Site example of a raw shot record (Upchurch and Dobecki, 2010).

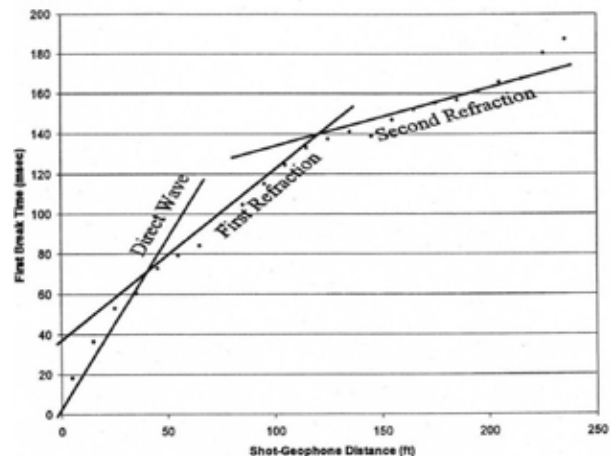


Figure 7b. Site example of a refraction travel time curve (Upchurch and Dobecki, 2010).

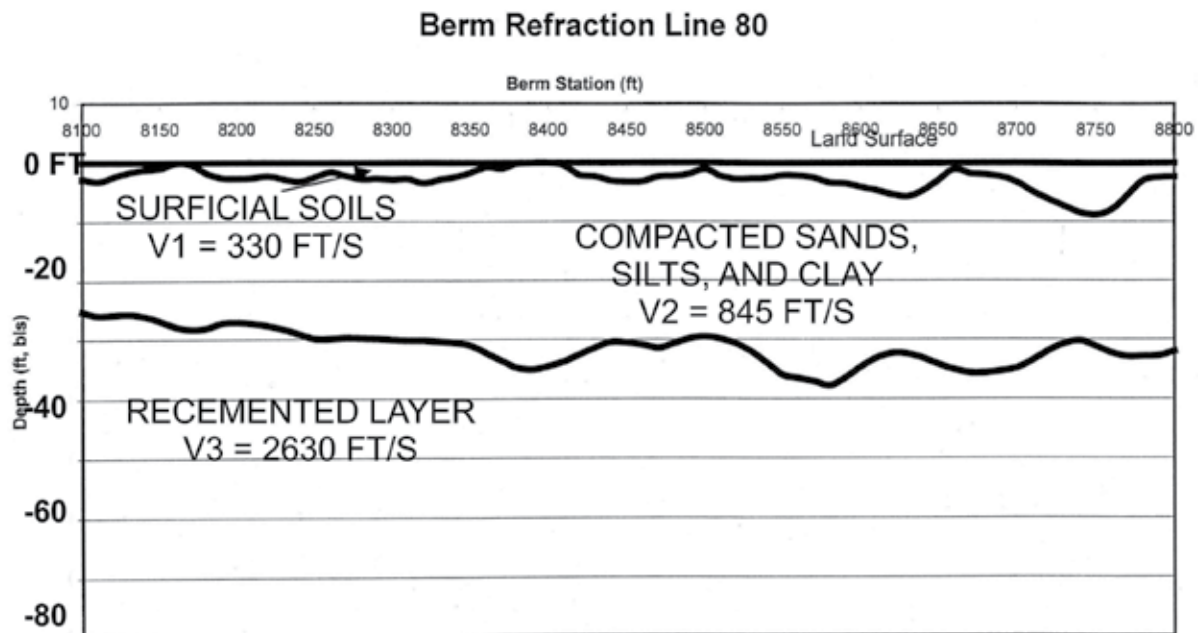


Figure 8a. Example of an interpreted S wave refraction cross section showing a typical section (Upchurch and Dobecki, 2010).

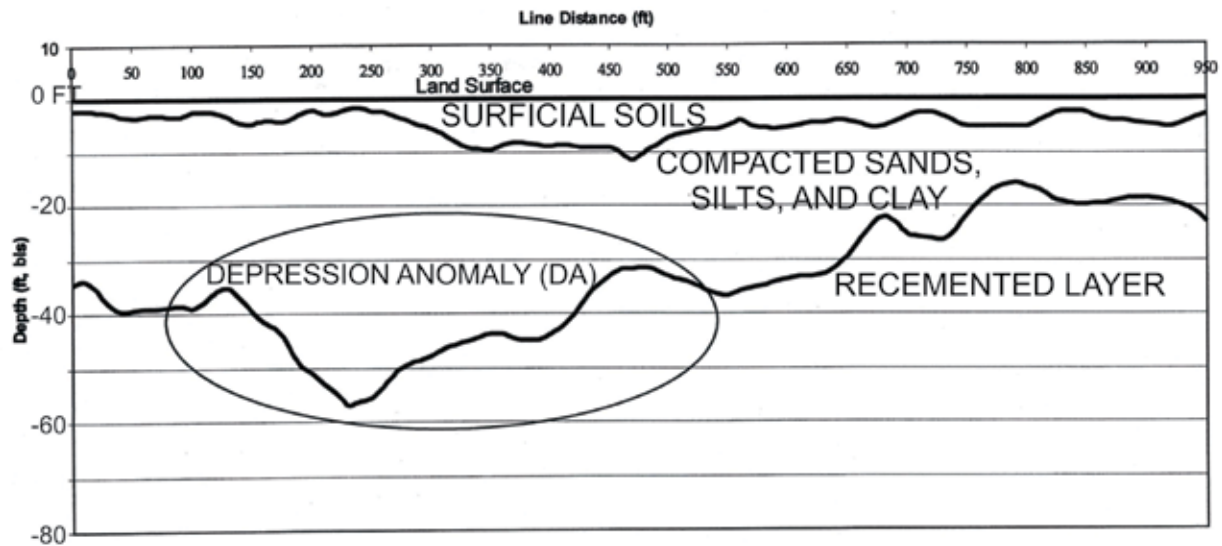


Figure 8b. Example of an interpreted *S* wave refraction cross section showing a depression anomaly (circled; Upchurch and Dobecki, 2010).

within a shallow augered hole. Approximately 5.2 km of high resolution seismic reflection profiling were acquired across the property (Figure 9).

Figure 10 is a sample processed seismic reflection section that was acquired across shallow radar and refraction anomalies. The dashed line near 0.03 sec is the interpreted top of the dolostone layer. We have circled two anomalous areas where there is a loss of continuity of the dolostone reflection and where there is a depressed and down warped appearance of that reflection. We also show the location of two SPT borings that were drilled at the locations of maximum disruption as seen on the reflection section. The results of these explorations are discussed in the following section.

Subsurface Geological Testing

SPT borings and CPT soundings, as well as selected rock coring, were completed in identified geophysical anomalies (Figure 11) and along the proposed berm and reservoir bottom to (1) verify geologic conditions for geophysical interpretation and (2) identify potentially active karst features. In all, more than 5.6 km of subsurface testing were completed as part of the geotechnical investigation at the site and included approximately 1.6 km of H and P-size rock coring (Table 1).

Rock core recovery was highly variable across the site with recoveries ranging from 60 to 70 percent. This is a high level of recovery for the unconsolidated and poorly cemented strata of the area. The subsurface testing locations are presented on Figure 12.

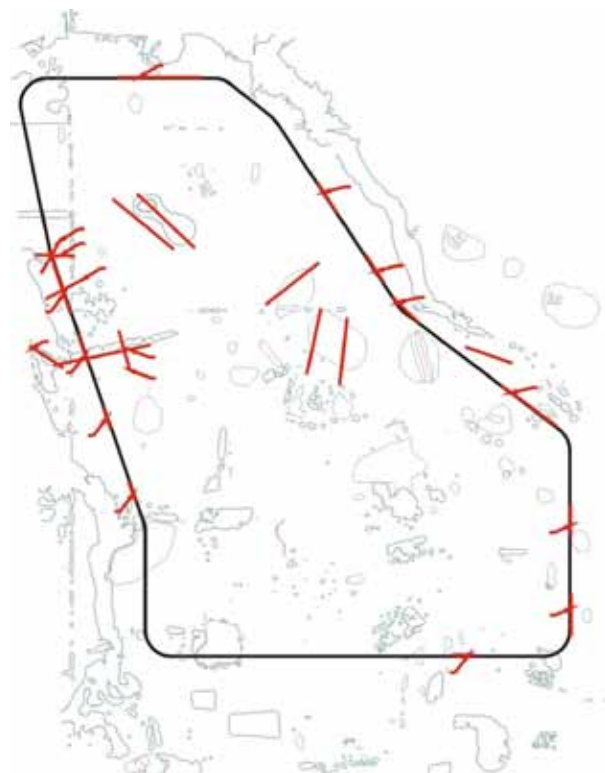
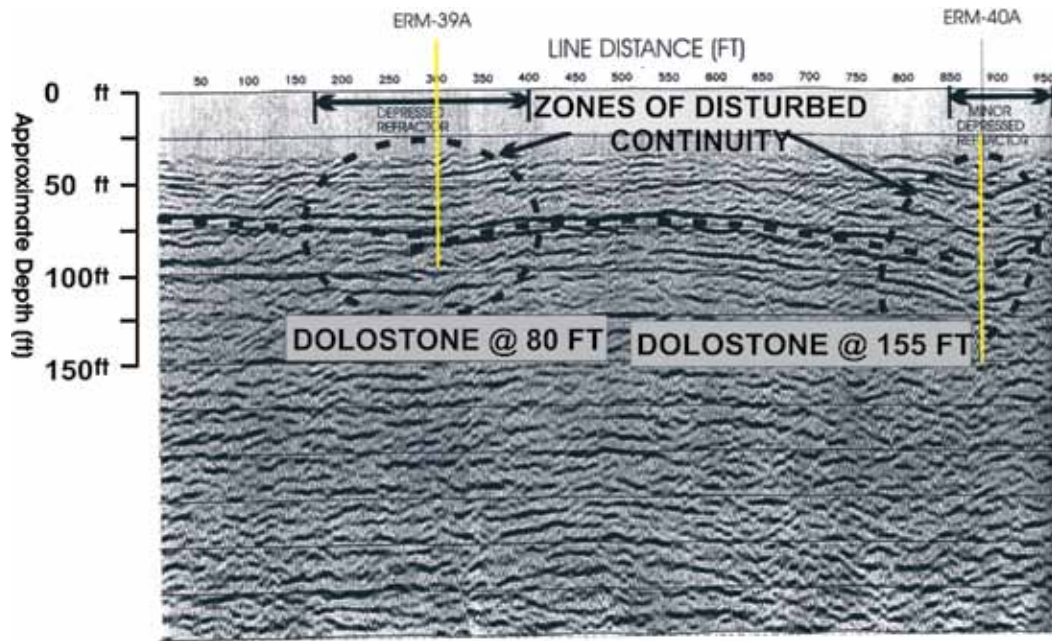


Figure 9. Location of seismic reflection lines (Upchurch et al. 1999).

Geologic formations were identified based on lithology. However, the upper 30.5 to 46 m of sediment at the site included well defined sequences of siliciclastic (sand, silt, and clay) and carbonate, which was determined to be well within the regional geologic context. Critical



ANOMALOUS SEISMIC REFLECTION SECTION - LINE 15

Figure 10. Example of an interpreted P wave reflection section and observed geophysical anomalies (Upchurch et al., 1999).

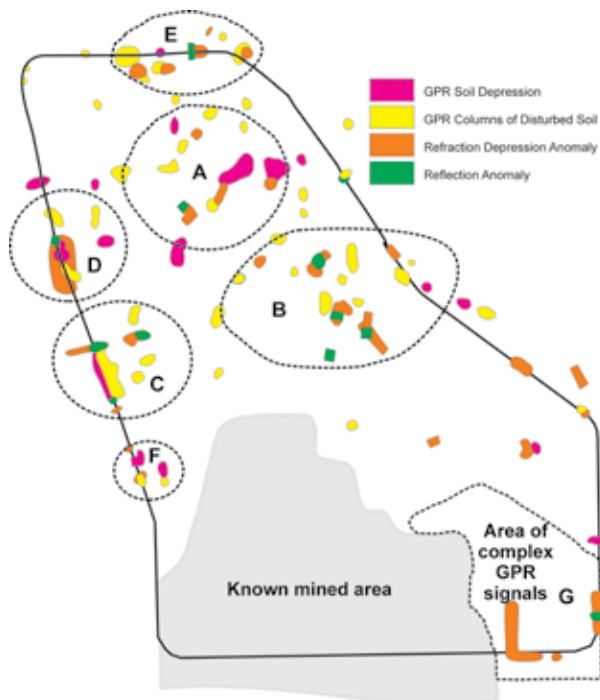


Figure 11. Identified geophysical anomalous condition areas A through G within the reservoir footprint. (Upchurch et al. 1999).

geologic observations which have a considerable influence in the photolinear interpretation include the leached zone and the epikarst. Both are discussed below.

Exploration Type	Number of Explorations	Total Linear Meters
Rotary/Wash Borings	165	4,084
Cone Penetrometer Test Soundings	109	975
Flat-plate Dilatometer Soundings	18	145
Auger Borings	60	274
Trenches	4	442
Piezometers	41	N/A
Aquifer Performance Test Soundings	2	N/A
Borehole Hydraulic Conductivity Tests	17	N/A

Table 1. Geologic engineering explorations and testing completed

From near the end of the Miocene through the Pliocene, sea level fluctuated greatly in this region of Hillsborough County, with long weathering events, erosion, and pedogenesis during the lower sea stands. Phosphorite-rich and clay-rich sediments were chemically altered during these episodes of extensive weathering.

The calcium phosphate mineral, carbonate fluorapatite, was leached, and the calcium moved downward in

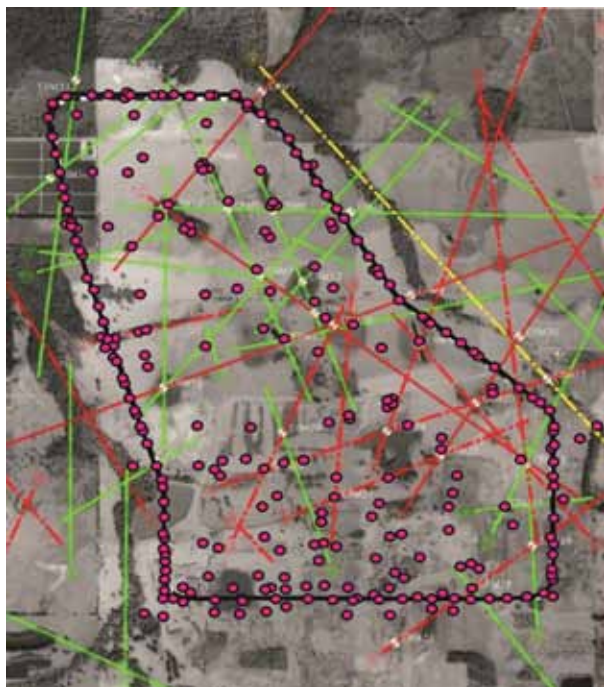


Figure 12. Location of subsurface testing sites (red circles; modified from Upchurch et al. 1999).

the stratigraphic column to contribute to formation of calcium carbonate cements in underlying strata. The phosphate was partly transported downward, but some remained to combine with aluminum, iron, and other weathering products in the resulting zone. The residual minerals formed by recombination of phosphate with other cations include wavelite, millisite, crandallite, and other aluminum phosphate minerals. This leaching process, therefore, formed two zones: a leached, aluminum-phosphate-rich zone at the top and a calcium-phosphate-enriched zone below. In mining terminology, the upper zone has been termed the “leached zone” (Carr and Alverson 1959). Carr and Alverson (1959) also showed that the dominant clay mineral in the strata being weathered was at least partially altered from montmorillonite to kaolinite. The resulting leached zone is, in fact, a fossil soil zone, or paleosol.

The leached zone is a portion of the thicker aluminum phosphate zone that contains aluminum phosphate minerals and is dominantly white to light tan in color or sediment colors developed as a result of the leaching of iron-containing minerals. The zone can be located in either the upper clayey sand unit of the Bone Valley Member, the upper clayey sand and top of the lower phosphorite unit of the Bone Valley Member, or both units of the Bone Valley Member plus the top of the Peace River Formation (Scott 1988). Carr and Alverson (1959) provide criteria for recognition of the aluminum phosphate zone, including: (1) vesicular-like texture;

(2) secondary cements; (3) white color; (4) low relative density; and (5) indurated or friable character.

The leached zone is present at the reservoir site and is a very critical component in the ground-truthing the photolineament assessment. At the site, the leached zone averages 4 m in thickness, with a range of 0 to 12 m. The thickness data indicate that the zone thins to the south, which would have resulted in higher phosphate values than in the north. The paleosol can be physically recognized by: (1) decreasing relative sediment strength (low penetration resistances measured during standard penetration testing); (2) weathered limestones; and (3) calcium carbonate-cemented sand, silt, or clay beds.

There are two patterns of thickened leached zone. First, in the center of the northern half of the site, there is some thickening of the leached zone. This coincides with a depression in the leached zone surface and the thicker overlying sediments. It is apparent that this area of the site was a region of enhanced weathering and pedogenesis, which contributed to the wetlands present at the land surface. There are also several locations of thickened leached zone in the small stream channels that exit the project site to the north and west. Again, this suggested that the paleosol surface represented by the top of the leached zone had drainage ways that were locations of enhanced weathering. These drainage ways have apparently redeveloped on the modern landscape, because of continual leaching (Upchurch et al. 2015).

The limestone and dolostone encountered below the leached zone within the Miocene Hawthorn Group clay-rich sediments were weathered in varying degrees via non-uniform dissolution and had an observable epikarst. Epikarst is the zone of weathering at the upper surface of a limestone stratum. Weathering of limestone results in development of rubble, fine-grained carbonate-rich silt, and clay, karren (including pinnacles and valleys in the limestone rock surface), and other features. Epikarst is frequently associated with losses of drilling fluid circulation, low penetration resistance (weight of rod or hammer events during standard penetration testing) and recovery of gravel-sized particles of rock. The epikarst can occur at the land surface or be buried under later sediments. Raveling of soil or sediments into the voids within the epikarst formation can lead to sinkhole formation, but in most cases, there is no evidence of ongoing or contemporaneous raveling, and the epikarst is not synonymous with sinkhole formation. The depth to these carbonate units varied due to the irregular surface of the epikarst, but on average was approximately 10 m BLS.

As an example of the results of subsurface testing as compared with the geophysical interpretations, Figure

13 is a boring-derived subsurface cross-section. Note the borehole results clearly show increased depth (depth is nearly double the normal dolostone depth) to the dolostone layer on one location, because of what appears to be a paleo-sinkhole.

Upon completion of the subsurface exploration program, the photolinears were again reviewed and any photolinear with a vertically extensive geophysical or stratigraphic signature was considered a fracture trace. All other unconfirmed photolinears were not considered further.

Post Hoc Photolinear Analysis

Table 2 presents the results of the *post hoc* review of photolineament verification at the site. The results were somewhat surprising given the confidence that we expressed in photolineament analysis prior to commencement of the investigation.

Approximately 48 percent of the photolineaments and potential karst features were confirmed as representing bedrock fractures or sinkholes. Of these, we had to adjust the apparent lengths of the photolineaments in the majority (Table 2), generally because the fracture was shorter than predicted by the photolineament.

The photolinear features that were not found to have deep subsurface indicators are apparently a result of conditions that are restricted to the marine terrace sand and/or paleosol. Upchurch et al. (2015) discuss the origins of the shallow depressions associated with the paleosol.

Discussion and Conclusions

The photolinear features that were confirmed as bedrock fractures by means of the geophysical surveys appear to reflect vertical fractures in the underlying carbonate rock, in many cases accompanied by depressions in the top of the leached zone or underlying strata. For the most part, the surface expressions of verified photolineaments reflect soil and sediment deposition and minor compaction into depressions in the leached zone and top of the upper siliciclastic and/or carbonate facies of the Miocene Hawthorn Group (Upchurch et al. 2015). Buried relict stream channels and other topographic features developed on the leached zone were also detected.

Outcome	Percentage
Photolineaments confirmed as fracture traces, no modifications of delineation required	5.8%
Photolineament confirmed as a fracture trace, length was shorter than predicted	32.7%
Photolineament confirmed as a fracture trace, length was longer than predicted	9.6%
Photolineament was not confirmed to represent a fracture trace	57.7%

Table 2. Results of the post hoc evaluation of photolineament accuracy.

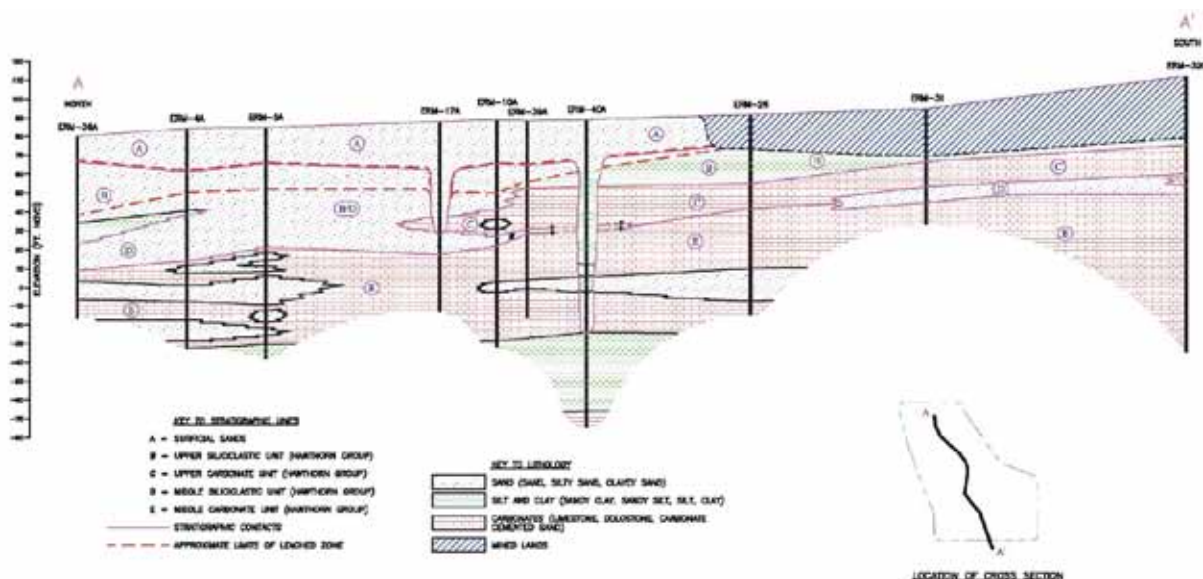


Figure 13. North-Northwest/South-Southeast geologic fencepost diagram (Upchurch et al., 1999).

Minor differential settlement in the Plio-Pleistocene paleosol features resulted in some of the photolineaments, which were not related to fracturing or karst in the underlying carbonate strata (Upchurch et al. 2015). One apparent paleo-sinkhole feature within the original alignment of the berm was considered of sufficient importance that the berm was realigned to avoid it. Otherwise, the paleo-karst features did not provide geologic or geotechnical evidence for reactivation and were found to be competent for reservoir development without a liner or other leakance prevention system. The reservoir has been in use for over a decade without incident, and leakage from the reservoir is less than predicted. To date, no sinkholes have developed at the site.

In respect to the photolinear interpretation (Figure 3), the analysis was conservative in that all potential photolineaments were identified. All points where a photolinear feature crossed the embankment were investigated with GPR and seismic refraction. Seismic reflection was employed if anomalies were detected by seismic refraction surveying. Because geophysical exploration was combined with subsurface geotechnical testing along the embankment centerline and in geophysical anomalies, the photolinear verification process was considered extensive and thorough.

It is important to note that even photolinears presented on Figure 3 with high levels of relative confidence (i.e., multiple, strong visual indicators of linear features) were found to have no or very weak subsurface indications of the causes of the photolinears. Many of the photolineaments (32/55 or 58 percent) were not confirmed by geophysical or subsurface exploration. Most features that have been confirmed by geophysical exploration are restricted in their lengths when compared to the original photolinear analysis. This *post hoc* review of the results of verification of photolinear features by geophysical and subsurface explorations demonstrates the fallacies of assuming that all photolinears represent vertical bedrock fractures in a covered karst terrain.

Regional and local photolineament analyses are valuable as a first approximation of the possible presence of bedrock structures such as vertical fractures in covered karst. However, one cannot rely on a correlation between photolinear features and fracture traces in covered karst areas without field verification. The results of our case study are consistent with the published literature (i.e., Wheeler 1983) in showing that ground truthing using other kinds of data is necessary to verify the correspondence between photolineaments and vertical fractures and karst features.

It is also important to point out that hydraulic pathways (i.e., cavernous porosity, solution-enlarged bedding planes, etc.) may exist in covered karst terrains. Therefore, the absence of verified fractures may not indicate low hydraulic conductivities of the underlying carbonate strata.

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ASSESSMENT OF HISTORICAL AERIAL PHOTOGRAPHY AS INITIAL SCREENING TOOL TO IDENTIFY AREAS AT POSSIBLE RISK TO SINKHOLE DEVELOPMENT

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Abstract

Use of historical aerial photography to perform desktop site assessments to mitigate cover-collapse sinkhole risk is not a new concept in the geoscientific arena. Unfortunately, it has not been a routine part of the decision matrix for land-use planning and development. This paper demonstrates the importance of historical aerial photography analysis as a preliminary tool to identify site-specific sinkhole risk. Three case studies are presented to underscore this observation. In sinkhole-prone regions in parts of Florida and many other states across the county, infrastructure siting and other land-use planning activities would be well-served to include this type of analysis.

Introduction

Littlefield et al. (1984) demonstrated that sinkholes tend to preferentially occur along fracture traces and at fracture-trace intersections. The use of historical aerial photography to identify photolineaments and, after ground-truthing, fracture traces is not a new concept. The Florida Geological Survey's Special Publication No. 57 recommends the use of historical aerial photography as an integral part of the desktop evaluations to assess potential subsidence (Schmidt 2005). In 2015, Florida Administrative Code (Rule 62-701.410, F.A.C.) required assessment of historical aerial photography to identify potential karst hazards for proposed landfill sites.

In areas where regolith thinly covers limestone, or is bare, there is a higher correlation between photo-interpreted features and fractures. This degree of correlation does not exist in covered karst terrains, such as Florida, which necessitates photolinear verification to minimize risk of harm or failure. Schmidt (2005) indicates semicircular depressions, wetlands, and other features observed on aerial photographs or other remotely sensed images may represent sinkholes or other karst features, but not in every case.

This paper documents results of historical aerial photographic review of three recent catastrophic sinkholes that were headline news in Florida, and in the international press, to determine if historical aerial photography might have provided clues to these future catastrophic events.

July 14, 2017: Ocean Pines Drive, Land O' Lakes, Florida

Sinkhole description and metrics

The Ocean Pines Drive sinkhole (Site 1) is a large cover-collapse sinkhole which formed abruptly the morning of July 14, 2017 (Figures 1 and 2). Two homes were destroyed by the collapse and eight others were condemned. No people or pets were injured. One of the two homes had been previously "remediated" for sinkhole activity with pin piles. The sinkhole dimensions were: length 50 meters (164 feet), width 42 meters (137.8 feet), and depth 12 meters (40 feet).



Figure 1. Ocean Pines Drive sinkhole, bottom of photograph is north (WFLA NBC 8, 2017)



Figure 2. Site 1 location on 2017 aerial imagery (Google Earth, 2017)

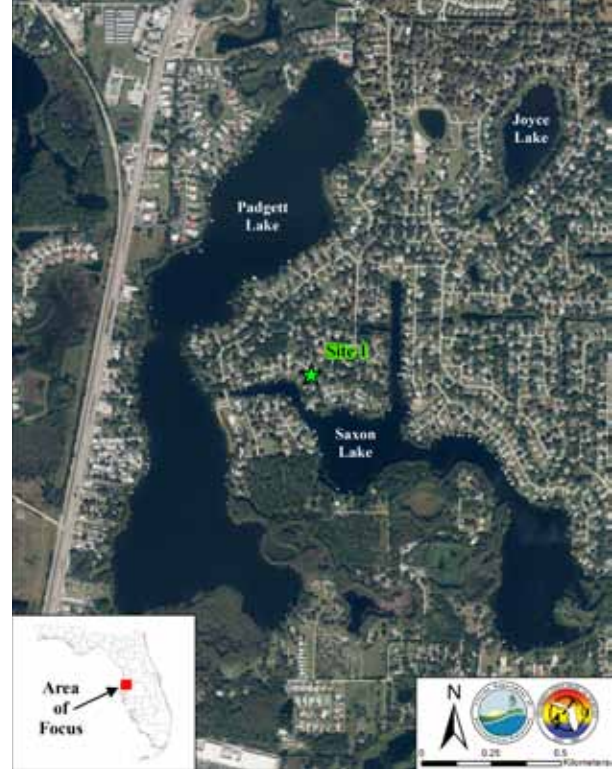


Figure 3. Site 1 location on 2014 aerial photography (FDEP LABINS, 2017)

Location map and historical aerals

Site 1 is located in Land O' Lakes, Florida, approximately 28 km (17.4 mi) north of Tampa, Florida (Figure 3). Land O' Lakes received its name from the hundreds of karst lakes in the region. The lakes gain their lobed appearance from millions of years of sinkhole development.

To assess risk to potential sinkhole formation at Site 1 using historical aerial photography, photos from 1938, 1957, 1965 and 1974 (Figures 4, 5, 6, and 7) were downloaded and georeferenced into a geographic information system (GIS). The advantage of analyzing photos from multiple years allows one to see the area of interest in predevelopment (Figure 4 and 5) and during development (Figure 6 and 7), at different water table elevations, historical drainage patterns, and most importantly, the presence of pre-existing karst features.

General Geologic Setting

The sinkhole is located in the Land O' Lakes Karst Plain province (Green et al., 2012a, Green et al., 2012b, Williams et al., in preparation) which is typified by a thin veneer of undifferentiated Quaternary sediments comprised of clayey sands, sandy clays, and clay sitting directly on top of Oligocene Tampa Member limestone of the Arcadia Formation of the Hawthorn Group. Nearby

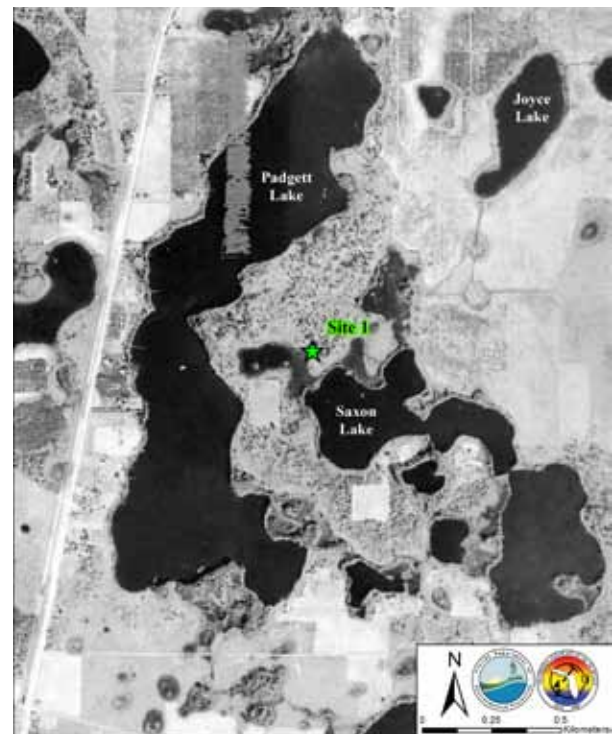


Figure 4. Site 1 location on 1938 USDA aerial photography (University of Florida, 2017)

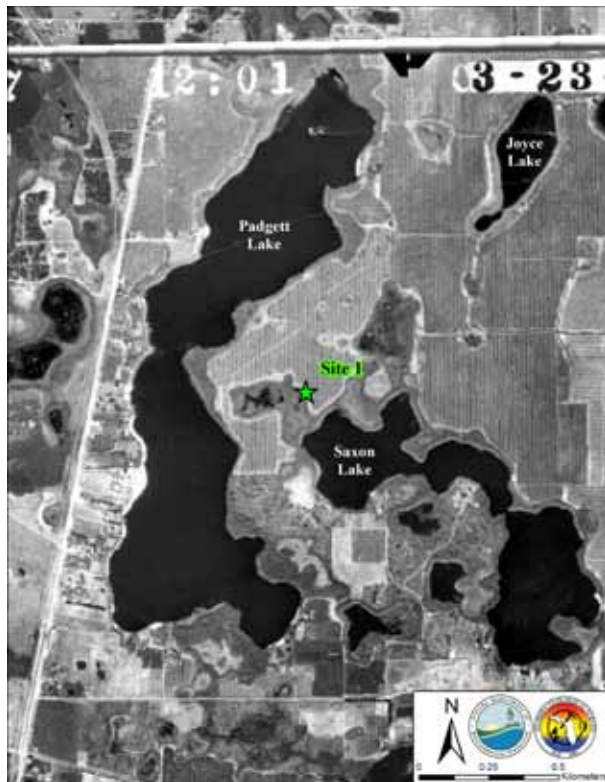


Figure 5. Site 1 location on 1957 USDA aerial photography (University of Florida, 2017)

lithologic boreholes indicate limestone is encountered approximately 15.2 meters (50 feet) below land surface (Green et al., 2012a).

Discussion of Observations

When comparing Figures 4 and 5 to Figures 6 and 7, the most immediate difference observed in the images is the shape of Saxon Lake. On the north and northwestern reaches of the lake, significant dredge and fill activity occurred beginning sometime between 1957 and 1965 (Figure 5 and 6). In Figures 4 and 5, Site 1 is located just inside a polje, with multiple circular sinkhole features visible, that were subsequently dredged and filled by 1965 (Figure 6). A photolinear of sinkholes arranged in a line oriented north-northeast starting at the bottom left of Figure 4 is nearly parallel to the long axis of Padgett Lake and passes through Saxon Lake up to Joyce Lake. By 1974 (Figure 7) the dredge and fill process is complete, Saxon Lake has been canaled to connect with Padgett Lake, and homes are beginning to be built on the newly created lake-front lands. In addition to an established history of sinkholes, the dredged fill material, where housing was later built, likely poses a risk to the general sediment stability due to compaction of former lake bed sediments.



Figure 6. Site 1 location on 1965 FDOT aerial photography.



Figure 7. Site 1 location on 1974 USDA aerial photography (University of Florida, 2017)

December 18, 2004: Howland Boulevard, Deltona, Florida

Sinkhole description and metrics

The Howland Boulevard sinkhole (Site 2) is a large cover-collapse sinkhole which formed abruptly on Saturday December 18, 2004 (Figure 8). As a precaution, twenty homes in the vicinity of the sinkhole were evacuated. The sinkhole formed when workers were attempting to compact, using pumped concrete, the soft sediment below the road's base, which had partially subsided shortly after the road was constructed. The road leading south from the sinkhole is an entrance to a local high school. The sinkhole eventually grew to an estimated diameter of 68.5 meters (225 feet) and a depth of 15.2 meters (50 feet).

General Geologic Setting

Site 2 is located in the DeLand Ridge province which is characterized by rolling karst hills with closed basin lakes and sand dune fields (Williams et al., in preparation). The ridge is underlain by approximately 23 meters (75 feet) of quartz sand with minor amounts of organics overlying limestone and dolostone of the middle Eocene Avon Park Formation.

Location map and historical aerials

Site 2 is located approximately 36 km (22.5 mi) southwest of Daytona Beach, Florida (Figure 9). To assess Site 2's risk to potential sinkhole formation using historical aerial photography, photos from 1943 and 1973 (Figures 10 and 11) were downloaded and georeferenced into a GIS.

Discussion of Observations

Immediately visible in the 1943 photograph (Figure 10) adjacent to Site 2 is a large circular stand of trees



Figure 8. Site 2 sinkhole, top of photograph is north (New York Times, 2004)



Figure 9. Site 2 location on 2012 aerial photography (FDEP LABINS, 2017)

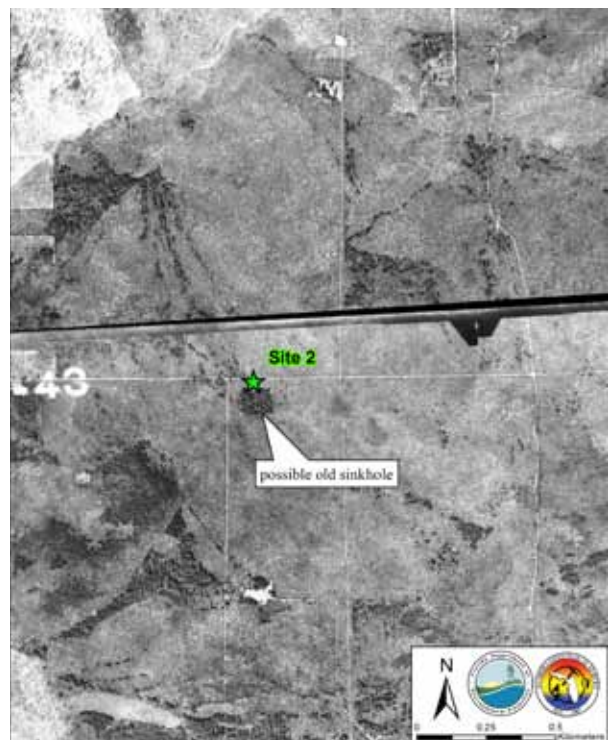


Figure 10. Site 2 sinkhole location on 1943 USDA aerial photography (University of Florida, 2017)



Figure 11. Site 2 sinkhole location on 1973 USDA aerial photography (University of Florida, 2017)

suggesting the presence of a historical sinkhole. The stand of trees exhibits a circular shape. Throughout Florida and other karst regions where sinkholes are common, tree clusters in a circular shape are a common occurrence and are generally related to karst. Furthermore, northwest-southeast soil-tone and vegetation photolinears cut through and are adjacent to the site (Figure 10). In Figure 11, the circular shape visible, but the vegetation has changed.

June 10, 2017 2701 SW College Road and September 11, 2017 3410 SW College Road, Ocala, Florida **Sinkhole description and metrics**

Separated by approximately 1.5 km (0.9 mi) and 3 months, sinkholes opened at two fast-food restaurants on SW College Road in Ocala, Florida (Figure 12). Both sinkholes made headlines due to the partial collapse of the parking lots that damaged two vehicles. The June 10, 2017 sinkhole at 2701 SW College Road, herein referred to as Site 3A, was approximately 7.6 meters (25 feet) in width and depth (Figure 13). The partial collapse of the parking lot damaged a Kia Optima. The September 11, 2017 sinkhole at 3410 SW College Road, herein referred to as Site 3B, was approximately 3 m in width, based



Figure 12. Site 3A and 3B locations on 2014 aerial photography (FDEP LABINS, 2017).



Figure 13. Site 3A sinkhole, top left of photograph is north (Miller, 2017).

on video review, however, the depth was not reported (Figure 14). The partial collapse of the parking lot damaged a Toyota Tundra.

General Geologic Setting

Both sites reside in the mature karst topography of the Ocala Karst Hills province (Williams et al., in preparation) and are geologically similar. The underlying strata at both sites are comprised of a thin layer of undifferentiated sediments containing primarily quartz



Figure 14. Site 3B sinkhole, top left of photograph is north (Kenyon, 2017).

sand with variable admixtures of clay and organics with minor chert, overlying the Eocene Ocala Limestone. The limestone occurs within less than 6 meters (20 feet) from land surface.

Location map and historical aerals

Sites 3A and 3B are located near the northeast off-ramp of I-75 and SW College Road in Ocala, Florida. To assess the risk of sinkhole formation at Site 3A and 3B using historical aerial photography, USDA and FDOT historical aerial photographs from 1956 and 1983 (Figures 15 and 16) were downloaded (FDEP LABINS, 2017) and georeferenced into a GIS.

Discussion of observations

Unlike the prior case studies presented in this paper, these sites are specifically presented to demonstrate that the review of historical aerial photography is only a screening tool and should never be considered a means to derive definitive evidence for sinkhole formation. The historical aerial photographs reviewed provided evidence of proximal karst features including: photolineaments, closed topographic depressions (CTDs), potentially related to coalescing features; air-filled and water-filled cave systems; and swallets (Figure 17). This demonstrates a relatively decent correlation of observed features in the aerial photography and field identified karst features. However, none of these karst features are identified at either site locations. Based on the aerial photography reviewed, neither site had readily identifiable changes in soil tones or identified photolineaments (individual or intersecting). Site 3A does align with a linear of CTDs (Figure 17); however, those CTDs are not interpretable from the photos. If a review of historic aerial photography by qualified professionals had been conducted prior to construction at either of these sites they would more than likely have yielded similar results as this current evaluation, but the identification of the near-by karst features would suggest the need for additional screening using geophysical and/or geotechnical subsurface testing, such as, but



Figure 15. January 11, 1956 USDA aerial photography (University of Florida, 2017).



Figure 16. March 2, 1983 FDOT aerial photography.

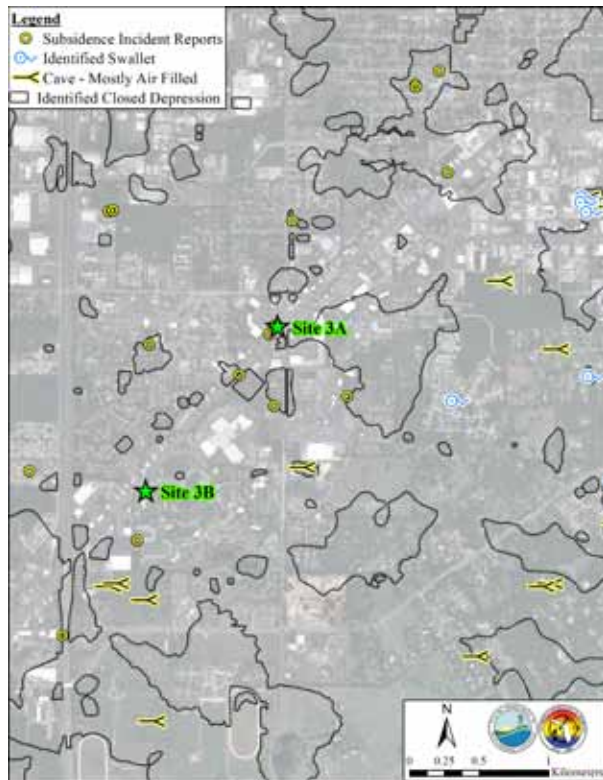


Figure 17. Karst related features proximity to Site 3A and 3B on 2014 aerial photography.

not limited to: ground penetrating radar (GPR), multi-electrode electrical resistivity (MER), multi-channel analysis of sub-surface waves (MASW), standard penetration test (SPT) borings, or cone penetrometer test (CPT) soundings, prior to construction to evaluate the potential for sinkhole formation at the sites.

Conclusions

Sinkholes may form catastrophically and instantaneously, or form over geologic time. At present, the specific timing and location of sinkholes are largely difficult to predict. The case studies presented herein demonstrate the value of historical aerial photography to assess sinkhole risk prior to development. Had a requirement been in place, prior to development, the loss of property and potential endangerment to human welfare potentially could have been avoided.

Greater consideration should be given to use of this assessment tool. In fact, outcomes of such assessments could guide improved engineering requirements, land-use planning, and development. This type of screening, however, is by no means definitive. Additional screening or subsurface testing should also be completed prior to determining if a site is susceptible to sinkhole formation.

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MAPPING OF POTENTIAL SHOW CAVES IN THE RACHA LIMESTONE MASSIF (COUNTRY OF GEORGIA)

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Abstract

The Racha limestone massif is located in the eastern part of the karst zone of western Georgia. The massif is a typical example of Georgian mountain karst regions, where diverse surface and subsurface karst landforms are found. The main aim of this research is to present mapping of two potential show caves, and document speleological information from the Racha limestone massif. The morphological parameters and tectonic directions of the Muradi and Usholta Caves were mapped using the compass-clinometer and laser distance meter, to compile 3D models of the caves. To our knowledge these are the first 3D models of karst caves in Georgia.

Introduction

The country of Georgia is home to multiple, widespread limestone massifs with well-developed karst areas and their associated landscape features found throughout the country. The limestone massifs occupy more than 4,475 km², or 6.4%, of the entire territory of Georgia (Asanidze et al. 2013a; Asanidze et al. 2013b), and contain over 1,500 known caves (Asanidze et al. 2017a).

Given the variable tectonic influences, nature of the bedrock structure and hydrological complexity of the areas, the development of different types of karst features, including both hypogenic and epigenic caves, is not surprising (Tintilozov, 1976; Palmer, 2007; Ford and Williams, 2007).

In this paper we present new information on the Muradi and Usholta Cave systems focusing on speleogenic processes and secondary mineralogical deposits. The Muradi and Usholta caves are developed on the Racha limestone massif, the total area of which exceeds 590 km² (Asanidze et al. 2017b; Asanidze et al., 2017c). Geographically, the Racha limestone massif is located in the Oni and Ambrolauri regions (western Georgia). The Racha limestone massif has the largest areal extent, but less relief compared to other karst regions in Georgia (Lezhava, 2015).

This work created the first 3D models of caves in Georgia, to our knowledge. The Muradi and Usholta Caves are important speleological objects and as potential show caves they can be used for the speleo-tourism purposes. The economic situation in this region is weak due to the lack of natural resources. The development of speleotourism is an important opportunity to improve the quality of life in this region (Debevec et al. 2012).

Geological Settings of the Study Area

The Racha limestone massif is a classic geomorphic region in the Caucasus in terms of the development of karst processes and landforms. The Bajocian porphyritic suite is the basis of the massif and Cretaceous carbonate rocks also influence the structure of the stratigraphy (Rakviashvili, 1985). Rocks from almost every part of the Early and Late Cretaceous exist in the region (Figure 1).

The massif consists mainly of upper and lower Cretaceous and Paleogene limestones, which have an important influence on the origin and development of the surface and underground karst features and on the water table and its fluctuations (Rakviashvili, 1985).

The prominence of karst processes in the region is high, due to the rapid movement of water along the structural weaknesses in the limestones. The fault dislocations provide locations for cave's inception and groundwater infiltration. Infiltration of surface water is rapid and there is almost no surface flow on the surface of the massif. Some small surface streams are mostly associated with the rainy and snowmelt periods.

General Description of the Caves

The Muradi Cave is located in the southwestern part of the Racha limestone massif in the Nakerala Range (Figure 1). The Nakerala Range comprises a small piece of the Racha limestone massif.

The Muradi Cave (elevation 1498 m a.s.l.) contains upper and lower levels. The lower level of the cave was discovered 15 years ago by a local resident and is about 171 m in length. In November 2014, the Mountaineers

and Travelers Club accidentally found a new narrow corridor. After navigating the corridor, the club members explored a previously unknown, very interesting, upper level of the cave. A complex scientific study supervised by the lead author was subsequently conducted in the cave by speleological expeditions of the Vakhushti Bagrationi Institute of Geography of Tbilisi State University (TSU).

The Lower level of the Muradi Cave is dry and easy to pass through. In some parts of the lower level limestone rocks are collapsed from the ceiling.

Secondary calcite deposits are rare in the lower section of the cave. The upper level of the cave is connected to the lower level via 10 meters of vertical passage and totally is 489 meters in length. The total length of Muradi Cave is 660 m. The upper level, in contrast to the lower level, contains almost all types and subtypes of calcite deposits which are recorded in the caves of the Caucasus region (Tintilozov, 1976).

The Usholta Cave is located in the eastern part of the Racha limestone massif at an elevation of 1817 m a.s.l.

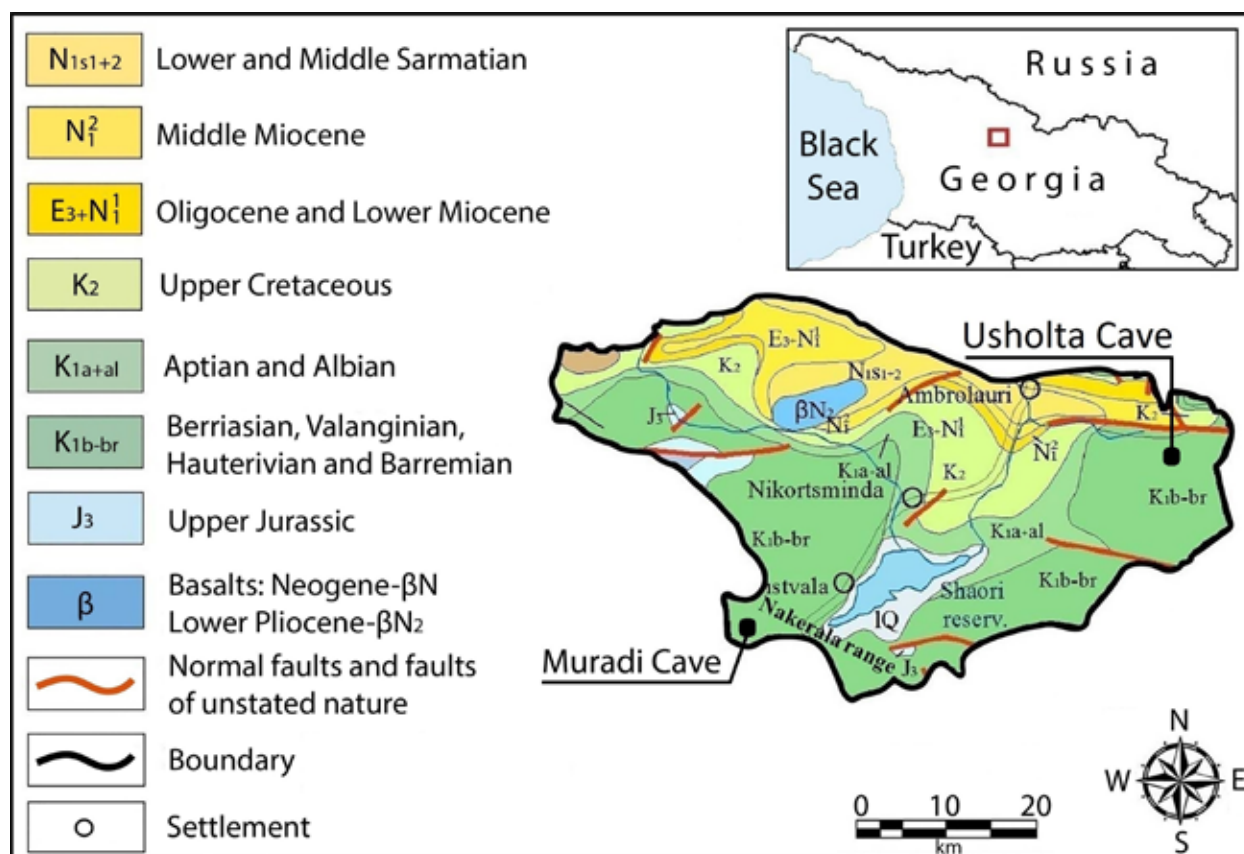


Figure 1. Geological map of the Racha limestone massif (after Gujabadze, 2003). Location of the Muradi and Usholta Cave systems.

(Figure 1). The Usholta Cave was discovered in the 1960s, but the cave was only partially explored. Only a line map of the cave was produced at that time. The cave has only one level with two main branches. Some parts of the cave floor are covered with the limestone rocks fallen from the ceiling, which makes it difficult to traverse these areas. A complex scientific study supervised by the lead author was subsequently conducted in the cave by speleological expeditions of the Vakhushti Bagrationi Institute of Geography of Tbilisi State University (TSU).

Methodology

The basic methods applied for studying classical karst regions and underground cavities have been used during this study. For the first step, at the entrances of the Muradi and Usholta Caves, we took several points using GPS 60cs, by which the coordinates and altitudes of the caves were defined. The morphological parameters and tectonic directions of the Muradi and Usholta Caves were measured using a compass-clinometer and a laser distance meter (in the Muradi Cave we took 40 points, and in the Usholta Cave we took 50 points at various distances between cave walls, ceilings and floors), from which we compiled the 3D models of the caves. Air and water temperatures (°C) were measured in different places within the caves using an Onset HOBO Pro V2 Data Logger and the Enviro Safe portable thermometer.

Results and Discussion

Cave survey, mapping and data processing

The goals of this research included the detailed survey and mapping of these caves and collection of information from speleological point of view for speleo-tourism development in the Racha limestone massif. The goals address the questions: 1) are these caves of sufficient scientific value to necessitate careful study, protection and preservation, and 2) to provide information to enable an economic evaluation of these caves potentials to be developed into viable speleo-tourist attractions.

While rough maps from traditional survey methods can be suitable for general navigation through a cave, for some applications, such as scientific research and environmental assessment, greater detail and resolution are required (Zlot and Bosse, 2014). At the same time, the limited accessibility and light conditions make mapping of cave morphology very difficult (Gallay et al. 2015).

During several expeditions in the Racha limestone massif, the caves were surveyed using a compass, clinometer, and laser distance meter. The survey of the Muradi Cave shows that it has one main passage (lower and upper passages) with three shorter branches – one is located in the lower passage, and two of them are located in the upper passage. The 171-meter long horizontal section of the main, lower cave level connects with the

upper level through a 10-m vertical passage. Near the end of the upper level of the cave there are four karst shafts 11, 42, 35, and 37 m deep respectively, which are connected to each other through the narrow holes. The cold air mass movements are palpable in the karst shafts section. In the authors' opinion, this air movement is probably related to unobserved holes existing in the cave. In the right corner of the passage (azimuth 95°), a wide (5 m) and long (34 m) tunnel-shaped passage is formed in the Urganian limestones. By the Compass cave survey software and ArcGIS the 3D map of the cave was created within the context of the landscape (Figure 2).

No permanent streams enter the Muradi Cave and no traces of modern, ephemeral stream actions are evident in the upper passage. On the other hand, the influence of infiltration and condensate waters is obvious. Intense movement of cold air (5°C) observed in the terminal section of the cave is evidence of a possible extension of the cave. Several times in 2015 and 2016, the air temperature was measured in the two sections of the cave, one – at the entrance (slightly above 7°C), and the second – at the end of the cave, near where the speleothems were formed in a pool of water. Near this pool, the water temperature was also measured to be 7°C.

The Usholta Cave is developed on a single, horizontal level with two main branches. The second, an 800 m long, previously unknown branch, was discovered in 2015 during a speleo-geomorphological exploration expedition led by the lead author. It is planned to investigate the mentioned branch, but it is related to certain difficulties, since the branch is periodically being narrowed, very much that makes it harder to move into the depths.

The cave, which has two main branches. The total length of the cave is 2 km. Based on the survey data, Compass cave survey software and ArcGIS was used to create a 3D map of the cave within the context of the landscape (Figure 3).

Episodic and seasonal speleo climate observations were conducted several times in the Usholta Cave between 2014 and 2016. No substantial changes in the air and water temperatures were observed at specific monitored locations. Water levels in the stream passing through the cave were almost constant and did not vary significantly. The air temperature was measured in the two sections of the cave, one – near the entrance (10°C), and the second – at the end of the cave (6.8°C). Also, the water temperature was measured in the two different places of the cave, one near the entrance (6.4°C), and the second at the end of the cave (4.8°C). In the opinion of the authors, significant difference of water and air temperature is caused by the following factors, including as follows: 1.

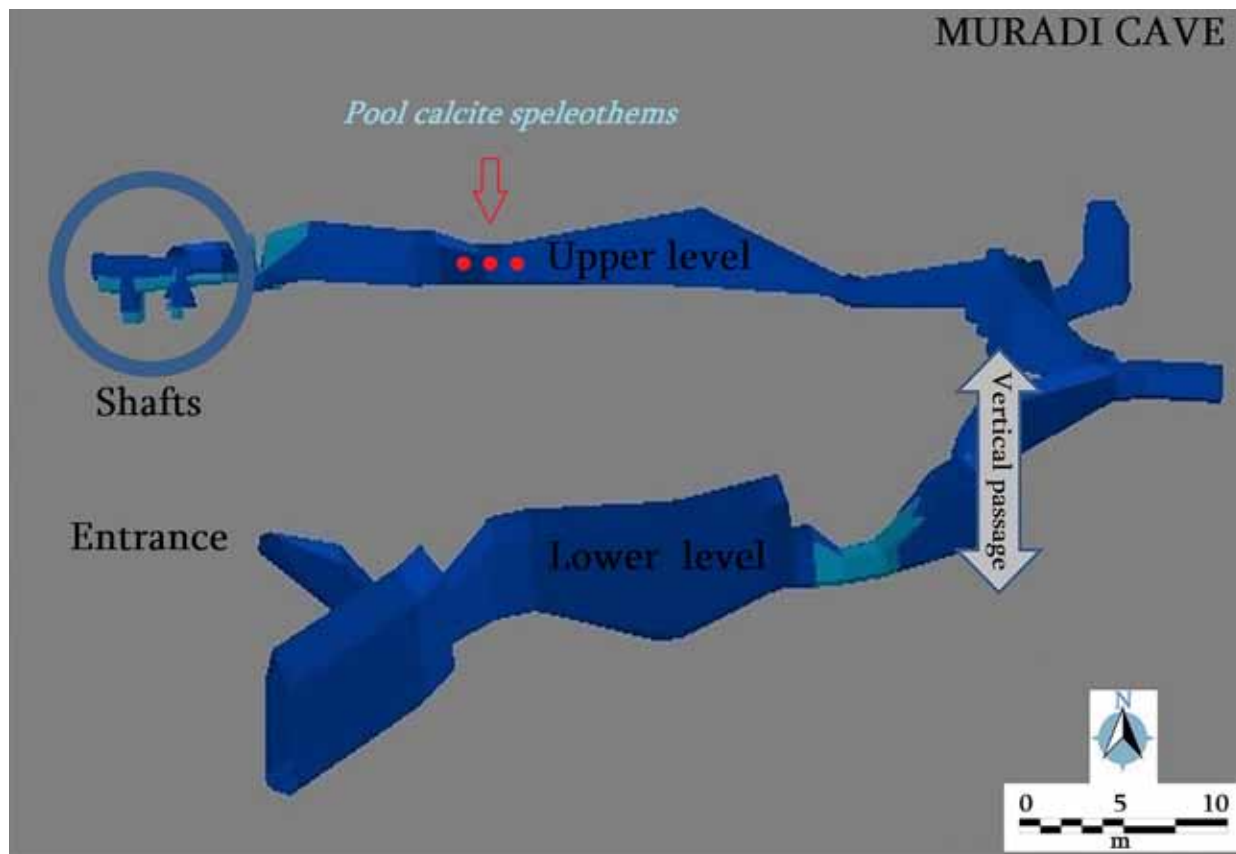


Figure 2. The Compass-generated 3D model of the Muradi Cave (by Lasha Asanidze).



Figure 3. The Compass-generated 3D model of the Usholta Cave (by Lasha Asanidze).

The morphology of the cave; 2. Intensive inflow of cold water in the cave; 3. Hypsometric location of the cave, etc.

Secondary mineral deposits (pool speleothems)

The Muradi Cave, which may become a very popular speleo object in this region, is a very rich in calcite speleothems. The cave contains almost all types and subtypes of speleothems recorded in the caves of the Caucasus region (Lezhava, 2015; Tintilozov, 1976). Beautiful examples of spherical formations (pool speleothems), formed by calcite mineral aggregates, give the cave particular uniqueness and there is no known analog in caves in the whole Caucasus region (Figure 4, 5). They are mostly subaqueous, lithified calcite balls of different sizes (the smallest is 16 cm and the largest is 180 cm in circumference) at one level in a shallow pool in the Muradi Cave in the upper level. They seem to have been formed at the same level in the water, perhaps as formations similar to phreatic overgrowth from supersaturated waters existing at higher water levels during times of tectonic change, flooding, or base level shifts and thus indicating a period of higher water table and stability in between tectonic shifts (Bieniok et al.

2011; Merino et al. 2014; Jacek, 2015). X-ray diffraction (XRD) analysis confirmed that these are 100% calcite deposits (Asanidze et al. 2017d; Asanidze et al. 2017e).

One of the interesting formations found in the Muradi Cave is a moonmilk, which is not very common in the caves of the Caucasus region (Tintilozov, 1976). This formation is mostly found in the wet passages and occurs in pools of water. The moonmilk is actively formed under the aggressive influence of condensate waters. The aggressive waters, by dissolving the limestone walls, lead to the formation of the moonmilk (Hill and Forti, 1997; Merino et al. 2014; Borsato et al. 2000) and, often, infiltration waters also participate in this process. A study by Geze (1965) suggests that microorganisms play an active role in their formation (biochemical weathering) as well, but more work is needed in the Muradi Cave to better determine that possibility.

However, other authors, such as Shumenko and Olimpiev (1977), did not find microorganisms in the moonmilk they studied. It appears, then, that microorganisms are possible, but not essential factor in the formation of moonmilk (Hill and Forti, 1997).



Figure 4. The spherical examples of pool calcite speleothems, which could be formed from water level fluctuations over time (photo by George Lominadze).

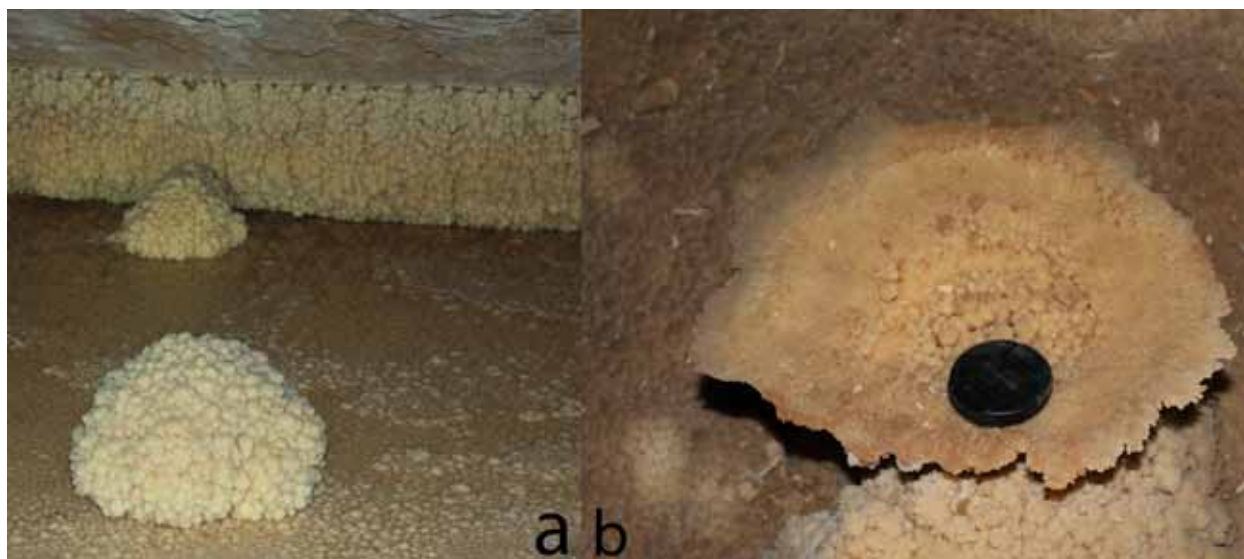


Figure 5. a) The pool calcite speleothems deposited subaqueously in cave pools at multiple places of the Muradi Cave. b) Cave cup developed in the shallow pool of the Usholta Cave (photos by Lasha Asanidze).

In contrast to the Muradi Cave, calcite speleothems are almost completely absent in the Usholta Cave. Based on the speleo-geomorphological and field studies we note that the ceiling and the walls of the Usholta Cave are devoid of crack chain and that limits the infiltration of the water into the cave. We interpret the absence of the crack chains to be one of the reasons that calcite formations did not develop in the Usholta Cave. The opposite condition is present in the Muradi Cave where the intensive fracturing contributes to the development of the unique calcite forms, which are developed near the clefts.

Conclusions

This research effort has created, for the first time in Georgia, electronic databases in Geographic Information Systems (GIS) for the Racha limestone massif. These data bases include: Climatic characteristics of the caves; Morphometric parameters; Speleological descriptions and more other information. This information is regularly updated and it can be provided for the cave research. This research effort also created the first 3D models of the caves in Georgia. Muradi and Usholta Caves are important speleological objects and they potentially can be used for the speleo-tourism purposes. Speleological surveys of caves and detailed 3D models will be useful background information for any future speleo-tourism development.

Acknowledgements

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A COMPARATIVE STUDY OF KARST SINKHOLE HAZARD MAPPING USING FREQUENCY RATIO AND ARTIFICIAL NEURAL NETWORK FOR EAST CENTRAL FLORIDA

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Abstract

Sinkholes are one of the most common geohazards occurring in East Central Florida (ECF). Identifying areas prone to sinkholes is vital for land use planning in the ECF area, and thus, sinkhole hazard mapping plays a critical role. The present study presents (1) sinkhole hazard maps of ECF by using frequency ratio (FR) and artificial neural network (ANN) models and (2) a validation and comparison of the performance of two models. An inventory map with a total of 757 sinkhole locations was prepared from Florida subsidence incident reports (FSIR). 70% (530 sinkholes) were randomly selected to calibrate the sinkhole hazard models, and the remaining 30% (227 sinkholes) were used for the model validation. Five sinkhole contributing factors were considered including age of sediment deposition, hydraulic head difference, groundwater recharge rate, overburden thickness, and proximity to karst features. The relationship between sinkhole occurrence and sinkhole contributing factors was investigated through a GIS-based statistical analysis.

Introduction

Karst topography occurs in terrains that contain distinctive landforms and hydrology created primarily from the dissolution of soluble bedrock. The soluble bedrock is typically carbonate rocks such as limestone, dolomite, and gypsum and common features of karst topography include sinkholes, springs, and caverns, etc. According to the US Geological Survey (USGS), karst topography makes up about 20 percent of the Nation's land surface and extensive karst topography is found in the states of Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania (Weary and Doctor, 2014).

A sinkhole is one of the most common and frequent natural geohazards in the karst terrain. It poses a threat not only to public safety but also to property, resources, and the environment. Sinkholes create at least \$300 million in damages each year in the United States and

the actual damage is probably much higher than this estimate as there is no formal nationwide tracking of damage costs (Weary, 2015). The Florida Office of Insurance Regulation reports that insurers received a total of 24,671 claims for sinkhole damage in Florida between 2006 and 2010 totaling \$1.4 billion. The report shows the insurers' expense has been rising with an increasing trend in both frequency and severity of sinkholes (FLOIR, 2010).

Considering that a number of factors contribute to sinkhole formation in karst areas, geologists and geotechnical engineers are faced with a difficult task when attempting to identify the most important factors that lead to sinkhole development. Past studies on sinkhole formation in Florida show that hydrogeological factors are strongly linked to its occurrence (Wilson and Beck, 1992; Tihansky, 1999; Xiao et al., 2016; Perez et al., 2017). These sinkhole-related factors include hydraulic head difference, groundwater recharge rate, overburden soil thickness, aquitard layer thickness, water table depth, and distance to karst features, as well as geological age (Kim et al., 2018, submitted).

Use of geospatial data and geographic information system (GIS) technologies enables sinkhole hazard assessment and mapping. Various methods have been proposed for geohazard mapping, and can be generally classified into two groups: qualitative methods and quantitative methods. The qualitative methods include field investigation procedures and/or overlaying of different factor maps and applying predetermined weights to develop a hazard map. The quantitative methods contain artificial intelligence techniques such as artificial neural networks (ANN) and fuzzy systems, statistical techniques and deterministic or probabilistic procedures (Bhardwaj and Venkatachalam, 2014).

This study aims to produce sinkhole hazard maps of East Central Florida (ECF), using frequency ratio (FR) and artificial neural network (ANN) methods using GIS as a

platform. In addition, an attempt was made to compare the two methods.

Study Area

Florida is one of the most sinkhole prone states in the United States due to its hydrogeology, geomorphologic characteristics, climate conditions, and human activities (e.g. groundwater pumping for drinking water and irrigation). According to the Florida Geological Survey (FGS), about 3,800 sinkholes have been reported in the state since 1954. The study area is defined as Central District established by Florida Department of Environmental Protection (FDEP). See Figure 1 for a detailed map showing the study area location.

The region is characterized by low-lying and flat land surface relatively with karst features such as sinkholes, springs, and caves. The geology of Florida is largely characterized by sedimentary rocks with no major

igneous or metamorphic provinces. Limestone is the main bedrock in the study area, and an impervious clay layer overlies the bedrock. The hydrostratigraphic units of ECF consist broadly of a surficial aquifer system (SAS), intermediate aquifer system (IAS), and Floridan aquifer system (FAS), from top to bottom (Miller, 1986). Due to the combination of hydrogeological conditions in ECF, the area is exposed to numerous sinkhole hazards. In the period 1961 – 2017 (July), a total of 954 sinkholes have been recorded in the study area.

Data Preparation

Sinkhole Inventory Map

The preparation of sinkhole inventory maps that show the location of previously identified sinkholes should be the first step for sinkhole hazard analysis. Florida Subsidence Incident Reports by Florida Geological Survey (FGS) with GIS was utilized to prepare the inventory map and locate the sinkhole positions. After

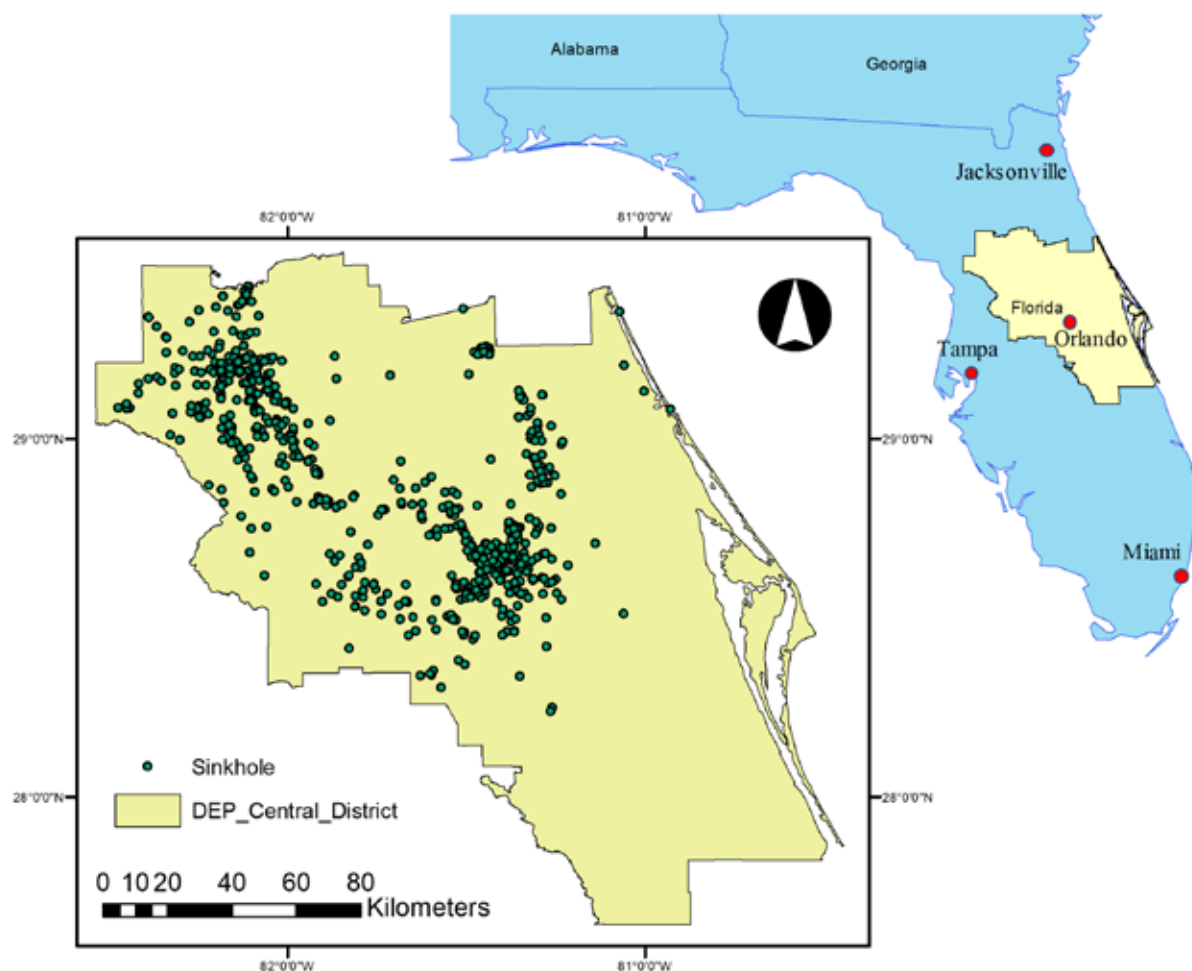


Figure 1. Location of the study area and spatial distribution of the reported sinkholes.

identification and removal of incorrect data, a total of 757 sinkholes available for analysis were recognized, 530 (70%) of which were randomly selected for model calibration, and the remaining 227 (30%) were used for model validation. All data layers were transformed into raster format with a thirty-meter resolution.

Thematic Layers

In this study, five key sinkhole contributing factors including age of sediment deposition (i.e. epoch), hydraulic head difference, groundwater recharge rate, overburden thickness, and proximity to other karst features were taken into consideration based on previous studies, data availability, and the hydrogeological conditions of the ECF region (Kim and Nam, 2017). Analysis of sinkhole occurrence and geological age shows that certain categories of epochs are more subject to sinkhole occurrence (Kim et al., 2017). Hydraulic head difference provides a driving force to cause the down-washing of overburden soil particles into carbonate cavities and voids. Groundwater recharge accelerates soil erosion and facilitates soil structure raveling (Stewart and Parker, 1992). The effects of these hydrogeological factors on sinkhole occurrence in East Central Florida (ECF) were investigated and found to be significant (Xiao et al., 2016). Overburden soil thickness is an important factor since it has shown that karst sinkholes mainly occur at sites with the thickness of 25 meters or less (Drumm and Yang, 2005). Proximity to other karst features is also an important factor to be taken into account. Sinkhole frequency increases as distance to karst features, such as caves, springs and sinkholes, decreases (Kromhout, 2017). Each model parameter was divided into a number of classes (Figure 2).

Methods

Frequency Ratio (FR)

In general, it is assumed that sinkhole occurrence is determined by sinkhole-related factors and that future sinkhole events are likely to occur under similar conditions to past sinkhole events. With these assumptions, the frequency ratio (FR) method derives the spatial associations between sinkhole locations and each of the factors contributing sinkhole occurrence in the study area. The FR method has been widely used for geohazard mapping such as for landslides, earthquakes, and sinkholes.

The FR of each class within a certain sinkhole-related factor can be calculated by the ratio of a class' percent area of the total study area and its percent of the total number of sinkholes in the study area (Equation 1). This density-based method holds the principal of conditional

probability, in which the relation analysis is the ratio the area where sinkholes occurred to the total area. Therefore, a value of 1 means an average value. If the value is greater than 1, there is a strong correlation, and lower than 1 means a weak correlation between sinkholes and factor classes (Lee and Pradhan, 2007)

$$FR_{i,j} = \frac{N_{i,j} / N_T}{A_{i,j} / A_T} \quad \text{Eq. 1}$$

where $FR_{i,j}$ is the frequency ratio for j th class of the factor i , $N_{i,j}$ is the number of sinkholes in j th class of the factor i , N_T is the total number of sinkholes in the study area, $A_{i,j}$ is the area of j th class of the factor i , and A_T is the total area.

Then, to calculate the Sinkhole Hazard Index (SHI), FR values of each factor are summed (Equation 2). The SHI represents the relative risk of sinkhole occurrence based on past sinkhole data, in which the higher the value, the greater the risk is

$$\begin{aligned} SHI &= \sum_{i=1}^n FR_i \\ &= FR_{age_dpstn} + FR_{head_diff} + FR_{rechrg_rate} \\ &\quad + FR_{ovrbdn_thk} + FR_{prox_karst} \end{aligned} \quad \text{Eq. 2}$$

where FR_i is the frequency ratio of each contributing factor i , and n is the number of factors.

Artificial Neural Network (ANN)

An artificial neural network (ANN) is a computational information-processing model that imitates the neural system of the human brain. ANNs, with the capability of acquiring knowledge through learning and storing information within interneuron connections, can extract patterns and detect trends that are too complex to be found by conventional methods (Yilmaz, 2009). The goal of ANN is to find the optimal paths to connect the inputs and outputs of neurons together, and to use them to predict outputs for a given set of inputs. Therefore, there are two stages involved in using ANN for multi-source classification: a training stage and a classifying stage. Compared with other statistical analysis and techniques, the ANN model has many advantages and ability to handle imprecise and fuzzy data. Therefore, it is considered an efficient approach for geohazard assessment and mapping.

The most popular and widely used ANN architecture is multi-layer perception (MLP) network, comprising of an input layer, one or more hidden layers, and an output layer. Input data are fed through the hidden

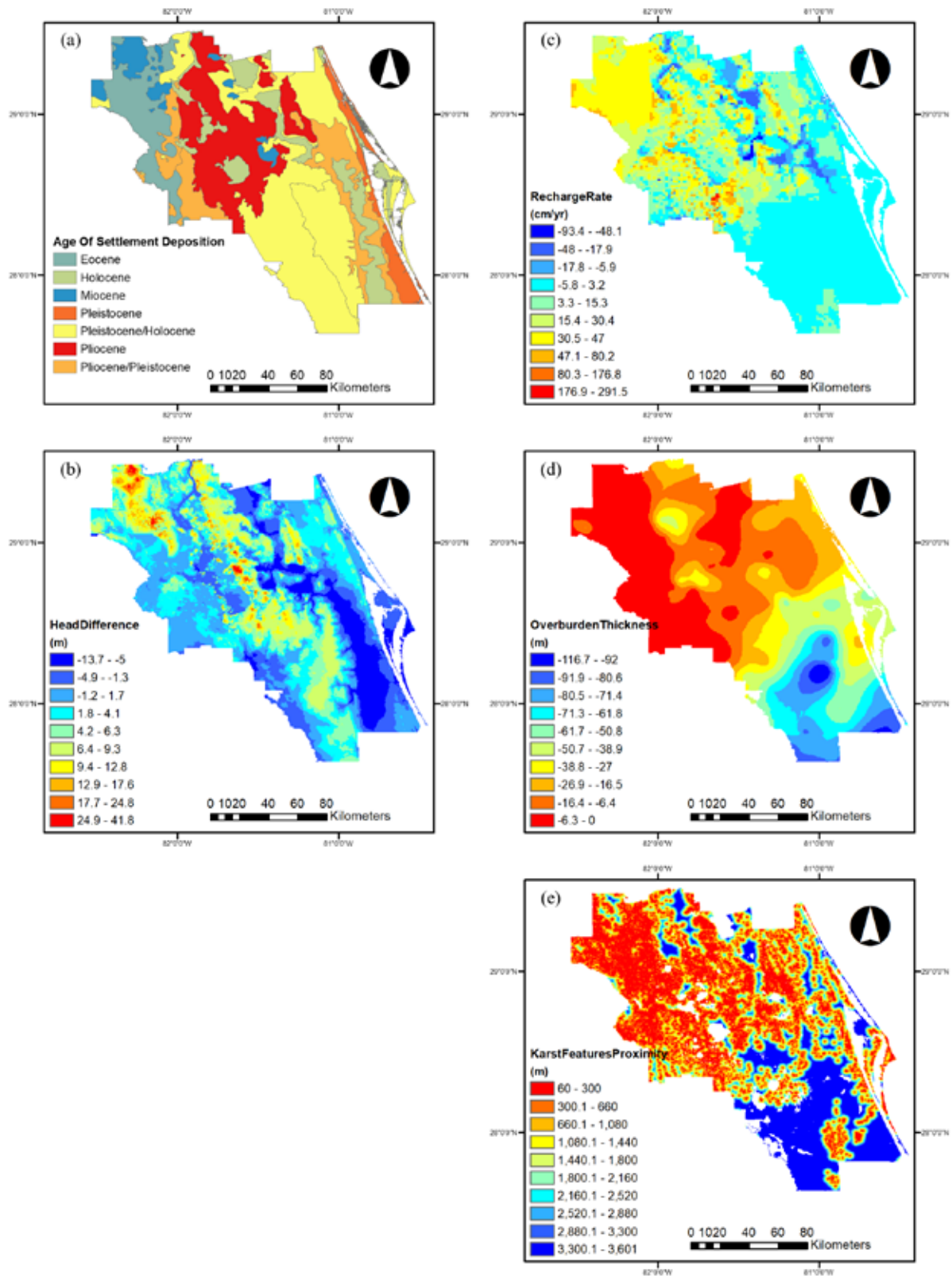


Figure 2. Sinkhole contributing factor maps: (a) age of sediment deposition; (b) head difference; (c) recharge rate; (d) overburden thickness; (e) proximity to other karst features.

layer that processes them to obtain the optimal output during training sessions. Each neuron in hidden and output layers processes its inputs by multiplying each input (x_i) by a corresponding weight (w_i), summing up the products (Equation 3), and then processing the sum (if that exceeds the neuron threshold, then the neuron is activated) using a nonlinear transfer function (Equation 4) to produce a result (y_i) (Polykretis et al., 2015).

$$net = \sum_{i=0}^n w_i x_i \quad \text{Eq. 3}$$

$$y_i = f(net) \quad \text{Eq. 4}$$

The proper weights for each input factor are learned gradually, and results are refined by adjusting the internal weights between neurons to reduce the difference between actual and target output values (i.e., errors). After a large number of iterations, at the end of the training stage, the neural network generates an appropriate model that can predict the target value correctly from given input values. A back-propagation (BP) algorithm is typically applied to train the network where the training process continues until the target error is achieved. After the completion of the training stage, the network is used as a feed-forward structure to produce a classification for the entire data set (Paola and Schowengerdt, 1995).

In this study, a three-layer feed-forward network trained by a back-propagation (BP) algorithm was selected to predict the distribution of sinkhole-prone areas. The input layer has 5 neurons (age of sediment deposition (i.e. epoch), head difference, recharge rate, overburden thickness, and proximity to other karst features), and the output layer has one neuron. In general, it is not easy to determine the number of hidden layers and the number of neurons in the hidden layer required for a particular classification problem. According to the Kolmogorov theorem (Kurkova, 1992), for a three-layer feed-forward neural network, the neuron number of the hidden layer is $2n + 1$, if the input layer has n neurons, and the output layer has m neurons. Therefore, the hidden layer has $2 \times 5 + 1 = 11$ neurons, and as a result, a three-layer system consisting of an input layer (5 neurons), one hidden layer (11 neurons) and an output layer (1 neuron) was used as a network structure of $5 \times 11 \times 1$, with input data normalized within the range of 0.1-0.9 based on the Sinkhole Hazard Index (SHI).

The sinkhole inventory map was reclassified by assigning a value of 1 to the sinkhole location pixels and a value of 0 to the non-sinkhole location pixels. From these two classes (sinkhole and non-sinkhole), 954 training location samples (530 sinkhole locations and 424 non-

sinkhole locations) were selected at random to be used as reference dataset in the weight adjustment process (Figure 3). 15 sample location data are presented in Table 1.

In this study, the MATLAB Neural Network tool was used to train the ANN model. The learning rate was set at 0.02, and the initial weights were randomly selected between 0.1 to 0.9. The root mean square error (RMSE) goal for the stopping criterion was set to 0.01. Other parameters of the neural network were taken as 10,000 for epochs (or iterations), and 0.9 for momentum factor. The final weights between layers acquired during training of the neural network were used to predict sinkhole hazard.

Results and discussion

Frequency Ratio (FR)

The relationship between the sinkhole occurrence and each sinkhole contributing factor for the study area was determined by the FR and the results are presented in Table 2. FR values greater than 1.0 represents significant correlation and values less than 1.0 indicates no significant correlation with sinkhole occurrence. FR analysis of the age of sediment deposition indicates that sinkholes were observed to occur predominantly in the Eocene, Miocene, and Pliocene sediments. Head difference, recharge rate, and overburden thickness are found to have good association with the sinkhole occurrence. In general, FR values increases when the head difference and recharge rate increase, and the overburden thickness decreases. A large number of sinkholes are likely to occur in areas where the distance to other karst features is within ≤ 300 meters.

Sinkhole Hazard Index (SHI) was determined by summing FR values of each factor. SHI values of each

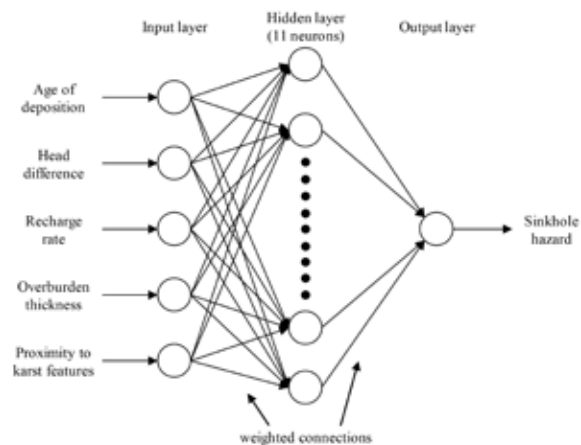


Figure 3. Back propagation ANN architecture for sinkhole classification.

Sample No	Age. dpstn.	Head. diff.	Rech. rate	Over. thk.	Prox. karst	Sinkhole occurrence
1	0.2	0.9	0.6	0.9	0.9	1
2	0.2	0.1	0.2	0.3	0.1	0
3	0.9	0.6	0.6	0.9	0.9	1
4	0.2	0.9	0.2	0.5	0.1	0
5	0.2	0.6	0.6	0.8	0.9	1
6	0.2	0.9	0.1	0.1	0.1	0
7	0.9	0.4	0.6	0.5	0.9	1
8	0.2	0.7	0.4	0.8	0.2	0
9	0.6	0.9	0.6	0.9	0.9	1
10	0.2	0.8	0.4	0.8	0.2	0
11	0.6	0.7	0.6	0.9	0.9	1
12	0.9	0.4	0.2	0.8	0.3	0
13	0.9	0.4	0.6	0.9	0.4	1
14	0.6	0.1	0.6	0.9	0.4	0
15	0.8	0.6	0.6	0.9	0.3	1

Table 1. Normalized sinkhole sample data.

Factor	Class		FR	Factor	Class		FR
Age of sediment deposition	I	Eocene	1.64	Recharge rate (cm/yr) (cont'd)	VIII	47.1~80.2	2.98
	II	Holocene	0.03		IX	80.3~176.8	4.38
	III	Miocene	2.28		X	176.9~291.5	4.74
	IV	Pleistocene	0.08	Overburden thickness (m)	I	-116.7~-92.0	0.00
	V	Pleistocene/Holocene	0.40		II	-91.9~-80.6	0.00
	VI	Pliocene	2.63		III	-80.5~-71.4	0.00
	VII	Pliocene/Pleistocene	0.40		IV	-71.3~-61.8	0.00
Head difference (m)	I	-13.7~-5.0	0.02		V	-61.7~-50.8	0.00
	II	-4.9~-1.3	0.06		VI	-50.7~-38.9	0.05
	III	-1.2~1.7	0.80		VII	-38.8~-27.0	0.46
	IV	1.8~4.1	1.24		VIII	-26.9~-16.5	0.91
	V	4.2~6.3	1.64		IX	-16.4~-6.4	1.64
	VI	6.4~9.3	2.08		X	-6.3~0	1.79
	VII	9.4~12.8	1.70	Proximity to other karst features (m)	I	60.0~300.0	2.49
	VIII	12.9~17.6	1.32		II	300.1~660.0	0.89
	IX	17.7~24.8	1.29		III	660.1~1080.0	0.73
	X	24.9~41.8	0.99		IV	1080.1~1440.0	0.60
Recharge rate (cm/yr)	I	-93.4~-48.1	0.00		V	1440.1~1800.0	0.35
	II	-48.0~-17.9	0.11		VI	1800.1~2160.0	0.48
	III	-17.8~-5.9	0.16		VII	2160.1~2520.0	0.25
	IV	-5.8~3.2	0.08		VIII	2520.1~2880.0	0.16
	V	3.3~15.3	0.80		IX	2880.1~3300.0	0.09
	VI	15.4~30.4	1.92		X	3300.1~3601.0	0.06
	VII	30.5~47.0	2.70				

Table 2. Normalized sinkhole sample data.

factor in each grid cell were calculated to construct the sinkhole hazard map of East Central Florida (Figure 4). For better visual interpretation, the map was classified into five categories (very low, low, moderate, high, and very high) by using the natural break method (Table 3). For the validation purpose, the remaining 227 (30%) sinkholes were projected on the GIS-based sinkhole map. 25.2% and 24.9% of the total area are found under very low and low hazard classes. Areas with moderate, high, and very high hazard represent 15.8%, 17.0%, and 17.2% of the total area, respectively. The percentages of the total sinkholes in very low, low, moderate, high, and very high hazard classes are 0.5%, 1.8%, 10.9%, 21.8%, and 65.0%, respectively.

Artificial Neural Network (ANN)

A back-propagation (BP) multi-layer artificial neural network with three layers and threshold of sigmoid function was carried out. The network structure is $5 \times 11 \times 1$, input, hidden, and output layers, respectively where the input data is Sinkhole Hazard Index (SHI). Parameters of the neural network were taken as 0.02 for learning rate, and 0.9 for momentum factor. One of the ANN outputs represents the weight of sinkhole contributing factors. The weights of factors were taken on average value to obtain the best result and used to update the SHI values.

As a result, proximity to other karst features had the highest weight, 1.612, meaning that it is the most influencing factor on sinkhole events in East Central Florida (ECF). The weights of recharge rate and the age of sediment deposition are 0.845 and 0.757, which are the second and third largest contributing factors to sinkhole

formation, respectively. The weight of overburden thickness is 0.455, and head difference had the lowest weight of 0.158. Based on the result of ANN model, sinkhole hazard map of ECF was produced (Figure 5).

The sinkhole hazard map produced by ANN was also grouped into five classes using natural break method (Table 3). According to the model, 30.9% of the study area is exposed to a very low hazard, and 22.9%, 16.3%, 13.7%, and 16.2% occupies low, moderate, high, and very low, respectively. It is observed that 0% and 5.0% of the total sinkholes falls in the very low and low hazard classes, respectively. Moderate, high, and very high hazard classes represent 11.4%, 27.7%, and 55.9% of the sinkholes, respectively.

Model	Sinkhole hazard class	Area (%)	Sinkhole (%)
FR	Very low	25.2	0.5
	Low	24.9	1.8
	Moderate	15.8	10.9
	High	17.0	21.8
	Very high	17.2	65.0
ANN	Very low	30.9	0
	Low	22.9	5.0
	Moderate	16.3	11.4
	High	13.7	27.7
	Very high	16.2	55.9

Table 3. Comparison of predicted sinkhole hazard class and observed sinkholes.

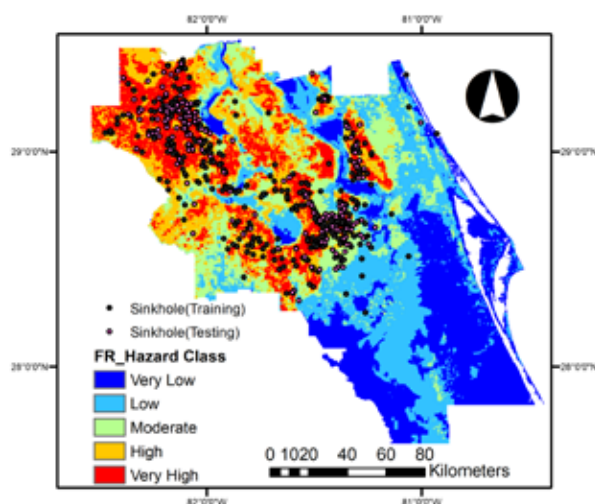


Figure 4. Sinkhole hazard map constructed by FR method.

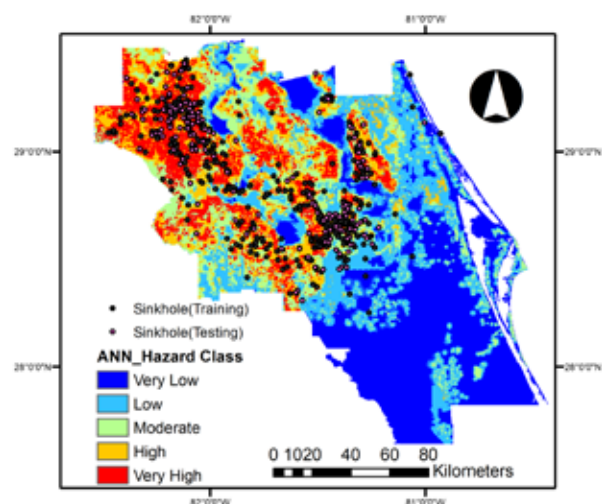


Figure 5. Sinkhole hazard map constructed by ANN method.

Figures 4 and 5 show that the sinkhole hazard maps of FR and ANN are slightly different in the spatial distribution of hazard classes, although both methods are similar in the percentage of each hazard class in relation to the study area. According to the FR hazard map, the very low to low hazard class and the high to very high hazard class show 50.1% and 34.2% of the study area, respectively. Similarly, from the ANN hazard map, 53.8% and 29.9% of the entire area are found to be of the very low to low hazard class, and the high to very high hazard class, respectively.

About 86.8% and 83.6% of the sinkholes fall into the high and very high classes of the hazard map by FR and ANN, respectively. The results show that the FR method tends to be more conservative as it produces less low hazard, and more high hazard zones compared to the ANN method. Considering the results of this study, both FR and ANN methods are adequate for producing a regional scale sinkhole hazard map. The FR method has advantages over the ANN method, especially in terms of simplicity and time efficiency. However, it is difficult to analyze the correlation between factors that can be overcome by the ANN method.

Conclusions

In this study, two mathematical models that are frequency ratio (FR) and artificial neural network (ANN) methods were used to construct sinkhole hazard maps, and the susceptible areas for East Central Florida (ECF) are identified. Five key sinkhole contributing factors were selected based on the findings from relevant studies and data availability of the study area, which includes age of sediment deposition (i.e. epoch), hydraulic head difference, groundwater recharge rate, overburden soil thickness, and proximity to other karst features. Both hazard maps were divided into five classes by the natural break classification method (very low, low, moderate, high, and very high). According to the results, both FR and ANN models show a similarly good performance. High percentages of test sinkholes, with 86.8% and 83.6% for FR and ANN respectively, fall in the classes of high and very high. The results of this study can be used to assist local authorities and decision makers for proper site selection and planning. It is important to note that both FR and ANN models in the present study were developed under the assumption of no seasonal effects (e.g. extreme weather events such as drought or heavy rain associated with tropical storms or hurricanes). A sinkhole hazard map accounting for the seasonal effect is currently under development.

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BULK CHEMISTRY OF KARST SEDIMENT DEPOSITS

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Abstract

Sediments are ubiquitous in karst systems and play a critical role in the fate and transport of contaminants. Sorbed contaminants may be stored on immobile sediments or rapidly dispersed on mobile sediments. Sediments may also influence remediation by either enhancing or interfering with the process. To better understand the potential effects of sediments on remediation, we conducted physical and chemical characterizations of 11 sediment samples from 7 cave and spring deposits from karst regions of Tennessee, Virginia, and West Virginia. The samples were analyzed for particle-size distribution using sieves and laser diffraction particle analysis. The sediment size fraction <2 mm (sand, silt, and clay) was analyzed for slurry pH and specific conductivity (SC) using electrodes and for bulk total carbon, organic carbon, nitrogen and sulfur on an Elementar™ Vario MAX Cube CNS. The same <2 mm fraction was subjected to a pseudo-total extraction using aqua regia with subsequent

solution analysis by inductively coupled plasma–optical emission spectrometry (ICP-OES).

Most of the samples were dominated by the <2 mm size fraction. Their slurry pHs ranged from 6.8 to 8.4 and their SCs ranged from 45 to 206 $\mu\text{S}/\text{cm}$ with the exception of two high SC samples (726 and 8500 $\mu\text{S}/\text{cm}$). The fraction of organic carbon (F_{oc}) in the sediments ranged from <0.1 to 2%. The sample from a saltpeter cave historically used for gunpowder production contained the highest concentrations of N and S (~ 3 g/kg) but lower total C than some of the spring samples. The pseudo-total extractions were analyzed for Al, Ca, Fe, Mg, and Mn. Of those elements, Mg was the most consistent across the locations (2.0–6.1 g/kg), and Ca was the most variable (1.4–52 g/kg). Given the importance of particle size and elemental concentrations in chemical reactions and remediation, more data of this type are needed to predict contaminant fate and transport and to plan successful remediation projects.

Introduction

Sediments are ubiquitous in karst systems and play a critical role in the fate and transport of contaminants. Contaminants readily sorb to sediments in all aquatic settings; if the sediments are mobile, contaminant transport can be facilitated but if the sediments are immobile then transport can be slowed causing long-term storage of contaminants. The potential for either outcome is accentuated in a karst aquifer because of (1) the ease with which sediments can be introduced to the aquifer; (2) the large mass of sediments that may be present; and (3) an open matrix that permits solid transport. Furthermore, the groundwater velocity in karst aquifers may respond rapidly and dramatically to storm events altering the distribution between mobile and deposited sediments. Numerous recent studies have reported punctuated transport of sediments during storms (Dogwiler and Wicks, 2004; Herman et al., 2008; Mahler and Lynch, 1999; Reed et al., 2010) and contaminant transport in association with sediments (Loop and White, 2001; Talarovich and Krothe, 1998; Vesper and White, 2003).

Sediments may also pose challenges for the remediation of karst aquifers. Remedial techniques that employ oxidation-reduction processes, such as bioremediation or electrochemical remediation, may be particularly prone to complications from sediments. Sediments can interfere with both redox and pH buffering capacity of the groundwater; sediments rich in redox-active species such as Fe and Mn can either enhance or interfere with the remedial process and well-buffered water samples can interfere with technologies relying on pH changes (e.g., Fenton reaction). For example, a remediation approach that relies on the addition of energy to change the redox state of the system may be forced to first change the states of elements in the sediments before it influences the contaminants of interest. The significance of this problem depends on the elemental concentrations and the associated standard reduction potentials.

The purpose of this study was to characterize karst sediments with a range of chemistries so that they could be used for remediation experiments. The purpose was not to characterize representative samples or to place them into the geologic context of each location. This paper reports the preliminary data obtained.

Methods

Sediments were collected from seven springs and caves in Tennessee, Virginia, and West Virginia (Table 1). The samples were collected from a small springhouse (believed to be largely mobile sediments) and deposits along cave streams that appear to have been in place for the long term. Several samples were obtained from Worley Cave, a location known to contain abundant Mn-oxidizing bacteria (Carmichael et al., 2013). One sediment sample was collected from a thermal, iron-rich, tufa-precipitating spring (CHAL) and one from a saltpeter cave (POLF) to provide a broader range of sediment chemical types. All samples were collected from locations believed to be free of contamination so that the results represent natural background conditions.

The sediments were collected as grab samples and composited manually. After air-drying, aliquots were created using a splitter. Particle sizes were determined on triplicates by sieving with subsequent analysis of the silt and clay fraction using a Beckman Coulter LS 13–320 single-wavelength laser diffraction particle analyzer. A separate aliquot of each sample was passed through a 2-mm sieve and retained for the chemical analyses.

Specific conductance (SC) and pH were measured using calibrated Hanna Instruments laboratory electrodes on slurries shaken at 100 rpm for 1 hour. Following

Location	Sample IDs	Description
Crabtree Farm Spring, WV	CRAB1 CRAB2	Sediment from a small springhouse; samples taken on different dates.
Dropping Lick Cave, WV	DLBK	From a high bank of deposited sediments along a cave stream.
Miss Effie Cave, WV	MEFF, MEFFC	From a deposit on the outside of a stream meander bend; MEFFC is a sample from a darker crust on the surface of the deposit.
Rocky Parsons Cave, WV	RPMS	Sediment from the main passage in a recently discovered cave that was dug open by the landowner.
Worley Cave, TN	WORL1, WORL2, WORL3	Composite samples from a cave known to contain Mn-metabolizing microbes (Carmichael et al., 2013).
Sweet Chalybeate Spring, VA	CHAL (tufa)	From the spring run of a thermal spring actively depositing tufa.
Anonymous Cave, VA	POLF (saltpeter)	From the floor of historic saltpeter excavations.

Table 1. Sample descriptions.

published methods (Hanlon, 2015; Kalra, 1995), a 1:1 sediment-to-water ratio was used for pH and a 1:2 ratio for SC; replicates of 6 were measured.

The <2 mm sediment was analyzed on an ElementarTM Vario MAX Cube CNS for total carbon, nitrogen, and sulfur. Organic carbon was determined on the same instrument but after first pre-treating the sediment with concentrated hydrochloric acid to dissolve any inorganic carbon. Sample CHAL, from the tufa-depositing spring, completely dissolved during the pre-treatment process.

Pseudo-total extractions were completed in replicates of three. Approximately 3 grams of each sediment sample (<2 mm) was subjected to an aqua regia solution for 16 hours at room temperature followed by heating for 2 hours at 130°C in a CEM MARS Express microwave. The extractant solution was filtered and analyzed using inductively coupled plasma–optical emission spectrometry (Agilent 720 ICP-OES). All concentrations are reported relative to the initial dry mass.

Results and Discussion

Sediment particle sizes ranged from sand to clay (Figure 1). Three of the sediments were dominated by sands (DLBK, MEFF, and MEFFC): these samples were collected from bank deposits on the sides of active cave streams. Sample DLBK was taken approximately 1 meter above the cave floor from a >2-meter high sediment deposit. The bank deposits in MEFF are thinner (<1 meter); the MEFF sample was a composite from the top 10 cm of sediment and MEFFC was from a darkened crust on top of the sediment. The spring samples (CRAB1, CRAB2, and CHAL) were fine-grained with some gravel. The two CRAB samples were collected from a springhouse that periodically fills with solids; this material is presumed to originate from the mobile sediments transported by the spring water. Sample CHAL was obtained from a tufa-depositing spring. Based on sample dissolution during the addition of acid, this sediment contained nearly all carbonate precipitates.

The average slurry pHs (Figure 2) were lowest for the spring samples from CRAB (6.7 to 6.8) and highest for the cave samples from WORL (8.2 to 8.4). The samples collected from limestone caves generally had pHs greater than 7.7; the samples from springs (CRAB1, CRAB2, and CHAL) and from the saltpeter cave (POLF) had slightly lower pH values (Figure 2). The range of pH values measured is comparable to that reported for

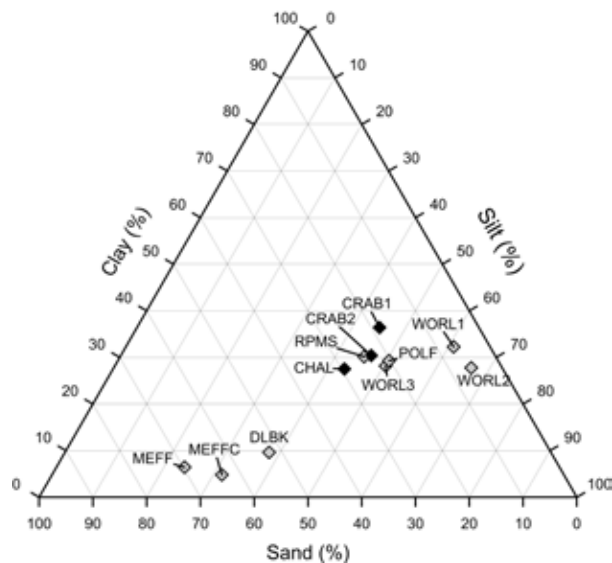


Figure 1. Relative distribution of sand, silt, and clay fractions. Sediments from springs (black) and cave deposits (light gray). Averages from three replicate samples are shown.

sediments from a Chinese cave system where pH ranged from 7.8 to 8.2 (Yun et al., 2016).

Most of the measured SCs ranged between 44 and 210 $\mu\text{S}/\text{cm}$ (Figure 2). The tufa spring sample CHAL was higher (726 $\mu\text{S}/\text{cm}$) and the saltpeter sample POLF was significantly higher (8500 $\mu\text{S}/\text{cm}$) than the others.

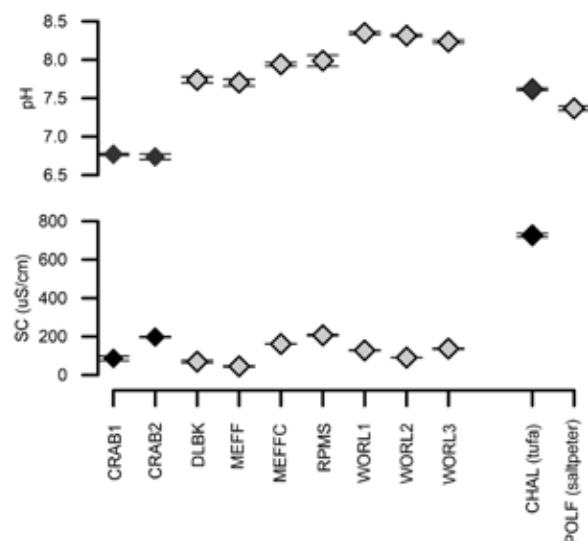


Figure 2. pH and SC from slurry samples from springs (black) and cave sediments (gray). Error bars are standard deviations for replicates of 6. The SC for POLF is not shown (8,500 $\pm$ 158 $\mu\text{S}/\text{cm}$).

The bulk concentrations of C, N, and S varied by location (Table 2). Total C concentrations are a mixture of inorganic and organic carbon. CHAL, the sample from the tufa-depositing spring, contained the highest concentration of total C but contained no organic carbon (and thus has effectively 0% F_{oc}). The other spring samples (CRAB1 and CRAB2) contained the next highest concentrations of carbon.

Organic carbon plays a critical role in the transport and storage of organic contaminants because sorption is generally proportional to the concentration of organic carbon naturally present in the sediments (Schwarzenbach et al., 2002). Spring sediments CRAB1 and CRAB2 contained the highest concentrations of organic carbon followed by the MEFFC crust sample. The range of F_{oc} in this study (0.1–1.9%) is comparable to reported data from karst sites in KY (0.15–2.0%) by Vesper and White (2004) and sites in China (0.2 to 0.7%) by Yun et al. (2016). Sediments with high concentrations of organic carbon are expected to affect redox-based remedial actions.

The POLF saltpeter sample contained the highest concentrations of N and S as would be expected. Saltpeter caves were historically used for gunpowder production (Hill et al., 1981; Powers, 1981). Although these are unusual deposits, the elevated concentrations

Sample	Total C (g/kg)	F_{oc} (%)	N (g/kg)	S (g/kg)
CRAB1	15.6	~1.6	1.51	0.33
CRAB2	23.9	1.81	2.00	0.47
DLBK	9.99	0.56	0.55	0.70
MEFF	6.52	0.42	0.44	0.61
MEFFC	13.0	1.02	1.01	0.45
RPMS	4.29	0.32	0.72	0.30
WORL1	1.21	0.10	0.35	0.44
WORL2	1.10	0.09	0.32	0.23
WORL3	8.20	0.26	0.59	0.27
CHAL (tufa)	33.9	~0	1.23	0.41
POLF (saltpeter)	10.0	0.53	3.17	2.84

Note: Organic-C concentration at CRAB1 was slightly higher than the total C indicating the values agreed within resolution of the measurement; Organic-C could not be measured for CHAL because the sample dissolved when acid was added. F_{oc} is the fraction of organic carbon (the concentration reported as a percent). The fraction of organic carbon (F_{oc}) is the measured concentration (mg/kg of dry mass) expressed as percent.

Table 2. Bulk chemistry for carbon, nitrogen, and sulfur.

of redox-sensitive species indicate that sediments of this type would be expected to have a major impact on remediation processes. All other samples had <2 g/kg N and <1 g/kg S.

Solutions from the pseudo-total extractions were analyzed for Al, Ca, Fe, Mg, and Mn (Table 3). The Ca and Mg were included as proxies for carbonate minerals, the Al for clays, and the Fe and Mn as redox-sensitive species that may affect the remedial processes.

The relative concentrations of the extracted element groups (Figure 3) are comparable to a similar data set collected from Kentucky (Vesper, 2002). The 2002 Kentucky dataset includes three aquifer samples collected during drilling operations and six spring sediment samples. Nearly all of the samples contain more Al than Fe, Mn, Ca, or Mg. Of those elements, Mg concentrations were the most consistent across the locations (2.0–6.1 g/kg), and Ca was the most variable (1.4–52 g/kg).

Al concentrations in karst sediments have been closely associated with metals. In Vesper and White (2003) the Al in suspended sediments correlated closely with concentrations of Fe, As, Cr, Pb, and Ni. Similarly, correlations between Al and Ni, Cr, Cu, and Cd have been reported for sediments deposited at the karst sediments at the Plitvice Lakes National Park in Croatia (Mikac et al., 2011). In this study, the Al concentration does not correlate closely with either Fe or Mn (Figure 4).

Location	Ca (g/kg)	Mg (g/kg)	Al (g/kg)	Fe (g/kg)	Mn (g/kg)
CRAB1	2.50	4.37	34.2	20.7	0.41
CARB2	2.95	5.21	36.9	20.0	0.21
DLBK	7.55	5.02	10.1	16.5	0.68
MEFF	3.78	3.96	19.3	15.8	0.45
MEFFC	4.10	3.84	13.2	18.4	0.69
RPMS	4.97	5.06	60.6	48.1	2.06
WORL1	1.82	4.66	18.0	25.2	0.44
WORL2	1.43	4.51	20.7	25.3	0.46
WORL3	15.2	6.10	24.5	24.7	0.46
CHAL (tufa)	51.6	3.09	16.7	102	0.50
POLF (saltpeter)	16.3	6.09	23.6	25.1	0.80

Table 3. Average concentrations of elements from pseudo-total extractions.

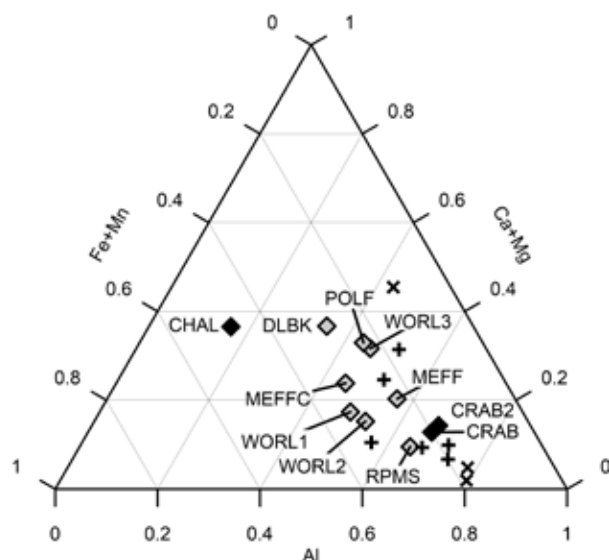


Figure 3. Pseudo-total chemistry data expressed as molar fractions of the included elements. Data from this study from springs (black diamonds) and cave sediments (gray diamonds). Samples from Kentucky-Tennessee from springs (+) and conduit sediment samples (X) from Vesper (2002).

The Ca and Fe concentrations were highest in the iron-rich tufa-depositing spring. This is a thermal-mineral spring and can be expected to have a different sediment chemistry than do the other locations. It has been provided in this study as an example of the range of possible sediments that may be encountered in karst areas.

The second highest Fe concentration was measured in RPMS along with the highest Mn concentration. This sample was collected from a cave located in a karst window; this cave was recently discovered by the landowner during building excavation. No water was flowing over the sediment at the time of sample collection although there were indications of previous water flow.

Summary

The concentration data obtained for sediments in this study are provided as an example of the potential materials encountered in sediments that may influence remediation activities. Most of the recent research conducted on karst sediments is focused on sediment size and transport processes rather on the sediment chemistry. The lack of significant correlations for Al

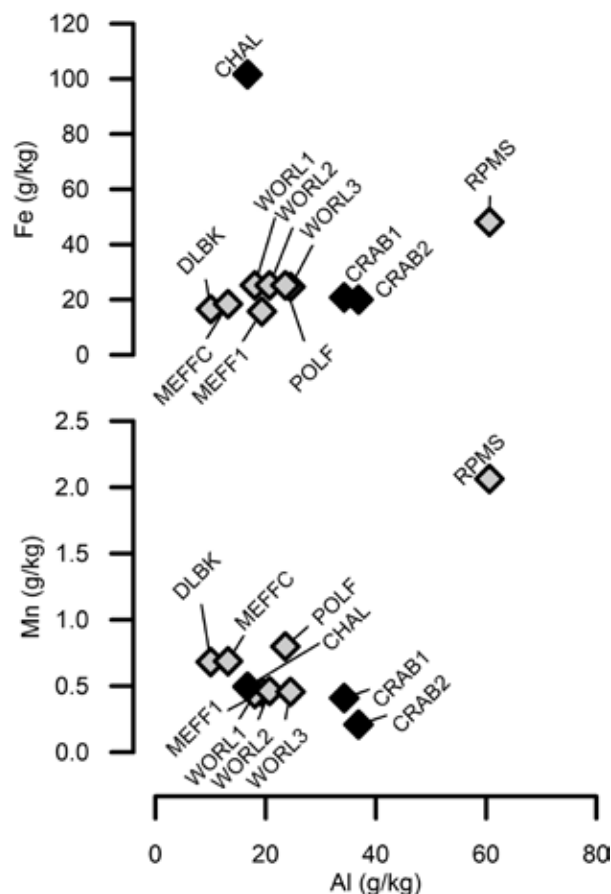


Figure 4. Comparison of Fe and Mn concentrations with Al for sediment samples from springs (black diamonds) and caves (gray diamonds).

with particle size, Fe or Mn may be due to the small number of samples. The sediments included in this study provide an example of different chemistries that exist in karst systems. More information of this type is needed for the design and evaluation of remedial systems.

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GEOCHEMICAL COMPARISON OF KARST AND CLASTIC SPRINGS IN THE APPALACHIAN VALLEY & RIDGE PROVINCE, SOUTHEASTERN WEST VIRGINIA AND CENTRAL PENNSYLVANIA

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Abstract

The Appalachian Valley and Ridge (V&R) Province extends over 11 states and is an essential water supply. The regional geology consists of more resistant clastic rocks, typically sandstones and mixed shales, which form the ridge tops and mountain flanks, and carbonate rocks that underlie the valleys. In this study, we report the geochemistry of different types of springs on and near Peter's Mountain in Monroe County, WV. More than 250 springs have been mapped in the ~225 km² study area on and adjacent to Peter's Mountain. These data are compared with preliminary data collected from sandstone-sourced springs from central PA and northcentral WV. Six sandstone springs in WV and PA were sampled and monitored for comparison to the Monroe County springs. Springs were grouped by geologic and geomorphologic location: Group 1: sandstone-sourced springs in WV and PA; Group 2: springs in the Martinsburg Formation on the western flank of Peter's Mountain; and, Group 3: springs in the carbonate valley west of Peter's Mountain. In general, Group 1 springs are smaller and more ephemeral than the other groups; their waters have low pHs (4.1–6.0), low specific conductivities (24 to 55 $\mu\text{S}/\text{cm}$), and low concentrations of dissolved ions. Group 2 springs are also small and ephemeral but have higher pHs (6.7–8.4) and specific conductivities (73–308 $\mu\text{S}/\text{cm}$) due to the mixture of shales and carbonates in the source formation. Temperatures in these springs range from highly consistent to highly variable. Although the Group 2 springs along Peter's Mountain have Ca and Mg concentrations similar to the Group 3 carbonate springs, they can be distinguished by higher Ca/Mg mole ratios.

In contrast, Group 3 springs have higher pHs (6.6–8.4) and higher specific conductivities (144–750 $\mu\text{S}/\text{cm}$).

Introduction

The Valley and Ridge (V&R) physiographic province of the Appalachian Mountains plays a key role in supplying water to downstream users. This province spans from Alabama to Vermont and contains abundant springs and streams throughout its extent (Figure 1). The springs of the V&R are critical resources for domestic, agricultural, commercial, and industrial use.

The V&R region is structurally and stratigraphically complex; differential erosion has resulted in ridges

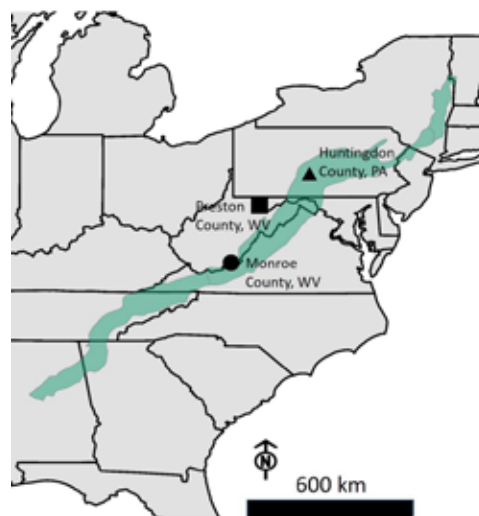


Figure 1. The V&R (shaded green) with locations of the three study sites.

defined by resistant clastic rocks and valleys underlain by more soluble carbonate limestones and dolomites. The clastic rocks include fractured sandstones on the ridge tops and mixed shale-carbonate units typically found on the ridge flanks or in high-elevation valleys. Much of the hydrogeologic research in the V&R has focused on case studies or on the carbonate units; however, other rock units also play an essential role in creating headwater streams, recharging the carbonate aquifers of the lower valleys, sustaining baseflow, and supporting ecosystems. Furthermore, the high-quality water from the ridge and flank springs make them valued sources by private landowners, public water supplies, and bottled water companies. The differences between the spring types also has implication for ecosystems: the different water chemistries support different faunal assemblages (Glazier, 1991; Glazier and Gooch, 1987).

Although past studies provide critical information and approaches to studying water flow in the V&R, they are almost completely focused on carbonate aquifers (Shuster and White, 1971; Herman et al., 2009; Loran and Reisch, 2012) and pay little attention to other spring types that contribute to recharge of the carbonate zones. Jacobson and Langmuir (1974) included the sandstone recharge waters in their study but only near the carbonate formations and with the purpose of illustrating why sinkholes develop when the aggressive waters reach the formational contacts.

Springs and ground water in the sandstone and shale units of the V&R have had little attention. Hobba et al. (1979) identified V&R springs issuing from clastic formations but focused on thermal waters. McColloch (1986) inventoried springs in WV but only included large springs. According to that report, only 31 springs are reported in the Monroe County study area (27 limestone, 2 shale, and 2 sandstone); although more than 250 springs have now been identified and mapped (Indian Creek Watershed Association, 2017; Richards, 2006).

Studies of the hydrogeology in Monroe County WV provide a more detailed background into the distribution of springs relative to rock units. Richards (2006) conducted hydrological and geochemical characterization of springs on the ridge and flanks of Peter's Mountain plus carbonate springs in the adjacent

valley in WV. In general, the valley carbonate springs were less common and had higher discharge. Chemically, the valley springs had much higher specific conductivity (SC) and concentrations of measured ions. Water flowing from the ridge and flank units had lower SCs and fewer dissolved ions. In a report to the WV Department of Public Health, Dean and Kulander (1992) mapped the geology, fractures and springs in the Gap Mills area. They concluded that groundwater flow from the ridge and flank units was a critical component to recharging the lower carbonate aquifers and that the upper system is tied to fracture and bedding plane orientations.

The purpose of this study is to compare between the springs based on screening parameters, major ion concentrations, and temperature variability. The data reported are based on an ongoing watershed study in Monroe County, WV (Bausher, in progress); these results are compared with a limited set of preliminary data collected from sandstone springs outside of Monroe County.

Methods

Spring Locations

The main study site is the V&R region of eastern Monroe County in southeastern WV, selected because the relief provided by Peters Mountain allows access to springs from all rock units (Table 1). The top of Peter's Mountain is formed by the highly resistant Silurian Tuscarora Formation quartzite. The western flanks of the mountain are underlain by the Martinsburg and Juniata Formations and the valley by the Moccasin Limestone, the Black River and St. Paul Limestones, and the Beekmantown series (Dean and Kulander, 1992; McDowell and Schultz, 1990). According to McDowell and Shultz (1990), the Martinsburg Formation/Series consists of the Trenton limestone at the base that grades upward into the interbedded shale, calcareous siltstone and sandstones of the Reedsville shale. The exact location of the springs relative to the lithologic contact is unknown; Monroe County is currently being remapped by the U.S. Geological Survey (Doctor, USGS, pers. comm.). The Monroe County study area is bounded to the west by the St. Clair Thrust Fault. The relief over the study area is ~550 meters.

Springs and streams are grouped for this study based on geologic location and follow the scheme used by Richards (2006) in Monroe County (Table 1, Figure 2):

Location and Group		Description of Location	Sample IDs
Monroe County WV (Western side of Peters Mountain)	1	Tuscarora Fm sandstone, near the ridge-top	APPL
	2	On the flanks of Peters Mountain in the Martinsburg Fm	BROY1, ECH1, GMILL2,3, HANCK2, LUGER2, OLDU3, OLSON1
	3	Valley carbonates within or on the contact of the Beekmantown Series	CRABT, DROPL, HATCH3, MEFF, ZEN1
	Stream	Streams draining the valley at the base of Peters Mountain	QHAN, QIND, QRCH, QSEC, QSWT
Preston County, WV	1	Underlain by the gently-folded sandstones and shales of the Conemaugh group in the Appalachian Plateau (Nicholson et al. 2007).	RBSH, RBWG
Huntingdon County PA	1	In a synclinal structure along the contact between Old Port (sandstone) and the Onondaga (shale) Formations (Dicken et al. 2008).	HCOLD, HDUBB1
¹ Private water supply; ² Part of a public water supply; ³ Used commercially for bottled water or a fish hatchery. Stratigraphy based on geology maps (Nicholson et al. 2007) and USGS Bulletin 1839-E (McDowell and Schultz 1990). Location coordinates are not included to protect the security of the public and private water supplies.			

Table 1. Sample location descriptions.

- Group 1 springs flow from sandstone units; Two of the springs (RBSH, RBWG) are located on the Appalachian Plateau and are provided for comparison with V&R springs.
- Group 2 springs flow from the mixed carbonate and siliciclastic units of the Martinsburg Formation on the western flanks of Peter's Mountain in Monroe County.
- Group 3 springs flow from the Ordovician carbonate units located within the valley west of Peters Mountain in Monroe County.
- Stream includes the five streams that drain the valley at the base of Peter's Mountain in Monroe County.

The assignment of a spring to a geologic unit is challenging for several reasons: (1) the geologic maps may not have sufficient accuracy at the necessary scale; (2) the location of the spring does not necessarily represent the geology of its entire catchment basin; and, (3) geologic contacts are often located by the springs and therefore selecting the geologic unit for a

spring from the map can be a circular process. This is particularly true in areas like the V&R where there is limited rock exposure.

Water Quality Measurements

A calibrated YSI Pro multi-meter was used to measure pH, temperature and SC at the field site. Grab samples were collected for alkalinity and major ions. Alkalinity was determined by titration using either a Hach Digital Titrator and calibrated pH meter or a Hanna Instruments autotitration system. A Gran titration with pH endpoints of 4.2 and 3.9 was used. Major elements Ca, Mg, Na, and K were measured using an ICP-OES on filtered (<0.45 µm) and acid-preserved samples. Anions Cl, SO₄ and NO₃ were measured using ion chromatography on filtered samples. More elements were analyzed but are not included in this paper. Only data with charge balance errors of <10% were included in this study. The proportions of major ions are illustrated on a Piper Diagram (Figure 3).

Continuous Data Logging

ONSET HOBO U22 data loggers were placed in 12 springs in Monroe County plus 4 additional sandstone springs in Preston and Huntingdon Counties. Data loggers in Monroe County were installed in the fall of 2015 while loggers in Preston and Huntingdon Counties were installed in April 2017. Monroe County data were truncated for compatibility with the Preston and Huntingdon County data. Temperature is recorded at 10 to 30 minute intervals.

Results and Discussion

Water Chemistry

Average values for field parameters and water chemistry were used to compare the springs (Table 2). Group 1 springs have proportionally higher magnesium and sulfate concentrations than do the other springs and may discharge magnesium-carbonate or magnesium-sulfate waters (Figure 3). Group 2 and Group 3 springs can be classified as having calcium-carbonate waters (Figure 3). The stream waters fed by Peter's Mountain are comparable to and overlap with both Group 2 and 3 springs. Group 1 springs have distinctly lower pHs and SCs than the other springs (Figure 4). The three V&R springs (HCOLD, HDUBB, and APPL) have pHs between 4 and 5; the two Plateau springs (RBWG, RBSH) have slightly higher pHs (5–6).

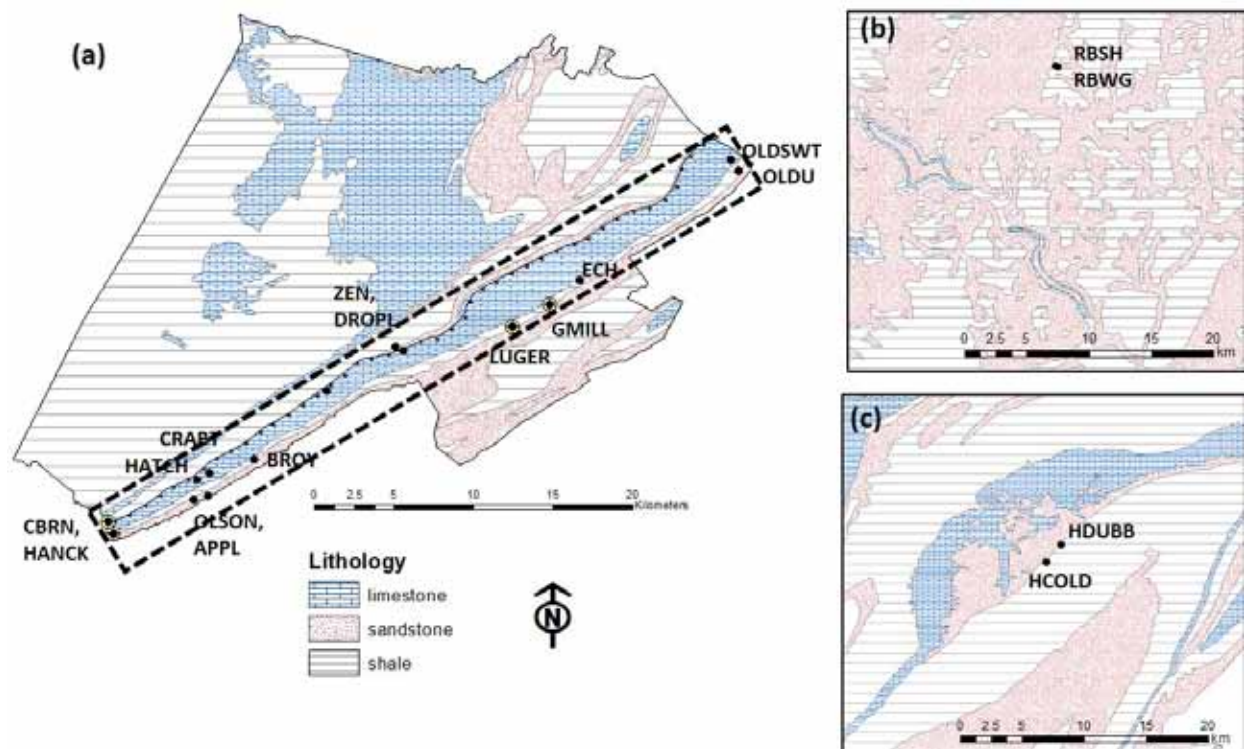


Figure 2. Locations of sampling sites and bedrock geology type. (a) Monroe County WV with the Peters Mountain area boxed; (b) Preston County WV springs; (c) Huntingdon County PA springs.

Group 2 springs have generally lower SCs than do Group 3 springs. It is possible that the Group 2 springs associated with the Martinsburg Formation likely also collect and discharge surface water from colluvium deposits upslope thereby diluting the carbonate signature. Group 3 springs generally have higher average SCs than the other groups. The sample with the highest SC (ZEN, 750 $\mu\text{S}/\text{cm}$, not

shown on Figure 4) discharges from dolomitic water. Additional evidence for this is seen in low Ca/Mg ratios and consistent water temperature (discussed later). As expected, the stream water chemistry is highly variable and overlaps with both Groups 2 and 3.

The Ca concentrations in Group 1 are much lower than detected in the other waters (Figure 5); however the Group 2 and Group 3 Ca concentrations are generally within the same range of values (Figure 5, Table 2). With the exception of OLDU, there is a trend within the Group 2 springs where the lower elevation springs contain higher concentrations of Ca (Figure 6).

The Ca/Mg molar ratio is a better indicator of the spring water source than the individual concentrations (Figure 5). Group 2 springs had higher Ca/Mg ratios (5.66–14.9, mean 11.5) than the Group 3 springs (1.12–5.65, mean 3.2). Higher ratios indicate the presence of purer limestone while lower ratios indicate dolomite-sourced waters. The spring with lowest ratio (1.1) is Zenith Spring (ZEN) supporting the interpretation that this spring discharges from dolomite. Olson Spring (OLSON, Group 2) has a Ca/Mg molar ratio closer to that of Group 3 springs, potentially due to a greater input

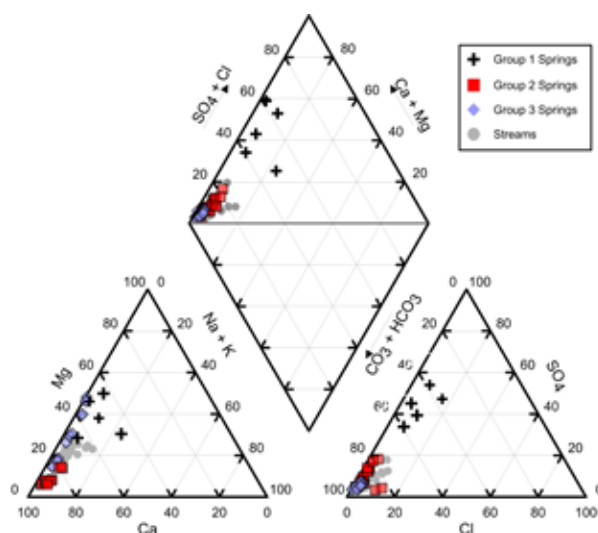


Figure 3. Piper diagram for water samples collected.

Group & ID		n	Temp (C)	pH	SC (μS/ cm)	Alk (mg/L CaCO ₃)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO4 (mg/L)
Group 1	APPL	1	15.60	5.04	55	0.94	2.04	0.66	1.08	0.82	1.28	7.05
	HCOLD	1	10.60	4.83	40	6.95	2.73	<1	1.22	0.64	2.20	8.63
	HDUBB	1	9.96	4.14	28	5.48	1.44	<1	0.78	0.09	0.77	7.40
	RBSH	1	11.20	6.02	24	9.89	1.60	<1	1.11	0.28	0.82	5.41
	RBWG	1	9.00	5.60	34	9.52	3.81	<1	1.01	0.43	0.58	8.17
Group 2	BROY	3	10.59	7.25	237	124	49.7	0.48	1.92	1.26	1.82	8.66
	ECH	2	9.60	7.56	131	67.3	25.9	0.36	1.26	0.90	1.29	4.07
	GMILL	3	9.26	7.30	116	52.3	20.9	0.46	1.17	1.11	1.05	5.87
	HANCK	2	9.97	7.51	182	101	42.7	0.44	2.31	1.47	1.88	7.26
	LUGER	2	8.95	7.72	109	45.3	18.8	0.40	1.03	1.03	0.94	6.91
	OLDU	2	10.29	7.60	243	124	48.0	0.55	1.99	2.75	11.5	5.27
	OLSON	3	9.23	7.06	100	46.5	18.7	0.64	2.02	1.45	1.02	8.96
Group 3	CBRN	1	11.00	6.75	166	96.9	38.7	0.73	5.40	1.03	1.53	6.91
	CRABT	5	11.32	6.85	272	135	40.7	1.01	10.3	1.30	1.68	7.85
	DROPL	3	10.44	7.49	226	116	28.5	0.77	11.4	0.86	2.00	6.34
	HATCH	2	10.55	7.38	165	95.7	35.1	0.68	3.76	0.98	2.02	7.19
	MEFF	2	9.87	7.61	185	95.2	31.8	0.62	4.40	1.21	2.39	5.41
	ZEN	4	11.14	7.23	498	217	50.5	1.14	27.4	0.60	1.16	9.01
Stream	QHAN	4	11.90	7.46	189	91.8	29.4	2.40	6.33	4.10	6.58	10.6
	QIND	2	9.20	8.07	183	102	33.4	0.96	6.58	2.71	3.50	8.82
	QRCH	3	10.47	7.59	194	99.1	35.0	1.83	6.85	3.71	5.85	12.0
	QSEC	4	11.13	7.94	193	105	35.9	1.44	6.57	2.02	3.52	4.39
	QSWT	4	11.28	7.15	297	146	47.2	1.78	8.92	2.65	4.20	11.9

Table 2. Average values for field data and major ion chemistry.

Notes: Groups as defined in text; n=number of samples for the average values. SC=Specific Conductivity; Alk=Alkalinity. Only complete datasets with charge balance errors <10% are included.

from carbonate sources. Additional data will be collected to clarify this difference.

Temperature Fluctuations

Temperature variations at the springs are highly influenced by the nature of the recharge and its transmission through the system (Luhmann et al., 2011). The balance between advective and conductive heat transport is a function of the amount of water and heat in the system and depends on porosity, thermal characteristic of the rock, flow rate, and the extent of conduits and fractures (Benderitter and Roy, 1993; Manga, 2001). Thus, the variability in spring water temperature is an indicator of how rapidly the spring is recharged from rainwater. Consistent temperatures indicate longer residence times and “flashy” temperature responses indicate shorter residence times.

Based on the available data from 2017, all three groups of springs included members that were highly consistent and members that varied significantly with storms and/or seasons, similar to the thermal patterns identified by Luhmann et al. (2011); (Figure 7, Table 3).

Of the Group 1 springs, the most variable is RBSH. This spring is located near the top of a sandstone knob and likely has a small catchment area. The nearby spring RBWG is located in an erosional channel at lower elevation. The two springs in Huntingdon County PA (HDUBB and HCOLD) map on the same geologic contact at near the same elevation. Their different thermal responses may be related to the exact location of the contact but there is little nearby rock exposure to evaluate that factor. Given the location for the logger at

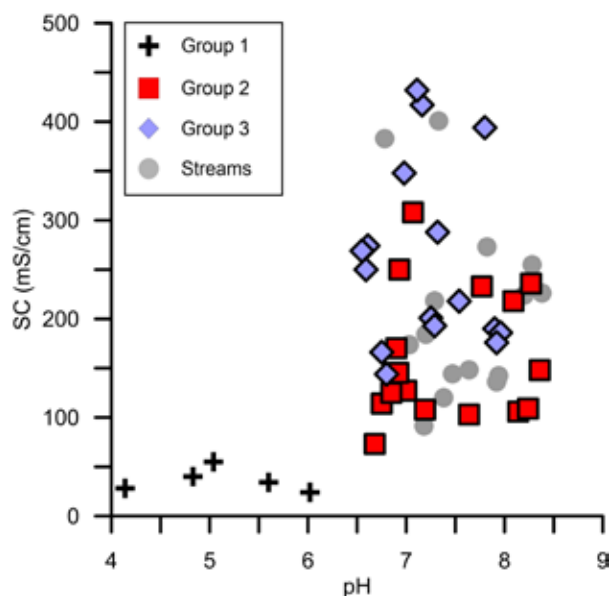


Figure 4. Average field screening parameters measured in springs and stream samples. The high value for ZEN (750 μ S/cm) is not included on the graph.

HCOLD, it is possible that the temperature spike may be due to overland flow from a storm.

Group 2 and Group 3 springs include locations with very consistent and more variable temperatures. For the Group 2 springs, there is a general trend between elevation and the temperature variability in 2017. This may be because the

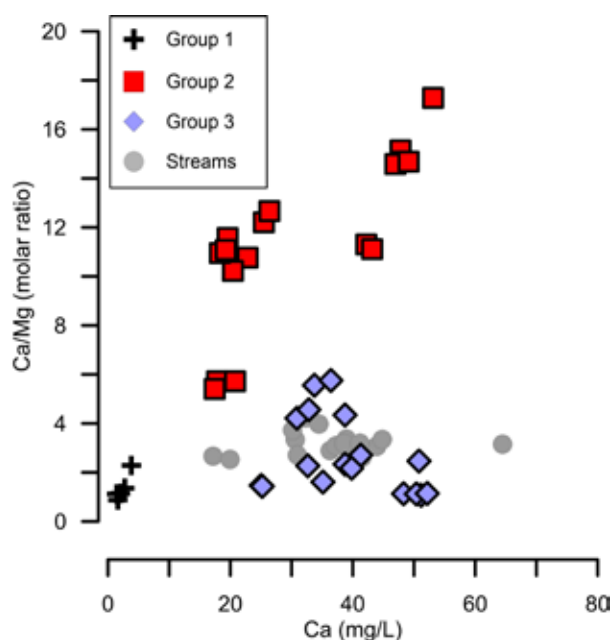


Figure 5. Average Ca vs Ca/Mg ratios for springs and comparison streams.

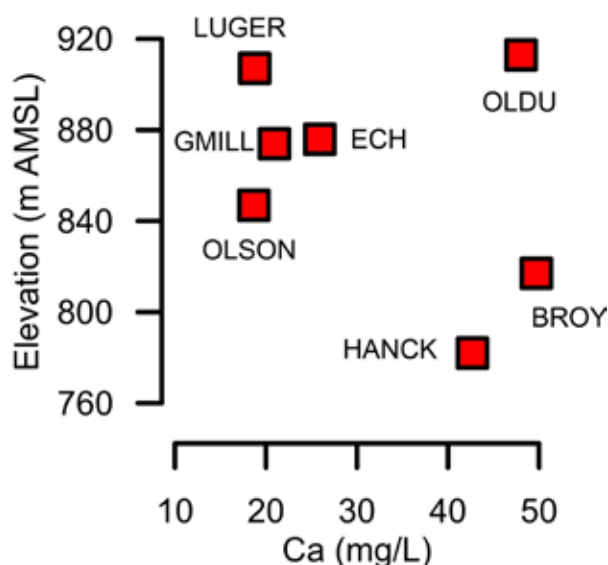


Figure 6. Average Ca concentrations and elevations for the Group 2 springs.

higher elevation corresponds to the less calcareous layers of the Martinsburg Fm. This interpretation is supported by the fact that the higher elevation Group 2 springs contain lower concentrations of Ca (Figure 6); however, it is also possible that there is sufficient change in the Martinsburg lithology from northeast to southwest to account for these variations. The Group 2 springs with the least variable temperatures are located in the northeast or central region of the study area while the most variable springs are located in the southwest region (Figures 3 and 7, Table 3).

Summary

The Appalachian V&R Province hosts a wealth of springs; although most of the research to date has focused on the carbonate springs, the springs located on the ridge tops and flanks also play a critical role as headwater sources and for ecosystem support. The smaller springs studied in this project had thermal fluctuations as the carbonate springs suggesting that the conceptual framework used for carbonate springs is also useful for these smaller and more ephemeral springs. The springs flowing from sandstone units (Group 1) are generally low in pH, SC and dissolved ions; the (Group 2) springs flowing from the Martinsburg Fm on the valley flanks may be similar to the carbonate springs or discharge a more dilute chemistry. The range of behaviors and chemistries of the Group 2 springs may be tied to changes in the formation either vertically or spatially.

Additional data are needed to better understand spring chemistries and storm responses. Better geologic

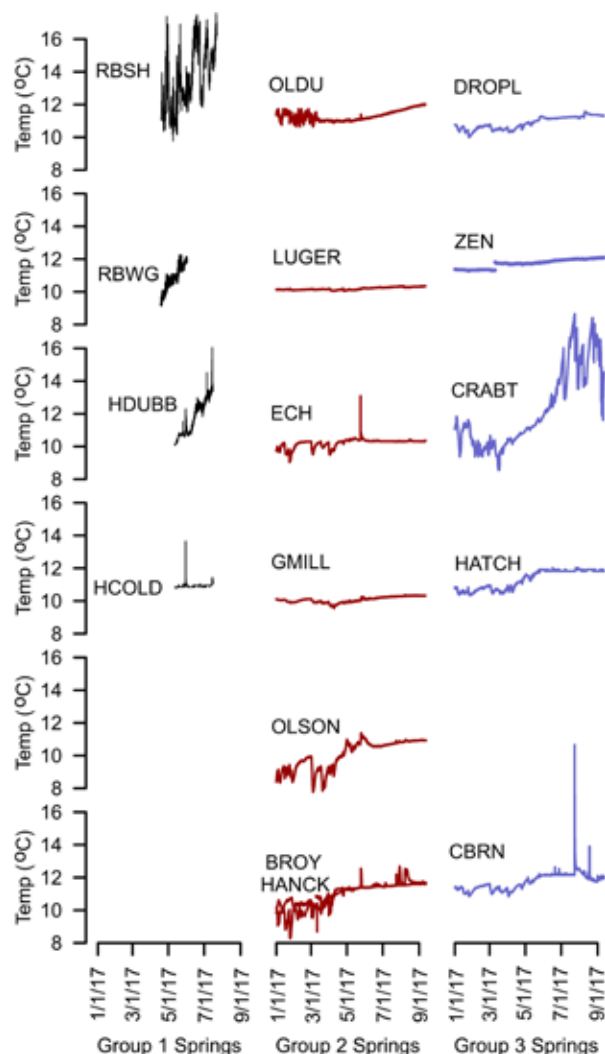


Figure 7. Temperature data for locations with dataloggers. All data plotted using the same scale. Within each group, the plots are organized by elevation with the highest elevation spring at the top and the lowest elevation spring at the bottom.

mapping is critical; if springs are used to map geologic contacts then the resulting geologic maps may not provide independent data about the source of the water. Natural tracers that can “fingerprint” the different water sources need to be identified to be able to distinguish between catchment areas and to quantify the input of the clastic spring waters into the carbonate aquifers.

Acknowledgements

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Location	Site ID	Elevation, m above MSL	Average Temp, C	RSD Temp, %
Group 2	BROY	817	11.0	6.2
	ECH	876	10.2	2.5
	GMILL	874	10.1	1.8
	HANCK	782	9.94	5.4
	LUGER	907	10.2	0.8
	OLDU	913	11.3	2.7
	OLSON	847	9.94	8.9
Group 3	CRABT	645	12.0	19.5
	CBRN	583	11.5	5.4
	DROPL	741	10.9	3.5
	HATCH	636	11.3	5.1
	ZEN	667	12.0	0.4
Group 1 (Preston County, WV)	RBSH	548	13.5	14
	RBWG	524	10.9	6.6
Group 1 (Huntingdon County, PA)	HCOLD	221	10.9	1.2
	HDUBB	221	11.7	8.9

RSD = (standard deviation)/(mean) expressed as a percent. Data logger lost at MEFF spring. Data for ZEN begin after change in logger on 3/10/17

Table 3. Elevation and temperature data for locations with data illustrated in Figure 7.

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AN UNUSUAL SPRING IN THE JACKSON RIVER, BATH COUNTY, VIRGINIA

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Abstract

Boiling Spring rises in the bed of the Jackson River about 0.5 km (0.3 mi) downstream of the USGS gaging station on the Jackson River near Bacova, Virginia. Five tracer tests to the spring have been conducted on sinking upstream tributaries to the Jackson River. The longest trace was 12.5 km (7.75 mi) from Muddy Run with the dye injected on the east side of the Cobbler Mountain Anticline. Additional traces to Boiling Spring are from Muddy Run on the west side of the anticline, Chimney Run, Creek Bed Cave, and Warm Springs Run. Travel times were greater than one mile per day. The gaging station is missing about one third of the total flow under low flow conditions. Discharge measured in October 2005 was 0.36 m³/s (12.8 cfs) from the spring, and 0.77 m³/s (27.0 cfs) at the Bacova gaging station. The ungaged discharge is probably not a significant part of the total flow at higher river levels. However, the annual runoff for the Jackson River station at Bacova—with a drainage area of 409 km² (158 mi²)—is 371 mm (14.6 in) per year, well below the 480 mm (18.9 in) per year for the nearby Bullpasture River at Williamsville that has a smaller drainage area of 285 km² (110 mi²).

Introduction

A boiling spring, at least as the term is used in Virginia, occurs where a rise tube in a stream channel discharges water under enough pressure to create a boil or disturbance at the water surface. Two reported Virginia boiling springs are Boiling Spring in Allegheny County and Boiling Spring on the Jackson River in Bath County upstream from Lake Moomaw. The water may reach the surface with considerable velocity. A couple of attempts to explore these springs by diving showed the spring outlets to be plugged by large cobbles. The number of boils appearing at the water surface may change, at least temporally. The springs usually show just one boil (Figure 1), but the Bath County spring has been observed with as many as three boils on the surface.

All of the sinking streams traced to Boiling Spring are on the eastern side of the Jackson River from Hidden Valley to the Richardson Gorge 3.2 km (2 mi) south of Bacova. The surface topography ranges from anticlinal ridges to rolling pastureland in the western portion of the Valley and Ridge physiographic province. Detailed geologic mapping is unavailable for the study area. A 1:100,000 scale geologic map (Rader and Wilkes, 2001) lumps all of the rocks as undivided Devonian and Silurian and little structural detail is given. A much more detailed description of the stratigraphic units is presented in Swezey et al. (2015). The rocks seen in road banks are primarily sandstones and shales with limestones exposed in water gaps cutting the anticlinal ridges of in feeder streams and along the Jackson River. All of the steam sinks traced to Boiling Spring are at the contact of the Licking Creek Limestone with the overlying Oriskany Sandstone so most of the recharge to the spring is allogenic water flowing off of the surrounding clastic rocks. Boiling Spring appears in a meander bend of the Jackson river and is probably near the axis of an anticline that brings the older Keyser Limestone to the surface.

Bath Boiling Spring

The Bath County Boiling Spring is on private property on the Jackson River downstream from Bacova in western



Figure 1. Photo showing Boiling Spring at low flow (photo by W. K. Jones).

Bath County. The spring is 1.4 km (0.9 mi) downstream from the U.S. Geological Survey gaging station (USGS 02011400) near Bacova (Figure 2). Water discharging at Boiling Spring is mostly the return of surface water from several tributary streams to the Jackson River that sink in their beds before reaching the river during dry periods. All of the tributaries traced to the spring have been infeeders on the east side of the river (Figure 2). The stream traces are summarized in Table 1.

The Jackson River was monitored for dye using passive carbon detectors at three locations above Boiling Spring, the spring itself, and one location downstream of the spring. Two other springs along the river upstream from Boiling Spring were also monitored using passive carbon detectors. Grab samples were collected at Boiling Spring at two to four day intervals. The presence and relative concentrations of the tracer dyes were measured using a Shimadzu RF5000U recording spectrofluorophotometer. The tracers were only found at Boiling Spring and the downstream Jackson River station.

The nearest sinking stream that has been traced to Boiling Spring is water from Warm Springs Run. This stream rises as a thermal spring (about 36°C, or 97°F)



Figure 2. Sketch map showing the tracer tests to Boiling Springs. Small stars show location of sink points used for dye injection and large star is Boiling Springs (map by P.C. Lucas; 1 mile=1.6 km).

Swallet	Date	Dye (lbs)	Travel (days)	Distance km (mi)
Warm Spr Run	9/14/2005	Eosin (2)	<3	4.8 (3.0)
Creek Bed Cave	8/16/2005	Fluorescein (2)	<5	6.4 (4.0)
Chimney Run	10/03/2005	Rhodamine (3)	<10	9.7 (6.0)
Muddy Run (E)	8/16/2005	Rhodamine (3)	4<d<11	12.5 (7.75)
Muddy Run (W)	9/28/2005	Fluorescein (1)	<4	12.2 (7.6)

Table 1. Tracer tests to Boiling Spring.

and flows to the southwest joining the Jackson River above Bacova. This water is highly mineralized and the water at Boiling Spring appears to be even more highly mineralized and contains sulfur species probably originating from Warm Springs.

Creek Bed Cave is in a small valley (Figure 3) and normally captures most of the flow from this unnamed tributary. This sink is just north of Rte. 39 and is the one stream that does not reach the river on the surface. A couple of miles to the north of Creek Bed Cave, Chimney Run sinks under low flow conditions and resurges at Boiling Spring.

Muddy Run sinks in its bed in two different places before reaching the Jackson River junction upstream from Hidden Valley. The first resurgence, about a mile above the mouth of the run, is located at the east flank of the Cobbler Mountain Anticline, capturing a part of the Muddy Run stream into a small cave at creek level (Figure 4). The straight-line distance to Boiling Spring is 12.5 km (7.75 mi) and this is the longest reported tracer test in Virginia. The second resurgence, on the west



Figure 3. Dye injection at Creek Bed Cave (photo by W. K. Jones).



Figure 4. Dye injection at the upper Muddy Run Cave resurgence (photo by W. K. Jones).

flank of the anticline occurs at a limestone outcrop in the stream bed. Clastic rocks separate these two sink points.

Conclusions

A discharge measurement at the spring during low flow conditions of October 2005 showed the spring discharge at 0.36 m³/s (12.8 cfs). The discharge at the gaging station just upstream of the spring was 0.77 m³/s (27.0 cfs), so the total flow for this reach of the river should be about 1.13 m³/s (40 cfs). The under-reporting of the flow for this station is probably not significant at high water levels. The reported drainage basin area of 409 km² (158 mi²) would be changed very slightly if the gaging station could be moved downstream of the spring. The calculated annual runoff of 371 mm (14.6 in) per year seems low compared to 480 mm (18.9 in) per year for the nearby Bullpasture River at Williamsville and other gaging stations with a similar water budget.

This is a rather immature karst area but has potential for significant cave development. These dye traces establish that an area about 12.9 km (8 mi) long and 4.8 km (3 mi) wide is being drained by underground flow routes. Despite a surface that lacks well-developed karst and has only a few small caves, there are probably many miles of caves below the Oriskany Sandstone caprock.

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STUDY ON EARLY RECOGNITION METHODS OF COVER-COLLAPSE SINKHOLES IN CHINA

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Abstract

Cover-collapse sinkholes pose a major geohazard occurring in mantled karst regions in the south of China in recent years. Cover deposits generally mask the subsurface development and propagation of the deformation to the topographic surface. Human security and land-use planning in sinkhole-prone areas need to be preceded by detailed investigations focused on identification of pre-existing sinkholes, subsurface dissolution, subsidence features, and groundwater condition. Therefore the abnormal, early hidden danger signs (ground, underground and hydrodynamic) of karst collapse are studied. Further, the corresponding identification techniques and methods are presented, such as surface surveying techniques (satellite remote sensing, the drone, etc.), underground detection technology (ground penetrating radar, microgravity, micro tremor, etc.), and monitoring of groundwater conditions. Finally, all kinds of techniques and methods can be combined to form a comprehensive system for identifying hidden dangers of karst collapse. This paper aims at identifying the early hidden dangers of karst collapse geological disasters. This has important theoretical, technical and social significance in order to minimize the impact of disasters on the people and the environment.

Introduction

Cover-collapse sinkholes are a major geohazard occurring in soil-covered karst regions. Cover-collapse sinkhole features are the result of the water-borne transport of soil or other related material downward into underlying voids in either the limestone bedrock or the soil profile. Cover deposits generally mask the subsurface development and propagation of the deformation to the topographic surface (Beck, 2004; Waltham et al., 2005; Gutiérrez et al., 2008, 2014).

When sinkholes, including sudden catastrophic collapses and subsidence at considerable depths, may adversely interact with the human environment, multidisciplinary approaches should be planned to 1.

Ascertain the surface subsidence and sinkhole features; 2. Locate and define precisely the subsurface dissolution and underlying subsidence features (such as karst cave, soil-cavities, the presence of active subsidence and so on); 3. Monitor groundwater conditions. Land-use planning in sinkhole-prone areas needs to be preceded by detailed investigations focused on the identification of pre-existing sinkholes, subsurface dissolution and subsidence features (Galve et al., 2009).

Karst collapses have occurred frequently in the south of China in recent years. The present study represents a contribution to monitoring and understanding the genesis and early stage evolution of a sinkhole using different methodologies.

Methodology

The multidisciplinary approach follows three aspects: 1. Surface surveying methods (field surveys, satellite remote sensing, the drone, etc.); 2. Underground detection methods (ground penetrating radar, Photoelectric monitoring, etc.); and 3. Hydrodynamic monitoring.

Surface Survey Methods

In some cases, pre-collapse surficial evidence can be identified by topographic depressions and geomorphological analyses. Field surveys and interpretation of remote-sensed imagery are often useful to identify sinkhole surface factors (Forth, et al., 1999; Kaufmann, and Quinif, 2002; Brinkmann, et al., 2007, 2008; Argentieri, et al., 2015).

To a certain extent, the remote sensing method can provide the data necessary to guide investigations and monitoring. Thorough reconnaissance of the ground may locate sinkholes not identifiable on aerial photographs, due to their reduced size, depth, or vegetation cover.

UAV Remote Sensing

In digital photogrammetry, unmanned aerial vehicles (UAV) are a relatively new technology that can be

used to capture digital images for large scale mapping with accuracy down to centimeter level from various waypoints for the mantled karst regions. UAV have several advantages over satellites because they can capture aerial images from certain flying height, and have flexible flying mission and timing (Anai et al., 2012; Mohd azhar et al., 2014; Yeh et al., 2016). The efficiency and high mobility of UAV makes them essential to aerial photography assisted survey and mapping.

Interferometric Synthetic Aperture Radar analysis (InSAR)

Interferometric Synthetic Aperture Radar analysis (InSAR) can be used to screen large areas for anomalous vertical movement and to guide intensive field investigations and detection to areas where significant change is occurring (Zhao, et al., 2009; Nof, et al., 2013; Intrieri, et al., 2015; Carbonel, et al., 2015; Galve, et al., 2015). Satellites record images of the Earth's surface and these images can be combined to reveal subtle movements or deformations of the ground surface. Mapping of ground displacement may serve to identify the location of future sinkholes. There are cases in which InSAR is used to detect and characterize sinkholes, as well as for reducing the associated risk when combined with other sources of data such as a sinkhole inventory.

Light detection and ranging (LiDAR)

The light detection and ranging (LiDAR) technology is one development in the field of photogrammetry and remote sensing. Airborne LiDAR systems can measure ground and sinkhole shapes with high resolution. Acquisitions of LiDAR data for the creation of highly accurate (sub-meter) elevation models that can be used for rapid, precise detection of sinkholes. (Daniel et al., 2013; Shaw et al., 2013).

Subsurface Detection and Monitoring and Geophysical Methods

Subsurface cavities and the processes that lead to the development of sinkholes cause changes within the subsurface (e.g., porosity, fracture density, and water saturation). Before collapse, these changes may be detected using geophysical methods (Frumkin, et al. 2011) such as ground-penetrating radar (Pueyo-Anchuela, et al., 2009; Lei M et al., 2007; Batayneh et al., 2002;), the direct current resistivity technique (Batayneh and Al-Zoubi 2000, Roth and Nyquist, 2003), microgravity (Eppelbaum, 2008; Alzoubi, 2013), and microtremor surveying (Rucker et al., 2013). These non-invasive measurements can be used effectively to provide reconnaissance ahead of detailed geological investigation, guide subsurface sampling and excavation, and provide continuous monitoring. The effectiveness

of each geophysical technique depends on its ability to reach the target depth with the appropriate resolution in different geological settings. Therefore, integrated geophysical approaches are often reported as well as the calibration/validation with information obtained directly from boreholes.

Boreholes

Drilling provides valuable information on the nature and geotechnical properties of the ground and allow the recognition of voids and sediments disturbed by subsidence processes, including raveling zones and breccia pipes. This is a requirement for borehole data that can guide the development of an effective scope and schedule for geophysical investigations, in order to observe and verify the accuracy of predictions. However, the expensive and time-consuming technique has other limitations. The normal site investigation practice of wide-spaced boreholes means that they may easily miss cavities and raveling structures.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a geophysical technique that offers a very high resolution to locate and characterize structural and sedimentological information of the subsoil (such as soil-cavities, the presence of active subsidence and so on).

Surface-based GPR

In the surface-based GPR profiles this information can be identified from the change in color that is related to the amplitude of the recorded wave in each point. Soil cavities are characterized by abrupt lateral contrasts in the electromagnetic properties of the materials (Figure 1). These features are represented by hyperbolic anomalies. Structural features obtained from GPR-profiles (on-lap geometries, zones with depressed reflectors, folded reflectors or laterally abrupt structural limits) can be linked to the presence of active subsidence processes without development of fully-grown cavities.

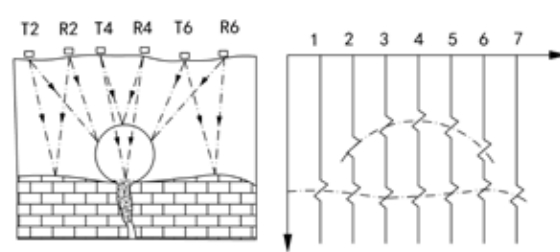


Figure 1. Soil-cavity reflections in GPR profiles. T1~T3: transmitting antenna; R1~R3: receiving antenna; 1~7: reflection waveform

Single-hole radar

A geotechnical borehole radar technique was used to acquire high-resolution two-dimensional radar velocity data. To record single-hole full-waveform radar data, a fixed-offset transmitter receiver antenna pair is pulled slowly up the length of a borehole. Such data supply information on the velocity and attenuation of radar waves in the vicinity of the borehole and on the nature of reflectors distributed along the borehole.

The principle of the single-hole reflection method is similar to that of surface-based GPR, except that reflectors may occur on all sides of the borehole recording line (Figure 2). Planar features (such as fault surface) intersected by a borehole will appear as V-shaped reflections on a single-hole radar section (Figure 2, b, B). The image of a point reflector (Such as soil hole) is a hyperbola (Figure 2, a, C). Due to the rotational symmetry of non-directional antennas operating in straight boreholes, the georadar data on their own do not provide sufficient information to determine unambiguously the locations of reflectors not intersected by the boreholes. To compensate for this limitation, constraints from other observations are necessary.

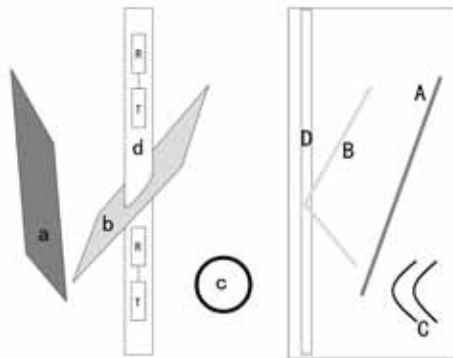


Figure 2. Single-hole radar reflection method. a,b:Fracture surface; c:Karst cave; d:Borehole; A,B: Reflection from Fracture surface; C: Reflection from cave; D: Direct wave; T: Transmitter antenna; R: Receiving antenna.

Cross-hole radar

Cross-hole GPR is a transillumination survey method in which two antennas are lowered down in adjacent, parallel boreholes. Using two boreholes, cross-hole level scanning was performed by placing the transmitting and receiving antennas at the same distance positions in separate boreholes. By transmitting radar signals from one borehole to another, radar velocities and attenuation between the two boreholes can be estimated. The transmitter antenna emits a short pulse, or shot, of

high-frequency electromagnetic energy. The receiving antenna, located in the adjacent borehole, captures the frequency-modulated signal and precisely measures the time required for the signal to travel through the ground, along the plane separating the two boreholes.

Transmission time imaging is a great way to detect the most water-filled areas (such as water-filled faults and caves), which are caused by the spread of the dielectric constant. The low speed belt represents the water filling area (Figure 3 red zone).

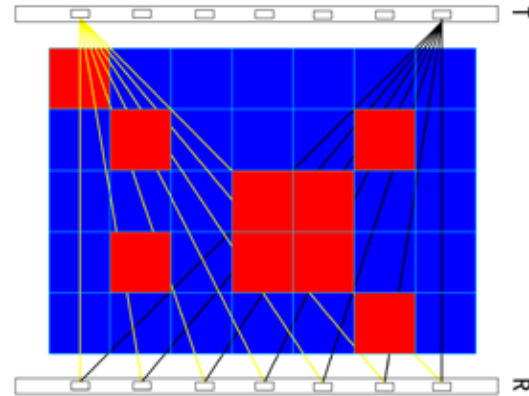


Figure 3. Crosshole GPR method. The red zone stands for water-filled faults and caves

Photoelectric monitoring method

Sinkhole collapses usually occur abruptly, so traditional land surface measurements are not very useful to forecast the occurrence of sinkhole collapses. Photoelectric sensors can play a role in precise and real-time monitoring and early warning. They may predict specific location and dimension of a potential sinkhole collapse (Lei et al. 2005).

This photoelectric monitoring method includes optical fiber sensing and coaxial cable sensing. The fiber or coaxial cable is buried underground and soil deformation is translated into strain of the fiber or cable, even up to its breakpoint. Using special measuring instruments, continuous monitoring for soil deformation and damage can be achieved for a specific site.

So, it will be a significant work to explore a way to predict the location and dimension of potential sinkholes. When embedded in sediments, optical fiber responds well to deformation of rocks and soils. It is possible to monitor soil and rock deformation by measuring the strain of optical fiber (Figure 4). Soil strain measurement using optical fibers is a promising technique for predicting karst collapse.

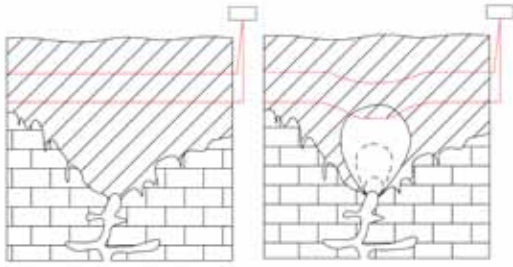


Figure 4. Photoelectric monitoring method schematic diagram. The red line stands for fiber or coaxial cable

Hydrodynamic Monitoring

Groundwater plays a key role in the development of both processes, as the agent responsible for the dissolution, and as a first order factor that determines ground instability. In fact, recent reviews reveal that a great proportion of recent sinkholes have been induced by anthropogenic changes in hydrogeological systems. There are a large number of papers that document the impact of human-induced water table declines on sinkhole occurrence (Perez et al., 2016; Linares, et al., 2017, Jiang X et al., 2017). Groundwater-level change conducive to sinkhole collapse formation in some countries related to aquifer over-exploitation, especially in China (Lei, et al., 2016) and it plays an important role in the formation and evolution of soil caves. Groundwater levels exceeding critical values can be indicative of soil cave formation and development. The merits of this method lie in the possibility of capturing real-time changes in the underground hydrodynamic forces and in the potential for dynamic appraisal. Therefore, the monitoring of groundwater-level could become an effective method for forecasting the appearance of sinkholes (Figure 5).

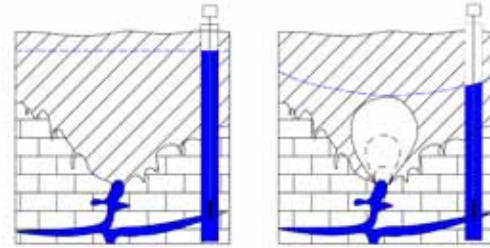


Figure 5. Hydrodynamic monitor method schematic diagram. The blue line stands for groundwater-level

Case studies in the south of China

Case 1: remote-sensing and Unmanned Aerial Vehicle Remote Sensing

The study in this case has incorporated the analysis of aerial photographs from historical cartographies (2014~2016) (Figure 6) and Unmanned Aerial Vehicle Remote Sensing (2017) (Figure 7) of the studied zone in the Conghua city in the south of China. The collapse occurred between November 2014 and March 2015. A total of 47 karst collapse pits are characterized by the historical geomorphological analysis with a field inspection.

The UAV is capable of flying at low altitude together with small format digital camera and it is suitable for in the studied zone in the collapse region in the Conghua city of China. The UAV which integrated GPS has ability to perform autonomous flight and automatic navigation along planned waypoints. These waypoints are usually planned beforehand easily by dedicated software as considering the camera parameter, area of interest, overlap of image, altitude and so on. Moreover, still



Figure 6. Historical cartographies from remote-sensing. Historical aerial photographs on October 28, 2016 and December 5, 2016.

images at planned waypoints are acquired automatically by digital still camera mounted on UAV.



Figure 7. Example of image acquired with UAV On October 20, 2015 in the studied zone in the Conghua city of China.

Case 2: InSAR and LiDAR

Interferometric Synthetic Aperture Radaranalysis (InSAR) and Light Detection and Ranging (LiDAR) are promising technologies for monitoring the ground subsidence and characterizing sinkholes, as well as for reducing the associated risk when combined with other sources of data such as a sinkhole inventory.

In Hunan province in China, high resolution Terrasar-X satellite data is ordered (spatial resolution 3m, April 2014 - January 2015 (Figure 8). Using LiDAR data, the three-dimensional model was constructed and the collapse volume was calculated (Figure 9). Through LiDAR 3D modeling, the collapse volume is more than 10,000 m³ in Hunan province.

According to work experience, InSAR and LiDAR methods should not be considered as an alternative to classical mapping methods, but a highly useful complementary approach.

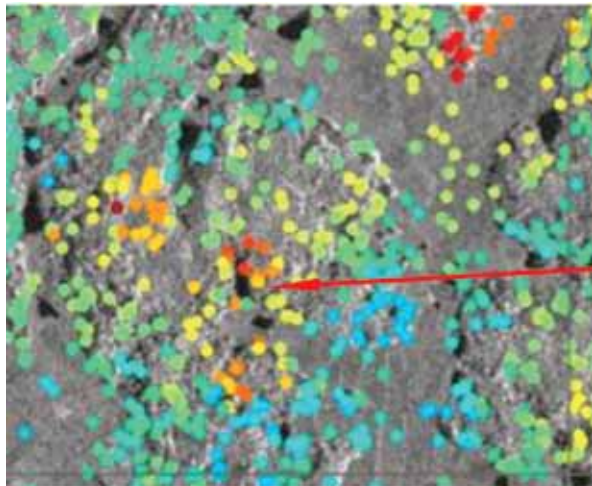


Figure 8. An example of ground subsidence points identified by InSAR data

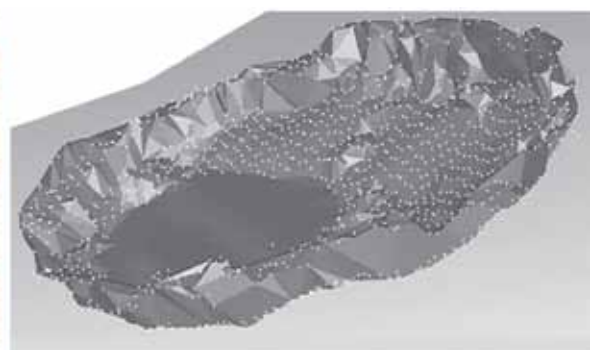


Figure 9. The photographs and the LiDAR data model for an example of a collapse pit

Case 3: Surface-based Ground Penetrating Radar (GPR)

The main goals for GPR surveys used in this work are to locate and characterize karst hazard zones in the Guilin-Yangshuo highway in Guangxi, China (Lei, et al., 2011). The entire highway was built through an active karst area characterized by tower karst, karst valleys, and watershed divides. The GPR system with shielded antennas and central frequency of 100 MHz was applied to a 12 km section highway to located subsurface voids in a highly active karst area (Figure 10). 337 subsurface voids, 1-6 m in diameter, 1-5.5 m deep, and density up to 48 per 100 m, were detected using GPR.

In this work, GPR profile data processing is included sequential zero-time corrections, running average filter, exponential gain function, band-pass filter and plotting. Depending on the shape and dimensions of these cavities it is possible to find either an isolated hyperbolic anomaly, or clustering of hyperbolic anomalies.

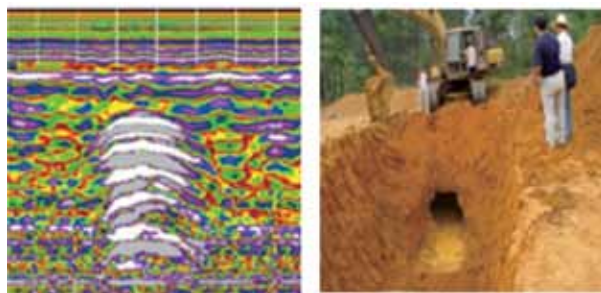


Figure 10. Left. hyperbolic anomaly in GPR profile Right. soil cavity. Results of radar collapse detection

Case 4: Borehole Ground Penetrating Radar (GPR)

The Mingxin village surrounding Foshan city in southern China, drilling and borehole radar is employed to detect deep karst activity in this study. A 15 meter deep water filled karst cave with a diameter of about 6 meters was found at the test site (Figure 11), using borehole radar (100 MHz). Earlier, it was not detected by drilling.

Case 5: Photoelectric monitoring methods

The photoelectric monitoring method is employed for monitoring and predicting potential sinkholes by the Institute of Karst Geology in China. Two pilot monitoring sites were established in 2006 and 2012 at Guilin and Guigang of Guangxi province to monitor potential sinkholes along the highway and the oil pipe, respectively (Figure 12) (Jiang, et al, 2016).

Case 6: Hydrodynamic monitoring

In areas susceptible to sinkhole collapse in the Guangzhou city of China, changes in groundwater level are monitored for early warning purposes. Figure 13 shows that historic sinkholes and groundwater-level changes are closely correlated with groundwater pumping related to underground construction. Before February 2, 2008, because of groundwater withdrawal in this area, the groundwater level at the well declined to an elevation of 1.50–1.88 m. Concurrently, in the surrounding regions, six large sinkhole collapses occurred and the underground construction was suspended. By February 18, 2008, the water level had risen gradually to an elevation of 4.10 m and no further ground collapses had occurred. By September 17, 2008, the underground water level had

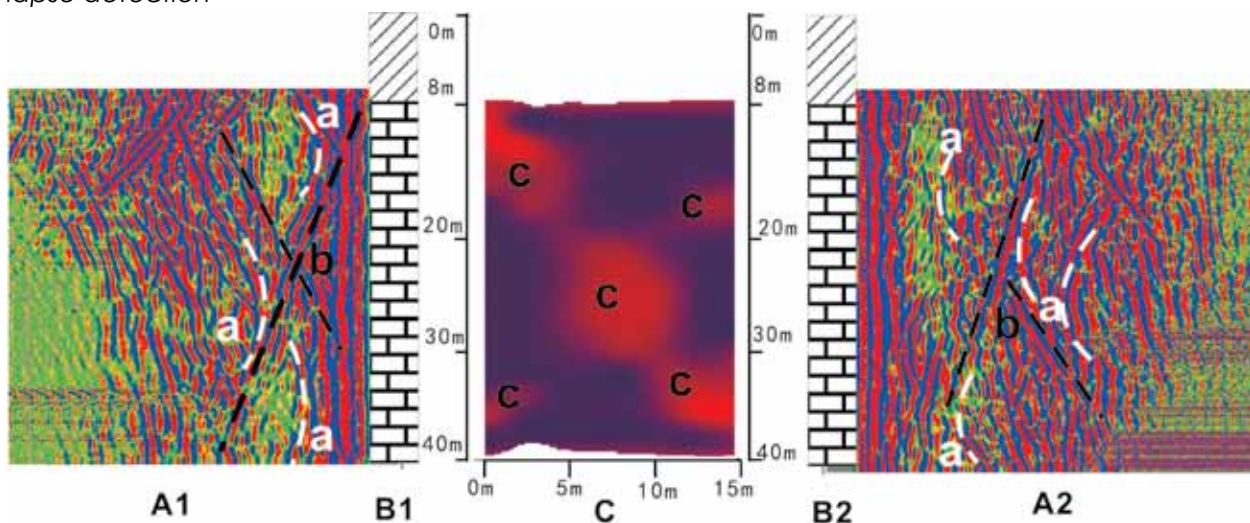


Figure 11. Borehole GPR survey and its results. A1,A2: Single-hole radar profile; B1,B2: bore histogram; C: crosshole radar profile; a: hyperbolic anomalies; b: line anomalies c: the low speed zone representing the water filling area (water-filled faults and caves);



Figure 12. Photoelectric monitoring along the highway and the oil pipe

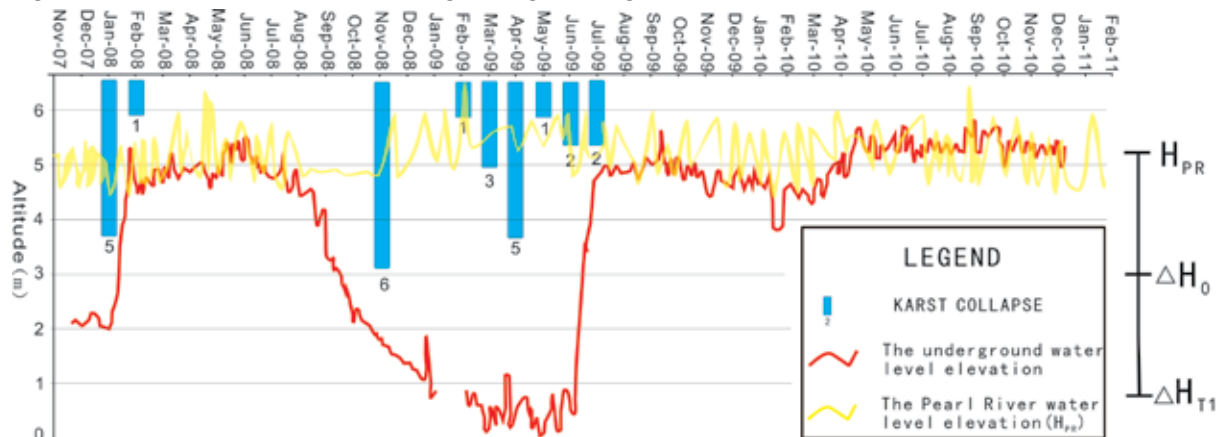


Figure 13. The groundwater-level data from monitoring well

again begun to decline. During this period, 12 further sinkhole collapses occurred, which were concurrent with the groundwater pumping activities.

Conclusions

Commonly, cover-collapse sinkhole may have a very subtle geomorphic expression or the collapse created by underground processes may not yet have reached the ground surface. It is essential to investigate as many sources of surface and subsurface information as possible to provide data about the past and current subsidence activity in the study area. The presence of active subsidence, soil-cavities and the changes of groundwater level can be used as indicators of active karst processes and karst geologic hazard. This study aims at developing a methodological framework for imaging common surface, subsurface and hydrodynamic features.

(1) Sinkholes are commonly mapped using conventional geomorphological methods like field surveys, aerial photographs and topographic maps. Unmanned Aerial Vehicle Remote (UAV), LiDAR systems and satellite

images photographs, especially large-scale stereoscopic images with high resolution, are very useful tools for identifying sinkholes. The geomorphological interpretations help to obtain minimum estimates of the probability of sinkhole occurrence and allow the analysis of the spatio-temporal distribution patterns of the subsidence phenomena. However, the effectiveness of this approach may be quite limited in areas where the geomorphic expression of sinkholes has been obliterated by natural processes or anthropogenic fill.

In addition, InSAR, under favorable conditions, allows the measurement of sub-centimetric deformation occurring over time spans of days or years, covering extensive areas with a high temporal and spatial resolution and without the need of conducting field work. So InSAR can be used to monitor surface subsidence prior to collapse.

(2) Sinkhole collapses usually occur abruptly without any the surface obvious indications. These reasons traditional land surface survey and measurements are not very useful to forecast the occurrence of sinkhole

collapses. Soil strain measurement using optical fibers is a promising technique for predicting karst collapse.

Geophysical methods also have been widely used for the study of sinkholes and the detection of the underground voids linked to their development or to identify and outline, within larger areas, the zones most susceptible to sink. Geophysical methods, specially ground Penetrating Radar (GPR), usually non-destructive and performed from the ground surface, offer a means by which to investigate the soil mass between borings or soundings in a more continuous manner. Although geophysical methods help characterize the soil mass between borings or soundings, ambiguous interpretation and a lack of engineering properties have limited their usage in the past.

Boreholes allow calibrating and validating the geophysical investigations. Drilling provide valuable information on the nature and geotechnical properties of the ground and allow the recognition of voids and sediments disturbed by subsidence processes. The drilling is the expensive and time-consuming technique, may easily miss cavities. To compensate for this limitation, the geotechnical borehole radar technique can be a complementary technique.

(3) Understanding the hydrogeology of the study area is a crucial aspect of sinkhole hazard analysis. Water monitoring was aimed at identifying the relation between the groundwater level fluctuations and the sinkhole activity. The position of the groundwater table and its fluctuations through time and space, obtained primarily by using long-term piezometric data, is essential to estimate the groundwater flow patterns and the development of the depression causes, which may play a fundamental role in the formation of sinkholes.

(4) These kinds of techniques and methods can be combined to form a comprehensive system for identifying hidden danger of karst collapse, understanding the causes of the deformation, assessing the kinematics of the cover-collapse sinkhole.

Acknowledgments

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ADVANCES IN ULTRA-PORTABLE FIELD FLUOROMETRY FOR DYE TRACING IN REMOTE KARST

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Abstract

Dye tracing is a powerful tool in karst hydrogeology, allowing to specify groundwater connections, drainage organization and groundwater flow characteristics in impenetrable places (underground rivers, flooded caves...). The use of in situ monitoring devices enables improved investigation quality and efficiency during field work. Autonomous field fluorimeters developed in the last decades now give reliable data for dye tracing with fluorescent tracers, with a limited investment on the field and limited human resources.

Nevertheless, the karst environment remains difficult to access and explore with scientific equipment. The size, weight, robustness and user-friendliness of the tool is determinant to improve the efficiency of field work and allow the acquisition of reliable data. In order to tackle this issue, we developed the Fluo-Green field fluorometer. This is a compact, extra-light and 2-in-1 field fluorometer (probe and data-logger) designed specifically for karst environment. The fluorometer allows the monitoring of fluorescein, turbidity, and water temperature with a user-defined resolution (1 minute to 1 day). An improved management of energy gives an extended lifetime that is useful for monitoring in remote locations. The compact device is especially useful to carry into the field and facilitates the monitoring of multiple sampling points.

Several dye traces in Belgian karst show the field performance of the Fluo-Green (precision, accuracy, resolution, lifetime...). Different karst environments were investigated using dye tracing: underground rivers, flooded caves, karst springs, vadose percolations. Those experiences illustrate the routine use of the Fluo-Green in various remote karst environments.

Introduction

Dye tracing by the mean of fluorescent dyes is widely used in hydrogeology and specifically in karst systems. This field methodology helps to refine groundwater connections, drainage organization and groundwater flow characteristics. The exploration of underground and impenetrable flow systems within karst networks can also benefit from this tool, in addition to scientific characterization of the karst media.

The measurement of dye concentration in groundwater can be performed with different methodologies. The most widely used techniques are the use of charcoal bags, manual or automatic water sampling and continuous monitoring using automatic field fluorimeters. This last technique has many advantages such as the automatic measurement, a better temporal resolution, precision and accuracy, no sample transportation or analysis, no

contamination of samples. Broadly speaking, it greatly improves hydrogeologic understanding, all the while saving time, human resources, and field efforts.

However, field work and scientific monitoring in karst environments are often difficult to implement. Access and progression in caves with scientific equipment may be challenging, especially in hydrologically active caves. For this reason, field equipment has to be compact and easy to use in variable cases of study, and replacement cost must not be prohibitive.

In order to deal with the challenge of cave dye tracing, this paper presents results from the Fluo-Green field fluorometer (Poulain, 2017; Poulain et al., 2017), which is a compact and user-friendly fluorometer that is designed for cave use. The main characteristics of the device are shortly presented as well as two examples of comparative field results.

Fluo-Green Characteristics

The Fluo-Green fluorometer combines a fluorescence-turbidity-temperature probe and a data-logger in one small submersible equipment (Figure 1). A 470 nm channel is used to measure the fluorescein as it is the most used fluorescent dye in karst hydrogeology (Benischke et al., 2007). An additional 625 nm channel is used to measure water turbidity in order to evaluate possible interference with the fluorescence signal. The controller manages the measurement sequence with a user-defined time step between 1 minute and 1 day. Six AA batteries give a lifetime of 8000 to 9000 sequences (30 days for a 5 minutes time step). The data are stored on an internal SD card that can be read with a computer.

The routine laboratory calibration is made using 1, 10, and 100 ppb solutions in a calibration bath and a computer. Standard resolution for fluorescein ranges between 0.06 and 0.09 ppb. The watertight casing is suitable for rivers, cave percolations and shallow karst pools. It has been successfully tested at -4 meter depth.

Field Performances in Belgian Karst

Field tests were performed to measure the performance of the fluorometer: lifetime, precision, accuracy, robustness. The main objective was to evaluate the ability of a simplified material to give reliable data that are consistent with the objectives and context of the trace (user expectations, financial resources...). Several

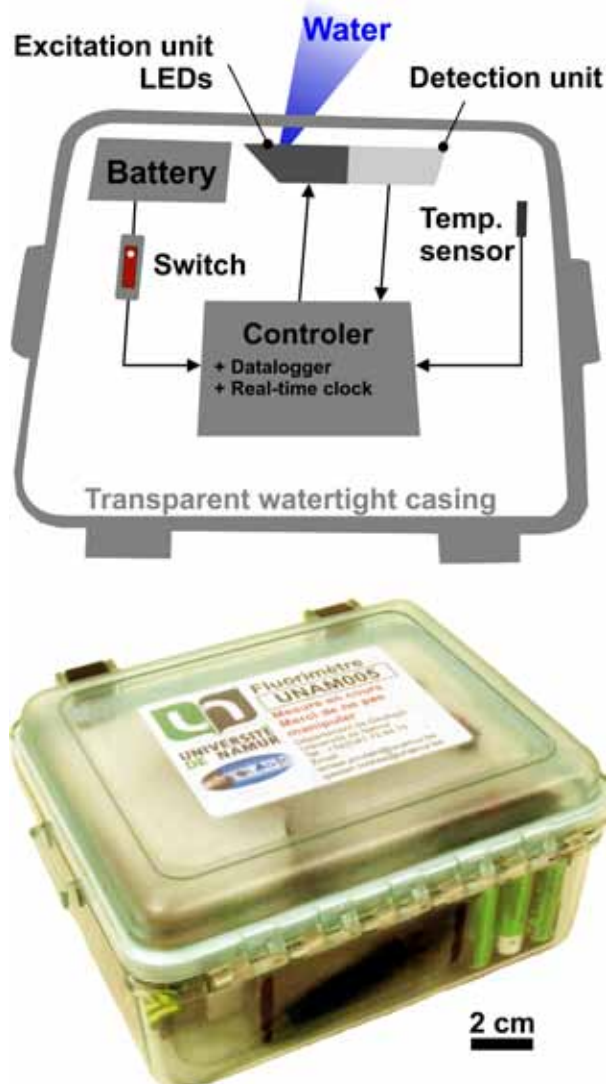


Figure 1. Schematic view and photograph of the Fluo-Green field fluorometer.

environments were tested, mainly in karst: underground rivers, springs, pools, and percolations. Two comparative traces are presented here: (1) the monitoring of a karst spring with Fluo-Green and automatic groundwater sampling, (2) the monitoring of a cave river with Fluo-Green and a GGUN filter fluorometer.

Figure 2 shows the location of the two study sites in the south Belgium karst. They are two classical sinkhole to resurgence systems with discharge around 50 liters/second at the sampling points.

The first dye trace was performed in order to compare the monitoring results between 3 Fluo-Green units and automatic groundwater sampling combined with

Properties	Value
Size	10x16x21cm
Weight	2.75 kg
Channels	470 and 625 nm Fluorescein and turbidity
Turbidity range	0.08 – 200 NTU
Time resolution	1 minute – 1 day
Fluorescein resolution	0.06 – 0.09 ppb
Saturation threshold	3000 ppb (theoretical)
Temperature resolution	0.06°C
Maximum depth	–4 meters
Battery lifetime	8000 measurements with 6xAA batteries

Table 1. Fluo-Green characteristics.

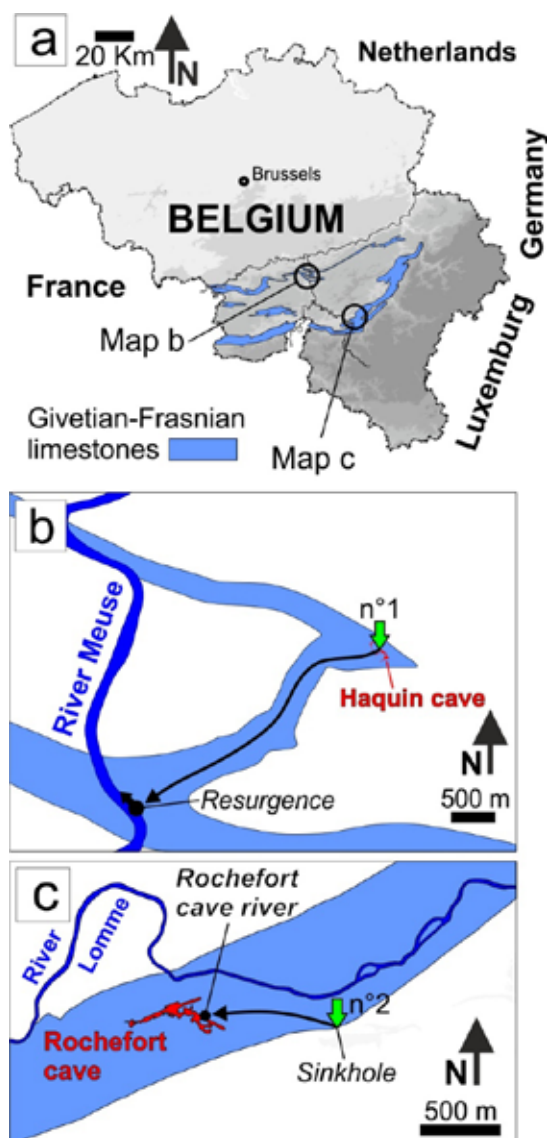


Figure 2. Location of the study sites in south Belgium karst.

laboratory analysis (Figure 3). The lab analysis were made at the University of Namur using an Agilent spectrofluorometer. The Fluo-Green time resolution was 5 minutes and the water sampling resolution was 1 hour during 48 hours. The Figure 3 shows the breakthrough curve of this trace. The Fluo-Green breakthrough curves show the same results, there are also in good fit with spectrofluorometer analysis. The precision (3 synchronous measurement) and accuracy (comparison with spectrofluorometer) are very satisfying. Daylight noise is observable in the Fluo-Green results and can be corrected with differential measurement and additional smoothing of the data. A daylight cover should be implemented for such surface measurements.

The second dye trace shows the comparison between a Fluo-Green fluorometer and a GGUN FL30 fluorometer (Schnegg, 2002). The monitoring was performed in a cave river. Figure 4 shows the results with a strong similitude between the two breakthrough curves. The small difference may be attributed to the calibration procedures. This is a promising result because no additional filters are used on the Fluo-Green, which could be a potential issue for an accurate measurement of fluorescent dye. Dye tracing during stable conditions of turbidity and natural fluorescence may be performed in a reliable way using the Fluo-Green.

Conclusions

The objectives of this tool development were: (1) to provide a compact fluorometer that is useful to carry and

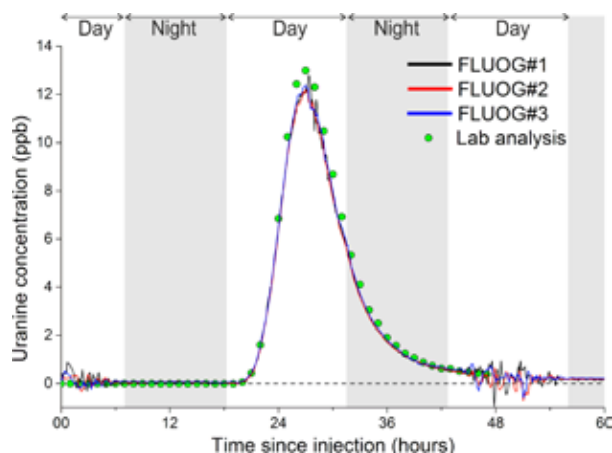


Figure 3. Breakthrough curves comparison between Fluo-Green and spectrofluorometer analysis in karst spring groundwater samples.

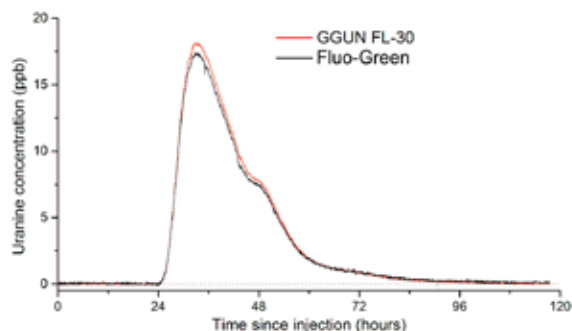


Figure 4. Breakthrough curve comparison between Fluo-Green and a GGUN FL30 filter fluorometer in the Rochefort cave river.

use even in the most challenging places (exploration, remote cave systems...), (2) simplify the material in order to limit the cost, size and user's handling and (3) ensure that the simplification affects in an acceptable way the precision, accuracy and field capabilities of the device. The tool should be adapted to the scientific issue and user's expectations. Thus, the Fluo-Green can be considered as an ultra-portable field fluorometer that is specifically suited for short-terms experiments, accessible for cavers and field researchers. So far, these objectives were reached but there is still a need for complementary experiences about field use, material durability and results in variable environments. Further improvements are expected as field results will bring new experience in the near future.

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LABORATORY TESTING OF THE POTENTIAL FOR THE INFLUENCE OF SUSPENDED SEDIMENTS ON THE ELECTROCHEMICAL REMEDIATION OF KARST GROUNDWATER

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Abstract

Due to the complicated nature of karst aquifers, many groundwater treatment technologies are difficult to implement successfully. A particular challenge arises because sediments are ubiquitous and mobile in karst systems and may either facilitate contaminant transport or act as long-term substrates for storage via sorption. However, electrochemical remediation is a promising technology to be optimized for karst aquifers due to easy manipulation and control of groundwater chemistry as well as low cost, ability for in situ application, and performance under alternative power sources. This study investigates the effects of suspended karst sediments on the electrochemical remediation of groundwater via electro-Fenton (EF) mechanism. The EF mechanism relies on direct electrolysis (i.e., water electrolysis and ferrous iron release) and indirect, electrochemically-induced processes (i.e., Pd catalyzed H_2O_2 production). These processes can be optimized for H_2O_2 generation and support of its activation to hydroxyl radicals – a powerful oxidant capable of degrading and transforming a wide range of contaminants (e.g., chlorinated solvents). In this study, we tested sediments varying in concentrations of Fe, Mn and buffering capacities. When the sediments were

introduced into the EF experiments, there were adverse effects on the H_2O_2 content: at steady state (120 min), Pd catalyzed formation of H_2O_2 decreased by 60%, 57%, and 75% in the presence of suspended sediment collected from three separate karst locations. Presented results imply that sediments' presence influences EF mechanism in electrochemical systems, but given the flexibility of the technology, it can be optimized in terms of electrode materials, current intensities and current regimes to address these challenges.

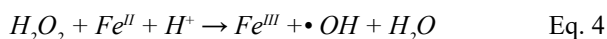
Introduction

Groundwater pollution is one of the greatest and most challenging environmental problems around the world. Toxic pollutants, defined by the EPA as those that cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction) or physical deformations, are introduced into the environment through a variety of mediums, including mining activities, agriculture, manufacturing, vehicle emissions, improper disposal of chemicals, and more. (USEPA). As of 2009, an estimated two billion people drank polluted groundwater or breathed in toxic gases daily (Kuppusamy et al., 2016).

In response to rising pollution levels, groundwater remediation technologies continue to evolve to remove contaminants in a safe, efficient, and cost-effective manner. One emerging technology that appears favorable is that of electrochemical groundwater remediation, due to its versatility, ability to be easily controlled, cost-effectiveness, and ability to be performed in situ. The electrochemical cells can be optimized to treat a wide range of contaminants, including chlorinated compounds such as trichloroethylene (Acar et al., 1993; Rajic et al., 2016; Yuan et al., 2012). Recent field work using electrolytic reactive barriers to degrade chlorinated solvents has found their use effective, as electrode materials (titanium MMO) lifetimes are long-lasting, necessary power supplies are low (6 amps/m²), polarity reversal removes buildup of precipitates, and ultimately 90% of TCE in the field study was degraded without the formation of VC and DCE (Gilbert et al., 2010).

In particular, karst aquifers are susceptible to pollution due to direct recharge from sinkholes and other areas while challenges in implementing conventional remediation methods arise from complexity of terrain and geochemistry (Vesper et al., 2000). While electrochemical remediation implementation in karst systems requires additional investigation due to their complex nature and high flow volumes, electrochemical systems are being considered for karst aquifers, due to ease of manipulation and control of groundwater chemistry. Moreover, this technology has the potential to be modified for ex situ point-of-use treatment in locations where complex or heterogeneous aquifers make in-situ treatment difficult.

One mechanism currently studied for contaminant degradation through the electrochemical systems is oxidation via hydroxyl radicals ($\bullet OH$). Oxygen gas produced at the anode (Eq. 1) of the reactor reacts with hydrogen gas produced at the cathode (Eq. 2), catalyzed by the presence of palladium. H_2O_2 is formed (Eq. 3), which is then catalyzed to form $\bullet OH$ in the presence of ferrous iron at low pH values (Eq. 4), in a process known as the Fenton reaction. The hydroxyl radicals, which are strong oxidants, non-discriminately degrade organic contaminants (Yuan et al., 2012).



Though the electrochemical mechanism can be optimized for maximum degradation efficiency in laboratory settings for given flow rates, electrode materials, currents, and electrolytic solutions, advanced oxidation processes are found to be influenced by naturally occurring substances (Austin et al., 2013). Specifically, Sra et al. (2010) found that, though the reaction rates were low, the presence of natural aquifer materials affected the concentrations of persulfate, a highly oxidizing chemical oxidant, relative to laboratory controls.

In particular, suspended sediments have been shown to be present in natural karst groundwater in turbidities from 0 NTU up to 200 NTU during storm events, and can reach up to 1000 NTU in sinkhole vicinities (Dussart-baptista et al., 2003; Pronk et al., 2006; Pronk et al., 2009). Due to the abundance of suspended sediments in natural karst systems, their presence during electrochemical treatments must be considered if the technology is to be used for the remediation of karst systems.

The purpose of this paper is to determine the effects that suspended sediments play on the creation of oxidizing species in an electrochemical flow-through reactor.

Materials and Methods

Materials

All chemicals used in this study were above analytical grade. $CaSO_4$ was purchased from J T Baker. Na_2SO_4 and H_2SO_4 were purchased from Fisher Scientific. NaOH was purchased from ACROS. Palladium pellets (0.5% wt. Pd on alumina pellets) were purchased from Alfa Aesar. Titanium sulfate ($TiSO_4$) was purchased from GFS Chemicals. Deionized water (18.0 m Ω cm) obtained from a Millipore Milli-Q system was used in all the experiments.

Simulated groundwater was created by mixing 3 mM Na_2SO_4 and 0.5 mM $CaSO_4$ in deionized water. Carbonates and bicarbonates were excluded from this study to decouple their effects on the electrochemical processes from the effects of suspended sediment, although H_2O_2 formation and the Fenton reaction are also expected to be affected by the high buffering capacity of karst groundwater.

Three sediment samples were collected from karst deposits in West Virginia. The samples, denoted as MC, DLC, and CTS, were sifted through 1.18 mm mesh before introducing into the reactor. Suspended sediment mixtures were mixed for two days before use; this is the amount of time necessary to reach chemical equilibrium.

Electrochemical Setup

A vertical acrylic column (Figure 1) was used as plug flow electrochemical reactor. Three titanium/ mixed metal oxide (Ti/MMO) electrodes were assembled in a sequence of anode, cathode 1, and cathode 2, from the bottom to the top of the reactor. Directly on the top of cathode 1 was one layer of glass beads, to prevent palladium/electrode direct reactions, on top of which was placed 10 g of palladium pellets ($\text{Pd}/\text{Al}_2\text{O}_3$). A constant current of 90 mA was supplied to the electrodes by DC source. Current was split between cathode 1 and cathode 2 at a corresponding ratio of 2:1 to optimize H_2O_2 production, based on prior experimental tests (data not yet published).

A constant flow rate of 5 mL/min was maintained by a peristaltic pump during 2 hours of experiment, when steady state was reached. The simulated groundwater with or without 2 g/L of suspended sediment (roughly between 100 and 1000 NTU, depending on the sediment sampling site) was supplied to the reactor. The samples

were taken from the defined sampling ports and analyzed for H_2O_2 content and pH. Experiments were conducted in duplicates.

Experimental Methods

H_2O_2 concentration was measured spectrophotometrically according to the method described by Eisenberg (1943). Samples containing suspended sediment were filtered through 0.22 μm Milipore filters prior to analysis. Excluding the removal of suspended sediment particles from solution, filtering revealed to have no additional effect on the H_2O_2 measurements (such as lowering H_2O_2 measurements relative to non-filtered samples).

Titration was performed by raising the pH of 100 mL of 2 g/L of suspended sediment samples to 10 by the addition of <1 mL 0.1 M NaOH. The pH was brought to 3 using 0.01 M H_2SO_4 .

Specific conductance (SC) and pH were measured on slurries shaken at 100 rpm for 1 hour. Following the methods of Kalra (1995) and Hanlon (2015), 1:1 sediment-water ratio was used for pH and a 1:2 ratio for SC; replicates of six samples were measured.

Instruments

H_2O_2 concentration was measured using a Shimadzu UV-1800 spectrophotometer. The pH of the solution during electrochemical experiments was measured using a portable Orion 3-Star pH meter. SC and pH of intrinsic sediment samples were measured using calibrated Hanna Instruments laboratory electrodes. Metal concentration was determined through inductively coupled plasma mass spectrometry (ICP-MS, Bruker Aurora M90) Turbidity was measured using a HACH 2100N turbidity-meter.

Results and Discussion

Sediment Chemistry

Prior to running the column experiments, sediment samples were examined for all relevant intrinsic characteristics. Specific conductance was determined to be an average of 44.78, 69.63, and 86.12 $\mu\text{S}/\text{cm}$ for MC, DLC, and CTS, respectively. The pH was determined to be an average of 7.70, 7.74, and 6.77 for MC, DLC, and CTS, respectively. Both SC and pH data are depicted in Figure 2.

The suspended sediment samples were additionally tested for turbidity and metal concentrations (Mn and Fe) using 2 g/L of the sample. The turbidity measurements

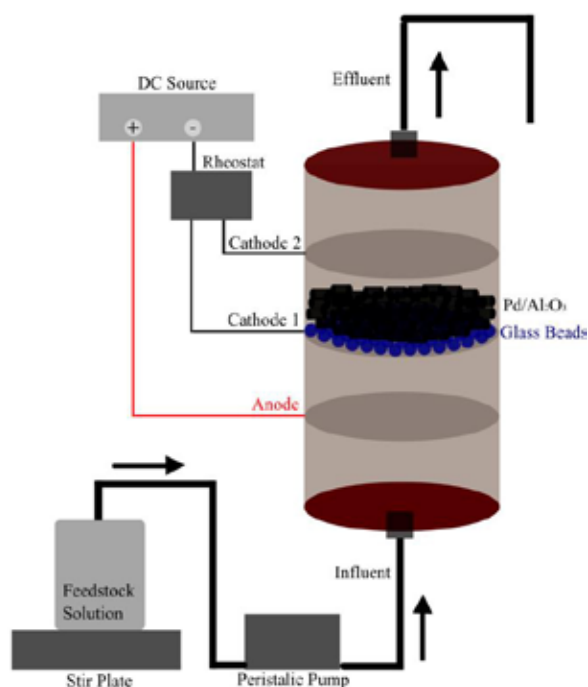


Figure 1. Electrochemical column setup.

indicated that CTS sample contains the largest number of smaller size fractions (Table 1). This is consistent to grain size analyses, not included in this study. CTS also contains the largest concentration of dissolved manganese, while DLC contains the largest concentration of dissolved iron. Both metals could play a role in the conversion of H_2O_2 in the reactor to hydroxyl radicals (Oturán et al., 2010).

As shown in Figure 3, all sediment types followed similar titration trends, although CTS was slightly dissimilar to the other two sediment types due to its increased resistance to pH changes throughout the entire titration. This increased buffering capacity could lead to greater pH resistances in the plug flow reactor, as is discussed in the following section.

Plug-Flow Experiments

The results of the plug flow H_2O_2 tests are displayed in Figure 4. The results show that the suspended sediments have a negative effect on the amount of H_2O_2 in the reactor during the experiments (Figure 4). At steady state (120 minutes), the H_2O_2 concentrations in solutions containing 2 g/L of MC, DLC, and CTS were 60%, 57%, and 75% lower than the control tests, respectively.

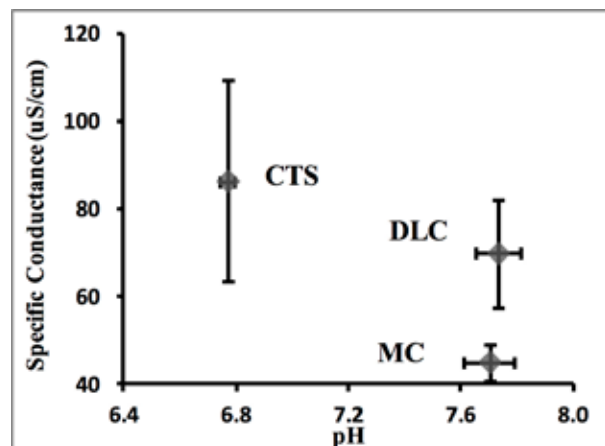


Figure 2. Specific conductance and pH of sediment samples MC, DLC, and CTS.

Sediment site	Mn (ppb)	Fe (ppb)	Turbidity (NTU)
MC	4.1	31.8	140
DLC	2.35	37.5	52
CTS	47.8	32.5	1254

Table 1. Leached Mn and Fe, and Turbidity of 2 g/L of suspended sediments from MC, DLC, and CTS sampling sites

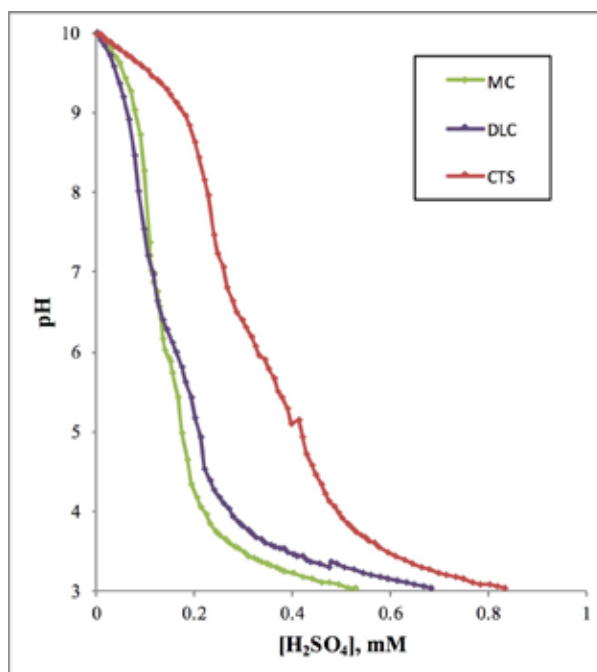


Figure 3. Titrations of CTS, DLC, and MC sediment samples from pH 10 to pH 3.

The pH of the solution above the anode, cathode 1, and cathode 2, is displayed in Figure 5. Though the pH of the solution is more variable in the vicinity above cathode 1 for all sediment types, it appears that the buffering capacities of the differing sediment types do not affect their respective pH values in the cathode or the variability of the pH values.

Discussion

Suspended sediment in high concentrations has a negative impact on H_2O_2 formed during the electrochemical process used to oxidize contaminants, and can lower the production up to 75% relative to a control.

Possible sources of suspended sediment interference in H_2O_2 production include: (1) covering of the palladium and electrodes with fine particles of sediment, impeding H_2O_2 formation, (2) the catalyzed breakdown of H_2O_2 into water due to the presence of suspended sediments, and (3) increasing the production of hydroxyl radicals from H_2O_2 , catalyzed by manganese and iron from the sediments.

Based on the preliminary tests (not included in this paper) suspended sediments accumulate on the electrodes during the course of the experiments but the coverage of the anode and cathode negligibly change H_2O_2 content.

The pH of the solution in the column ranged between ~2.5 above the anode to ~10.5 above cathode 2. Maintaining the pH zones within the reactor is of great importance for efficient electro-Fenton reaction (optimum pH is 3). While the sediment samples displayed differing buffering capacities in relevant pH values, the spatial variability

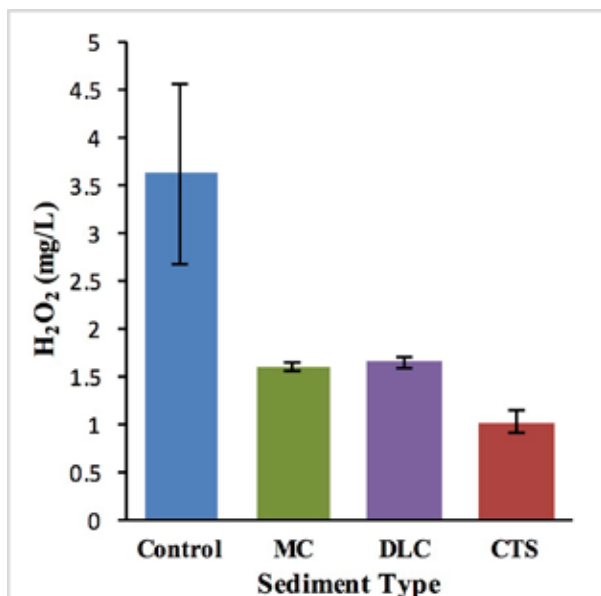


Figure 4. Concentration of H₂O₂ at the steady state flow rate condition measured after 120 minutes using 2 g/L of suspended sediment. Error bars depict one standard deviation from average values.

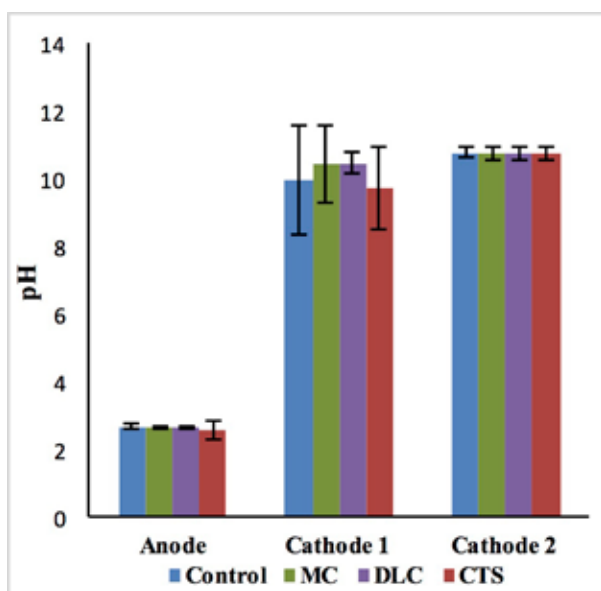


Figure 5. Column experiment pH values above the anode, cathode 1, and cathode 2. Error bars depict one standard deviation from average values.

of pH values throughout the column in the presence of different sediment types did not differ significantly from the control (maximum of ± 1.2 pH units in cathode 1 vicinity). Therefore, the influence of innate buffering capacities of sediments appears to negligibly affect the pH profile of solution in the electrochemical column.

An additional influence of pH relates to the breakdown of H₂O₂ in the presence of suspended sediment, where at pH 10, H₂O₂ decreases up to 35%, while at pH 4 changes are negligible. These data (not shown here) are part of an ongoing study on the effects of sediments on batch experiments, and may be a factor in the lower concentrations of hydrogen peroxide measured in the column reactor in the presence of sediments.

Future work will include investigation into concentrations of redox species (Mn and Fe) catalyzing H₂O₂ degradation into hydroxyl radicals. Though the concentrations of redox species from the suspended sediments samples were low (Table 1), further tests including the direct measurement hydroxyl radicals will confirm if this metal presence due to the presence of suspended sediments contributes to the production of these highly oxidizing species.

Ongoing and future work focuses more thoroughly on the mechanisms affected by the suspended sediments in order to identify weak spots and optimize the electrochemical oxidation/reduction of contaminants in the presence of large amounts of suspended sediments. Future work will include breakdown of contaminants such as trichloroethylene and pesticides in the presence of suspended sediments to determine if the presence of sediments affects contaminant degradation.

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THE WATER CHEMICAL CHARACTERISTICS OF QINGLONGDONG KARST SPRING, KUNMING CHINA

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Abstract

Karst water plays a very important role in providing a municipal water supply in Kunming City, Yunnan Province, China. It contributes approximately 50% of the drinking water for the city. Given the rapid growth in urbanization and of the economy of Kunming City in the last decades, most karst springs have been suffering from human impact, in both quality and quantity. Qinglongdong Spring (QLDS) is located in Dabanqiao village, Northwestern Kunming, 23 km away from Kunming downtown and is an important component of the water supply system of Kunming City. It was previously abandoned in 2003 and 2004 due to high levels of organic contamination.

In order to better understand factors impacting the spring water quality and quantity, a Greenspan CTDP300 multi-parameter data logger (water level, pH, EC, and T), and a rain gauge were installed. Water samples were manually collected and analyzed between May and August 2003 to 2009. The test results revealed that the Qinglongdong Spring study area not only has a well-developed groundwater drainage system, but also the vadose zone is very thin. Given this hydrogeological situation, QLDS has a rapid response to rainfall events, and therefore, the pollutants are transported inside the aquifer rapidly as well. Manual sampling indicates an increasing trend of nitrate content in the spring from 2006 to 2009. It is possible that this area may be influenced by sewage, which is being disposed of illegally, but this would need further investigation.

Introduction

Kunming is the capital city of Yunnan Province, China, with a population of over 6 million. Geographically, it is located within the Yangtze River and Pearl River watershed. Dianchi Lake is located downstream of

Kunming city, and is one of the largest surface water bodies in Yunnan province. It once was one of the main water sources for municipal water supply. Unfortunately, it has been heavily polluted since the late 1980s, which exacerbated the water shortage of Kunming. Kunming is located within a karst faulted basin, which is a unique landform. Hundreds of karst springs exist in this basin. These karst springs are now the other main water sources for municipal purposes for the city and most are used by the municipal water supply systems. Karst water contributes around 50% of the drinking water in Kunming.

Karst aquifers are fragile and are very sensitive to human activities and environmental change (Ravbar, 2007). The influence of industry and agriculture on karst aquifers is a global problem, which has attracted worldwide attention (Drew et al., 1999). With rapid urbanization and a growing economy in the last decades, many human activities are straining the karst groundwater resources of Kunming City. The groundwater has been overexploited because of the increasing demand for water. This large-scale land use change in karst areas inevitably results in negatively affecting the quality and quantity of the groundwater. Hundreds of springs in the Kunming faulted karst basin have dried out and produced less water. Some important water source springs have been contaminated, including Haiyuansi Spring and Kunming Heilongtan Springs. The latter has been abandoned as a drinking water source.

Nevertheless, there are few studies that have been done to investigate those springs. In 2007, construction on Kunming City's new international airport was started. This site is adjacent to the outlet of Qinglongdong Spring (QLDS), which is an important drinking water source spring. Most of the recharge area of the spring

was occupied by the new airport (Figure 1). In order to understand the impact of the new airport construction on the spring water, with respect to quality and quantity, a comprehensive research was carried out in 2007. This paper presents some of the results of this study.

Study Area and Methods

The study area is located in the northeastern portion of Kunming, about 20 km from the Kunming downtown area. The climate in this area is a latitude plateau monsoon climate, with mean annual air temperature of 14.5°C and the mean annual precipitation of 1035 mm. There are two seasons in this region, the rainy season and the dry season. The rainy season occurs from May to October. The rainfall during the rainy season contributes 90% of the annual precipitation. The following dry season is from November to April of the next year. This pattern of precipitation has a very substantial impact on the behavior of groundwater.

The recharge area of these springs is dominated by Paleozoic carbonate rocks of Cambrian to Permian age (Figure 1). Lithologically, the Lower Permian carbonate is composed mainly of limestone, dolomitic limestone and dolomite, and the percentage of dolomite increases from Carboniferous to Devonian. There are some thin inter-layers of mudstone or sandstone within the Devonian and Cambrian carbonate formations. Karst features can be seen on the Lower Permian and Carboniferous carbonate rocks, where there are many dolines, depressions and sinkholes. The poorly permeable Cambrian, Carboniferous, and Permian clastic layers between the carbonate sequences constitute the hydrogeological barriers. Quaternary alluvial

sediments are deposited along the surface water courses. These used to be farmlands planting orchards, vegetable or corn fields, or paddy fields planting rice before the construction of the new airport.

Qinglongdong Spring is located at the contact zone between the karst aquifer and the alluvial sediment. A sub-vertical fault cuts through from the northwest to the southeast. 100 meters away from the fault to the northwest, there is another spring named Huanglongdong Spring, which is also used as a municipal water supply. Between these two springs, there is a thin belt of impermeable Permian clastic sediments extending in a northerly direction. This impermeable belt acts as a hydrological barrier separating the catchments of the two springs. There are several sinking streams distributes in the western part of study area. However, the direction of their underground flow has not been reliably proven yet. There is a sinkhole, named Qiaotou Sinkhole, at about 1 km north of the springs.

The annually mean discharge of QLDS is 473 liters per second (l/s). The minimal discharge is about 5 l/s and the maximum can be up to 3 cubic meters per second (m³/s) or more.

The QLDS had been utilized as a water source for years. Water is mainly pumped by the Baoxianghe water plant, and partly pumped by neighboring villages and factories for the purposes of drinking and industrial use. Along with the rapid urbanization, the nearby town, named Dabanqiao, has become a suburb of Kunming city. In the 1980s, and especially after the 1990s, some factories and other enterprises such as a cement factory, and an oil depot were built in the karst area, as well as highways extending in all directions (e.g., a beltway, new airport highway), the railway network, and countless quarries. Several farms used for food crops have shifted to vegetable cultivation, which increased the use of fertilizers and pesticides. As a consequence, QLDS once had been abandoned due to the pollution of aromatic hydrocarbons substances during 2003 and 2004. However, it has been used again since 2005, because of limited water supplies for municipal supply.

A Greenspan CDTP300 data logger with probes for the continuous measurement of water level, temperature (T), electrical conductivity (EC) and pH at 15 min intervals was installed at the QLDS in February 2007 and data

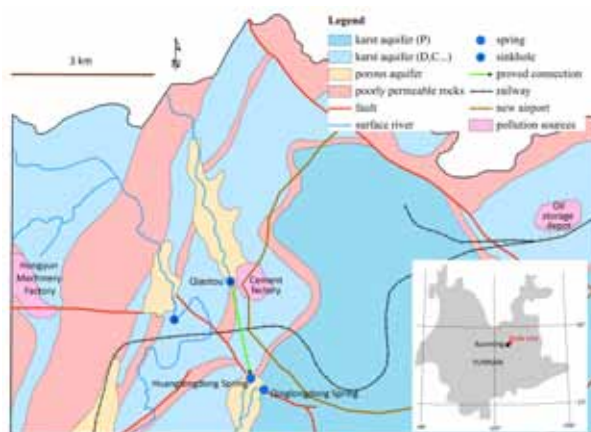


Figure 1. Hydrogeological map of the study area.

was collected until September 2007. A rain gauge was installed on the roof of the pumping station building, which is 50 m away from the spring. The spring discharge was measured with an OTT C20 Current Meter in July 2008 and May 2009. For other sampling times, the discharge was estimated empirically.

The spring water was sampled between 2006 and 2009 in the period from May to August for physical and chemical analyses. T and EC were measured in situ with WTW MultiLine P4 in 2006 and 2009, and WTW 330i conductivity meter in 2007 and 2008. The contents of nitrates, o-phosphates, and ammonium were analyzed by using the corresponding Visicolor-ECO colorimetric tests field laboratories. Total hardness (Ca+Mg) and calcium content (Ca) were determined using the standard titrimetric method (Greenberg, 1992).

Results and Discussion

The monitoring results of Greenspan CDTP300 data logger are presented in Figure 2. The small serrate fluctuation of the spring water level was caused by water pumping from Dabanqiao horticultural farm. They pumped water from a karst window, 20 m upstream of our monitoring site.

The responses of water level, temperature, EC and pH of QLDS to rainfall event were different. The general trend is that the temperature, EC and pH of the springs will rise briefly and then drop in half an hour after heavy rain. The response of water level to precipitation is special. The water level started to rise in half an hour after rainfall, but then fell soon thereafter. At the beginning of rainy season, the soil water deficit is serious after a long dry period. Therefore, following the first heavy rainfall has no obvious effect on the spring water flow or has longer lag time. The rapid response of QLDS to precipitation shows that its vadose zone has limited capacity as a water buffer. Alternatively, there exists a well-developed groundwater drainage system. A dye tracing in this area showed that a fast groundwater flow system exists in study area (Knez et al., 2012). Of course, this may relate to the thin vadose zone of QLDS, with average thickness of 30–40 meters. However, for some rainfall events, the event of 22 mm precipitation on 29 April 2007 for instance, the response of the spring water level showed a delay of one day.

For the whole time period of data logger monitoring, water level of the spring is more sensitive to rainfall, especially for heavy rainfall events. It should be noted

that it is difficult to explain two broad peaks formed in the time from 29 April to 28 May and from 15 August to 15 September. Each of them lasted for around 30 days. We proposed that another water source had joined in. The trend of temperature was relatively stable, only departing from this trend after heavy rainfall events. In contrast, the EC value was continuously increasing until the heaviest rainfall event occurred. For pH, we observed a slowly increasing trend during the period of no rain, and slowly decreasing after the first heavy rainfall event.

Some anomalous hydrologic events can be observed in Figure 2. At the first glance, it seems like anomalous data that might be caused by instrument error, but after examining more closely on a scale of days, it can be observed that each event which appears in Figure 2 is represented by a group of data, and the parameters (water level, T, EC, and pH) changed synchronously for between 5 and 10 hours (Figure 3). Most of the events began in the early morning before sun rise. One of events might be caused by small quantity of sewage disposal near the outlet of the spring. This pulse may have arisen

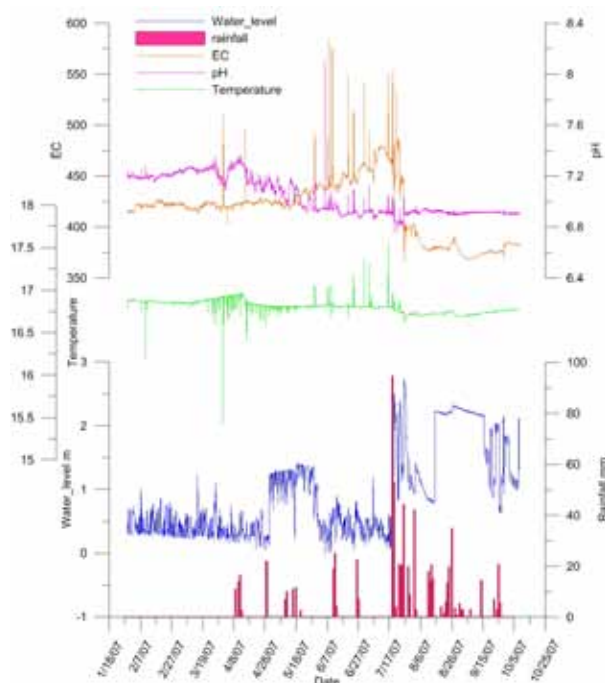


Figure 2. Variations of physical chemistry (rainfall, T, EC, pH and water level) of Qinglongdong Spring. The responses of water level, temperature, EC and pH to rainfall event were different on long term trend (seasonal), but on short-term (few hours) were synchronously and rapidly.

from the wastewater discharge. But this conclusion needs be verified by further tracer testing.

The results of chemical parameters are shown in Figure 4. The content of nitrates increased from 10 mg/l (May 2007), to 15 mg/l (July 2008), and 22 mg/l (June 2009) to 70 mg/l (August 2009).

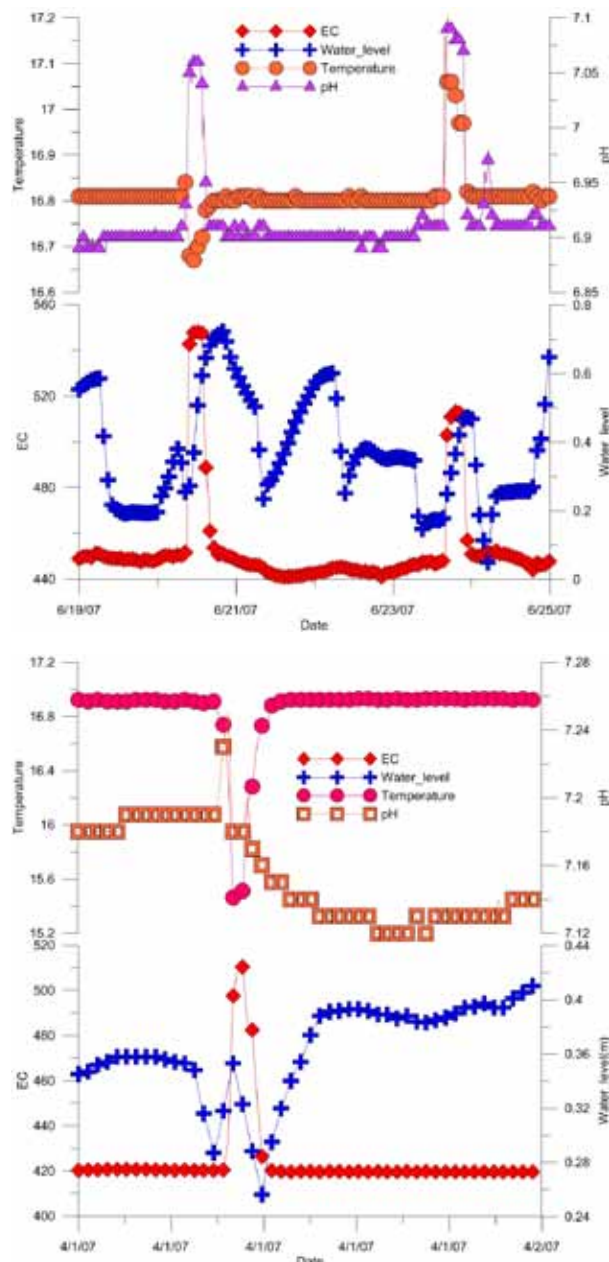


Figure 3. Samples of outlier data: upper panel, during the first heavy rain event on April, 2007; lower panel, during 20 to 24 of June, 2007. Water level, T, EC and pH synchronously respond to rain events.

This area had been included in a long-term monitoring project, which was carried out by the geological environmental agency, during the period from 1988 to 2000, and 2005. During each study year, two samples were collected, in the rainy season and in the dry season respectively. A total of 52 parameters were analyzed for each sample, including macro elements, trace elements, and organic and inorganic pollutants. Based on this 14 years long dataset, the agency concluded that different pollutants have different performance at different time and under different hydrological conditions. The interval of 1990 to 1995 is the key time period for the onset of industrial pollution, because dozens of factories moved to this area during this time period. The year of 2000 is the time node for agricultural related parameters change because cultivated land in the upstream agricultural area had been transformed from food crops to vegetable fields from then on, which result in greater use of pesticides and fertilizer.

Another important pollution source of QLDS is an oil storage depot named Hunlongtan, in the northeastern part of the study area. It was built in 1995 and began operations in 1996. The oil storage capacity was about 34000 m³, stored in dozens of tanks of sizes 60–5000 m³. Every three to four years the tanks needed to be washed, or when the type of oil change for a tank. In general, oil storage varieties and quantities are adjusted according to the market each year. Some oil storage tanks needed be washed every year. There was no oil and water separation pool built until 2000, and the waste water drained directly into the karst depressions. Later the oil and water separation pool was actually built at the bottom of a karst doline. Unfortunately, there is a visible

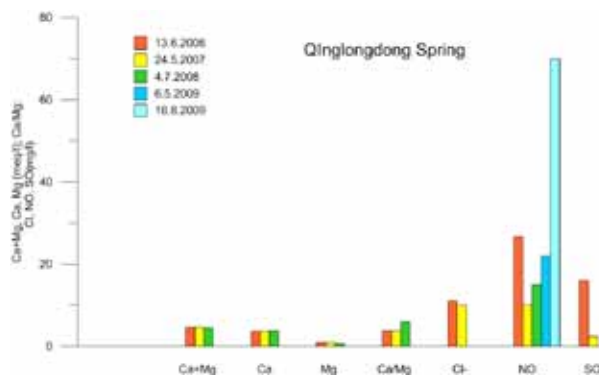


Figure 4. Chemical parameters of samples: Ca+Mg (total hardness), Ca (calcium), Mg (magnesium), Cl (chlorides), NO (nitrates), SO (sulfates) (modification after Knez et al., 2012).

dissolution fissure which is 20 to 30 cm in width. During a continuous heavy rain, the oil might overflow from the top of the pool, and then rapidly recharged into the karstic groundwater, where it could be held in storage in the karst aquifer for a long period of time (Kogovsek, 2004). Most of the time the samples from the spring showed visible oil spray. Therefore, oil leakage pollution is still of great concern for Qinglongtan Spring, which must be dealt with.

Conclusions

After nearly one year's continuous measurement of water level, temperature (T), electrical conductivity (EC), and pH of Qinglongdong Spring showed that the study area has a well developed groundwater drainage system and/or the vadose zone is very thin. Under such a hydrogeological situation, the response of QLDS to rainfall events is fast, and the pollutant transport into the aquifer is rapid. Meanwhile, the analysis of specific time periods in the data revealed that there might exist some additional pollution sources and pathways, but further work is required to understand these occurrences.

The investigation of nitrate content from 2006 to 2009 showed that the concentration of nitrate in the spring increased from 2007 to 2009, which might be influenced by a new airport construction project over the source area to the spring.

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REVIEW OF MONITORING AND EARLY WARNING TECHNOLOGIES FOR COVER-COLLAPSE SINKHOLES

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Abstract

Sinkhole collapse has become a major geohazard in many karst areas. The development of monitoring and early warning technologies is essential to investigate mechanisms of sinkhole formation. This paper reviews latest research on monitoring and early warning technologies surrounding cover-collapse sinkholes. Monitoring the hydrodynamic conditions in areas susceptible of sinkhole collapse has proven to be useful to help understand the relationship of rainfall, surface water, and groundwater in karst areas. Monitoring hydrodynamic conditions of karst groundwater includes rainfall monitoring, groundwater level monitoring, air pressure monitoring, and groundwater quality monitoring. Observations from the monitoring system and known sinkhole collapses could be used to simulate and predict hydrogeologic, geologic, and atmospheric conditions favorable to sinkhole formation. Monitoring technologies of deformation for the overburden soil include Ground Penetrating Radar (GPR), Time Domain Reflectometry (TDR), and Brillouin Optical Time Domain Reflectometer (BOTDR). GPR is more suitable

to investigate relatively flat terrain with dry soil cover. TDR and BOTDR were more suitable for linearly distributed monitoring sites because of the cohesion between soil mass and optical fiber.

Introduction

Sinkhole collapse is a dynamic phenomenon, which usually takes place in karst areas (Kang, 1984). The total karst area in China reaches 3,650,000 km², which occupies more than one-third of the territorial area of China. In the past few decades, more than 3315 sinkhole collapse events were recorded (Kang, 1984). Most of these collapse events occurred in southwestern, central, and southern China. Sinkhole collapse became a major geohazard in many karst areas in China. The sinkhole hazard not only destroyed land and infrastructure but also impacted socio-economic development and human lives and properties (Papadopoulou-Vrynioti, 2013). Due to subtle development and abrupt collapse, it is very difficult to predict and prevent sinkhole collapses. Therefore, monitoring and early warning technologies are crucial to prevent sinkhole collapse and to mitigate damage caused by sinkhole hazard.

Characteristics of Sinkhole

Sinkhole collapse is a dynamic phenomenon, which is caused by the deformation and fracture of rocks and sediments. Influential factors on the deformation and fracture could be natural or human induced (Lei, 1998).

According to the lithological characteristics of collapsed substances, sinkhole collapses could be classified into three types: cavern collapse, soil cave collapse, and non-carbonate rock roof above carbonate bedrock collapse (Williams, 1983). According to Kang (1988), 96.7% of sinkhole collapses were soil cave collapse in China (overburden material collapse) and mostly occurred in areas where the thickness of soil layer is less than 30 m. The process of soil cave collapse involved four steps: (1) groundwater took away soil particles; (2) small soil void formed and enlarged; (3) soil cave expanded near ground surface; (4) the roof of soil cave collapsed. Therefore, three conditions including flowing groundwater, soluble bedrock, and non-cohesive soil exist in most cases of cover-collapse sinkholes. However, there was no warning before most sinkholes collapses. Even though many methods have been carried out to investigate sinkholes such as field surveys, geomorphological mapping, and borehole logging (Cooper, 2008; Gutierrez and Cooper, 2002). Spatial and temporal prediction of sinkhole was immature with little success. More practical technology and tools are needed to predict sinkhole collapses and to minimize casualties and property losses.

Influential Factors on Cover-collapse Sinkhole

Sinkhole development is mainly influenced by hydrodynamic conditions, characteristics of overburden materials, and the degree of karstification of underlying bedrocks (Wu, 1999). Sinkholes are more likely triggered by multiple factors. However, single factor could be predominant in certain sinkhole collapse event.

In general, groundwater plays a significant role in the process of forming soil voids and sinkholes. Investigations of hydrodynamic conditions in recent collapse events and physical experiments reveal that sinkholes mainly occurred in the process of groundwater level decline, groundwater level rise, and groundwater fluctuations around the boundary of soil and bedrock (Jiang, 2016). Wang (2000) stated that frequent fluctuations of groundwater level not only change the state and strength of overlying soil mass but also lead to alternating normal

and negative pressures in the subjacent caves and soil voids, which eventually result in collapses.

Characteristics of overlying soil include composition, compactness, and permeability. Soil voids could form in sandy and gravelly soil because of lower cohesive force and tend to collapse after heavy rainfall (Zhu et al., 2000; Liu et al., 2000). The thicker the overburden sediment, the longer amount of time a cavity can grow, and the larger a cavity can become.

The degree of karstification of underlying bedrock is determined by the quantity and scale of cavities and fractures. Soil particles can move into cavities and fractures through the process of soil piping. If the underlying bedrock is highly karstified with large cavities and numerous fractures, the overburden soil and sediments could be easily eroded and form substantial voids and eventually trigger cover-collapse sinkholes.

Monitoring Hydrodynamic Conditions of Karst Groundwater

Monitoring hydrodynamic conditions of karst groundwater includes rainfall monitoring, groundwater level monitoring, air pressure monitoring, and groundwater quality monitoring.

Rainfall Monitoring

The recharge of rainfall and surface water would affect groundwater conditions. The fluctuation of groundwater could affect the condition and strength of overburden materials. Meanwhile, the air inside karst caves could be compressed or expanded when groundwater level fluctuated through cave conduits.

Therefore, rainfall monitoring is necessary. Rain gauge could be used to collect rain water and measure rainfall intensity. A typical rain gauge consists of event data logger and a tipping-bucket device. The rain gauge used for case studies in this paper collected rain water and recorded time, duration, rainfall amount, and temperature data. Data recording frequency was set every 10 minutes and the battery capacity could sustain at least 4 months.

Groundwater Level and Air Pressure Monitoring

The karst groundwater-monitoring network was established to monitor changes of groundwater level and temperature. Each monitoring site consisted of water pressure probe, cable, data logger, storage battery, timer,

and data transmission module (Figure 1). Data logger was used to receive and store data of water pressure through the probe and transmitted data to terminal computer via data transmission module. Storage battery supplied electric power to data logger and data transmission module and connected to a solar panel for recharge. The installation of monitoring equipment involves the following steps: (1) drill a borehole and insert a perforated PVC pipe; (2) the depth of borehole and groundwater level are estimated so a suitable water pressure probe would be selected; (3) probe should be enclosed in a gauze bag filled up with sand; (4) the borehole near the ground surface would be sealed.

Case Study 1 – Groundwater Monitoring in Dachengqiao, Ningxiang, China

A groundwater monitoring network was established to monitor changes of groundwater in May 2013 in Dachengqiao, Ningxiang, Hunan Province, China (Figure 2). The goal of this case study is to examine the development of sinkhole collapses in relation to changes of groundwater level. The ultimate goals are to better understand the formation mechanism of sinkhole collapse and to forecast sinkhole collapse events in the future. Figure 2 illustrates groundwater level changes at site yr4-1. The daily precipitation on May 18, 2013 was 30.4 mm. Groundwater level abruptly increased about 2 m and then fell back very rapidly after the rainfall even though the net change of groundwater level increased, which may indicate the overburden soil was disturbed and soil void collapse caused the anomaly of the level of groundwater. At 9:00 am on May 24, 2013, water table suddenly increased 3 m (Figure 3) and a 1 m-diameter sinkhole formed on the east side of the monitoring station (Figure 4).

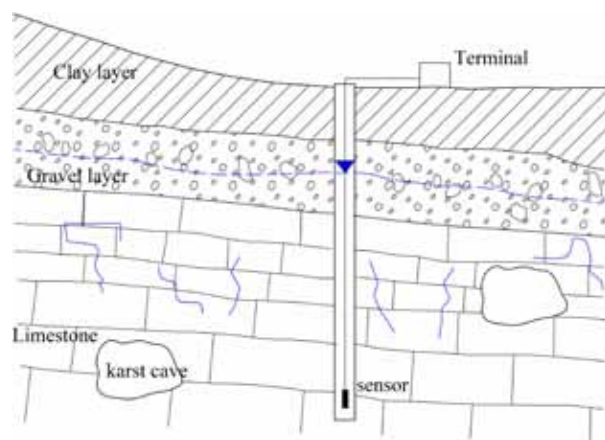


Figure 1. Schematic diagram of groundwater level monitoring.

Groundwater Quality Monitoring

Groundwater quality parameters include temperature, pH, conductivity, and concentrations of cations and anions. A portable water quality meter was used to measure temperature, pH and conductivity of groundwater in the field. Additional water samples were collected using appropriate sampling bottles by following correct sampling protocols. These water samples were analyzed for cations and anions in the research lab at the Institute of Karst Geology.

Monitoring the hydrodynamic conditions would help understand the relationship of rainfall, surface water, and groundwater in karst areas. Observations from the system and known sinkhole collapses could be used to simulate and predict hydrogeologic, geologic, and atmospheric conditions favorable to sinkhole formation.

Overburden Material Deformation Monitoring

Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) has been widely used in hydrological and engineering investigations. The



Figure 2. Location of Dachengqiao, Ningxiang, China.

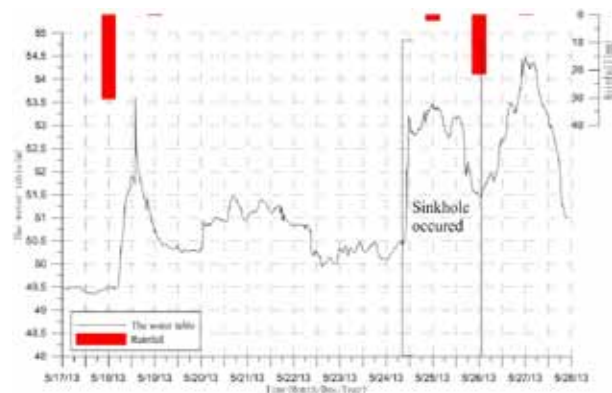


Figure 3. Drastic increase in water level of yr4-1 in Dachengqiao, Ningxiang, China (5/17/2013–5/28/2013).



Figure 4. A small sinkhole collapse (1m diameter) formed on the east side of monitoring site yr 4-11 in Dachengqiao, Ningxiang, China.

MALA radar system consists of control unit, shielded antenna, electrical cable, and measuring wheel. GPR system transmits electromagnetic wave through its antenna. Portions of electromagnetic waves would be reflected to ground surface when electromagnetic wave encountered abnormal medium in the process of spreading underground. The reflected waves were analyzed through terminal machine. GPR was widely used to detect and monitor deformations in rock-soil layer of geohazard area (Zhang et al, 2000; Jiang et al, 2008; Xiong et al, 2014). The detection capability of GPR is limited by hydrogeological conditions and infrastructure. For example, the travel distance of radar is affected by groundwater level, metal object, and high-voltage wire in the study area. In general, GPR is more suitable to investigate relatively flat terrain with dry soil layer.

Case Study 2 – Detecting soil voids along Guilin-Yangshuo Highway, Guangxi, China

GPR was used to locate and characterize karst hazard zones within K9–K23 section of Guilin-Yangshuo highway in Guangxi, China (Figure 5) (Lei et al., 2011). Soil voids along the highway were detected by using a GPR with the 100 MHz frequency (Figure 6). A total of 337 subsurface voids, 1–6 m in diameter, 1–5.5 m deep, and density up to 48 per 100 m, were detected using GPR.

In this work, GPR, multi-electrode electric resistivity, and shallow seismic reflection were used for a preliminary survey. Comparison of the three geophysical methods indicates that GPR can detect subsurface voids in a more effective and timely manner.

Time Domain Reflectometry (TDR)

Time Domain Reflectometry (TDR) was first used for detecting the malfunctioned segment of telecommunication cable and electric transmission line in electric power industry. It was then used to measure water content of soil in the 1980s (Topp, 1985). O'Connor et al. (2001) installed TDR under a highway for real-time monitoring of ground deformation and changes. Chen et al. (2004) investigated TDR properties of coaxial cables under different test conditions and proposed valuable conclusions for practical applications. Jiang et al. (2011) conducted a series of geotechnical and material tests in both laboratory and field settings and proved that coaxial cable could be used to monitor and forecast karst collapse under suitable conditions. The coaxial cable grouted with cement mortar was paved under places where soil voids tend to occur. The coaxial cable with cement would be fractured by the impact of overlying soil at which the soil void underneath the coaxial cable developed to a certain scale (Figure 7). Location of soil void could be determined through the TDR curve image.



Figure 5. Location of Guilin-Yangshuo Highway, Guangxi, China.

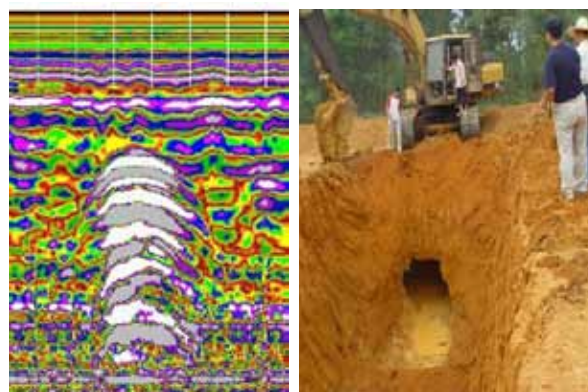


Figure 6. Detecting soil voids along Guilin-Yangshuo Highway, Guangxi, China. Left, hyperbolic anomaly in GPR profile; Right, soil voids after excavation.

5.3 Brillouin Optical Time Domain Reflectometer (BOTDR)

Brillouin Optical Time Domain Reflectometer (BOTDR) is inbuilt the optical fiber in the rock-soil mass, where soil void or sinkhole collapse tend to occur. The deformation or fracture of rock-soil mass could be detected when the status of rock-soil mass changed. The location and development rate of soil void could be calculated to forecast potential karst collapse.

Tkach et al. (1986) came up with BOTDR technology. Horiguchi et al. (1995) measured strain- and temperature-induced changes in Brillouin frequency shift. Bao et al. (2001) conducted a series of experiments both in the laboratory and outdoors and took temperature compensation into account for strain measurement. Their accuracy of strain measurement was improved to 5 m. Jiang et al. (2006) applied BOTDR to measure soil deformation in the process of sinkhole collapse in a large-scale model experiment. The experimental results showed that BOTDR would be a reliable technology to monitor and predict sinkhole collapse or subsidence, especially along linear infrastructure constructions. Guan et al. (2012) found that key factors affecting the application of BOTDR included changes of stress field distribution, void size change during the formation of the void, and the difference of responding sensitivity to the stress field change among different optical fibers.

Case Study 3 – Application of BOTDR to forecast soil void development in Chaoshan village, Tongling, Anhui, China

BOTDR was used to forecast potential soil void development in the drainage area of Chaoshan village, Tongling, Anhui, China (Figure 8). A total of 500 m optical fiber was buried along a 1 m deep and 0.8 m wide trench. Optical fiber was fixed into the bottom of



Figure 7. Schematic diagram of TDR monitoring technology for soil cave detection (Qin et al, 2010).

the trench and then backfilled with soil. Observations in 2016–2017 from BOTDR showed no obvious soil deformation in the drainage area, which indicates normal soil deposition and compaction in the study area (Figure 9). No soil voids and sinkhole collapses occurred from field investigation during the same time in the study area. Results of BOTDR monitoring agree with field investigations.

At present, TDR and BOTDR were more suitable for linear investigation because of the cohesion between soil mass and optical fiber. On the other hand, the practical application of TDR or BOTDR was mainly focused on areas close to the optical fiber.

Conclusions

Due to subtle development and abrupt onset of cover-collapse, it is very difficult to predict and prevent sinkhole collapses. Monitoring hydrodynamic conditions of karst groundwater has proven to be useful in cases of soil void development caused by rapid fluctuations of karst water table. GPR was very effective to detect soil voids in



Figure 8. Location of Chaoshan village, Tongling, Anhui, China.

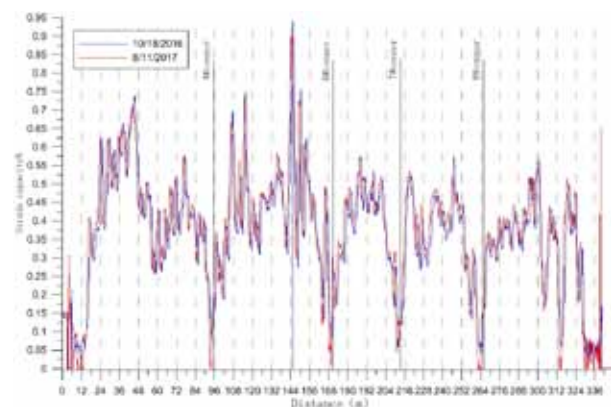


Figure 9. The strain capacity of BOTDR in Chaoshan village, Tongling, Anhui, China (10/18/2016–8/11/2017) indicates normal soil deposition and compaction.

karst areas of relatively flat terrain with dry soil covers. TDR and BOTDR had some successes to monitor soil deformation along linear monitoring network. However, sinkholes are more likely triggered by multiple factors, joint application of more than 2 monitoring technologies would be necessary in many cases (Zeybek et al., 2015). Monitoring and early warning technologies are crucial to prevent sinkhole collapse and to mitigate damage caused by sinkhole hazards.

Acknowledgements

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ELECTRONIC ACCESS TO MINNESOTA SPRINGS, KARST FEATURES & GROUNDWATER TRACING INFORMATION

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Abstract

Minnesota karst related information has been made electronically accessible through three interrelated databases, the Minnesota Karst Feature Database (KFD), the Minnesota Groundwater Tracing Database (MGTD), and the Minnesota Spring Inventory (MSI). Collectively, this information is a significant asset for use in water resource planning and management in the State of Minnesota. The KFD and MGTD focus primarily on the karst regions of southeastern Minnesota while MSI has extensive coverage within the karst regions of Minnesota, but also extends to all other areas of the state. Reporting associated with four decades of collaborative work pertaining to karst is also available via the Dye Trace Reports Collection on the University of Minnesota Library's Digital Conservancy.

Introduction

Minnesota is located in the northern United States (Figure 1). Much of the state was glaciated during the Wisconsin Glacial Period. Precambrian igneous and metamorphic rocks underlie much of the state. In the southeastern portion of the state, Cambrian, Ordovician and Devonian carbonate and siliciclastic bedrock lies unconformably on Precambrian rocks.

Karst feature mapping, groundwater tracing data and related karst hydrogeologic information has been gathered through four decades of joint projects from the University of Minnesota, the Minnesota Geological Survey (MGS), the Minnesota Department of Natural Resources (DNR) and numerous other organizations. Much of that information has been obtained and published in the context of ongoing state-wide county geologic and hydrogeologic mapping projects by the Minnesota

Geological Survey and the Minnesota Department of Natural Resources, respectively (Dahlgleish and Alexander, 1984; Alexander and Maki, 1988, Witthuhn and Alexander, 1995, Alexander et al, 1995; Tipping et al., 2001; Green et al, 2002; Alexander et al 2003). Three databases, the Minnesota Karst Feature Database (KFD), the Minnesota Groundwater Tracing Database (MGTD) and the Minnesota Springs Inventory (MSI), now share a relatable unique identifier field with the Minnesota County Well Index (CWI). Each database, including its contents, uses and benefits is described in detail below.

Minnesota Karst Feature Database

The Minnesota Karst Features Database (KFD) geospatially depicts the locations of sinkholes, stream sinks, dye trace sampling points, and a limited number of agricultural drain tile inlets and outlets (sinkholes and sinking streams shown in Figure 2). Associated relate tables contain additional attributes that can be joined using the unique identifier field (Gao et al, 2005). The bulk of the features found in the KFD are found in areas of southeastern Minnesota that are underlain by Devonian, Ordovician and Cambrian bedrock and have less than 16 meters (50 feet) of unconsolidated material. An additional cluster of features are located in east-central Minnesota in, Pine County, where sinkholes and sinking streams are located in sandstone karst (Shade et. al., 2015). Tipping et al. (2015) have reviewed the history and development of the KFD.

Karst features use county code (numeric) along with a feature code (alphabetic letter) and feature number (numeric) to make a unique identifier for each feature. Sinkholes (dolines) are labeled with D, stream sinks are labeled with B, and dye trace sampling points are labeled with X. For example, the first sinkhole in Fillmore County, the county with the most sinkholes in



Figure 1. Location of Minnesota in USA.

Minnesota, would be labeled 23:D0000001. Attribute tables in Figure 3 are linked to the spatially enabled index table – kfix using this identifier. An ESRI file geodatabase version of the KFD and associated metadata is available at: <ftp://mgsftp2.mnngs.umn.edu/pub4/karst/>. The KFD contained over 16,000 features as of 23 August

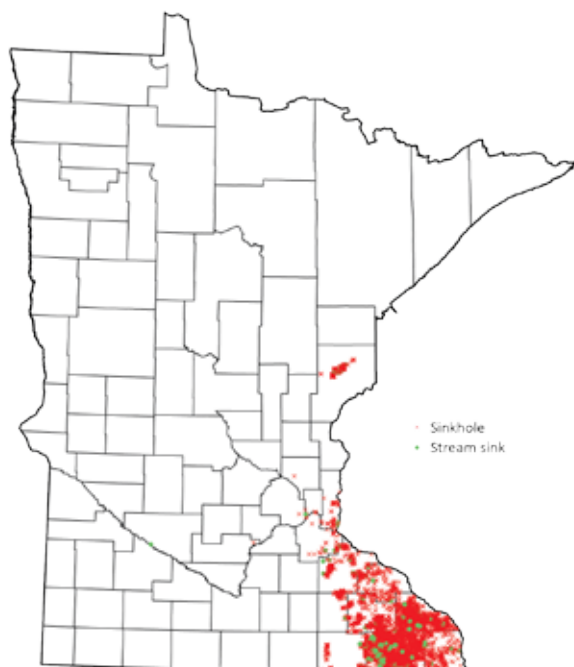


Figure 2. Karst feature distribution. Karst features are concentrated in southeastern Minnesota.

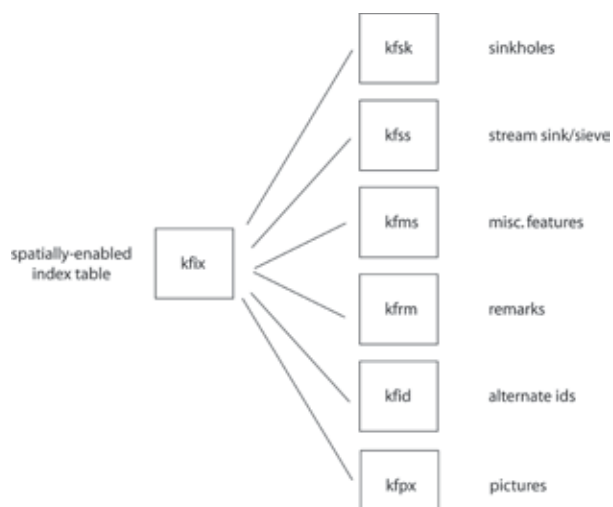


Figure 3. KFD structure – spatially enabled index table and related attribute tables. Index table and attribute tables are linked by a unique identifier for each feature.

2017 and is updated with additions and edits every few weeks.

Minnesota Spring Inventory

MSI is a statewide spring and seep database that evolved from feature code A within KFD (feature code A represented springs). Current fieldwork is primarily mapping new springs on public owned lands, however original KFD springs data included springs on private property. Additional data collected, where feasible, includes spring flow rates, water parameters, biota, and photos. Historic data have been and are being gleaned from files and reports (Brick, 2015). A significant source of information was 1:24,000 United States Geologic Survey topographic maps of southeast Minnesota. Biologists from the Minnesota DNR Section of Fisheries and its predecessors walked along the banks of trout streams and surveyed fish habitat and stream conditions and included springs as one of the data points recorded (Johnson and Ignatius, 2015). Spring locations have additionally been inventoried in southeast Minnesota as part of the dye tracing fieldwork completed for County Geologic Atlases and other projects. Some of the areas covered by the geologic atlas mapping had very detailed spring mapping efforts that consisted of field staff walking along and wading in streams to locate springs. This labor-intensive process was not repeated on all streams due to the time involved.

A Springs Inventory Reporting App was developed to garner local knowledge from citizens to obtain locations and information about springs on private lands. Springs submitted through this application are reviewed by project hydrologists for validity. The app is available at: <https://arcgis.dnr.state.mn.us/gis/CitizenSprings/> The MSI contained 4,162 springs (of which 1,586 were field checked) as of 23 August 2017. The statewide coverage is shown in Figure 4.

Minnesota Groundwater Tracing Database

The Minnesota Department of Natural Resources has been working closely with the University of Minnesota to make available decades worth of groundwater tracing information via the MGTD.

Groundwater tracing, especially using fluorescent dyes, has proven to be an effective method for understanding groundwater flow, travel times and interconnections with surface water. Groundwater tracing involves pouring a semi-conservative tracer into a sinkhole or a sinking stream and observing if and where it emerges after flowing through the karst conduit system, usually

at (multiple) springs or wells. Results have important implications for the protection of trout streams and other ecosystems in Minnesota and elsewhere (Green, 2015). Additionally, understanding subsurface conduit flow in karst terrain is significant to water protection and management efforts associated with spill response, water supply planning, and land use planning.

An expansive list of historic and recent groundwater tracing reports is now available on the DNR Springs, Springsheds and Karst webpage (http://www.dnr.state.mn.us/waters/programs/gw_section/springs/dtr-list.html). The available reports summarize dye trace investigations across the southeastern portion of the state (mostly in Fillmore, Houston, Olmsted, and Winona counties but also sparsely in Dakota, Dodge, Hennepin, Mower, Pine, and Wabasha counties). The reports are permanently stored via the Dye Trace Reports Collection hosted by the University of Minnesota Library on the University Digital Conservancy (UDC; available at: <https://conservancy.umn.edu/handle/11299/184770>) This repository archives groundwater tracing reports, published articles and papers related to karst and groundwater flow, unpublished reports, maps, summaries, journal proceedings, and other related information.

Geospatial data for these traces includes tracer input locations, a comprehensive list of sampling and detection points associated with each trace, important

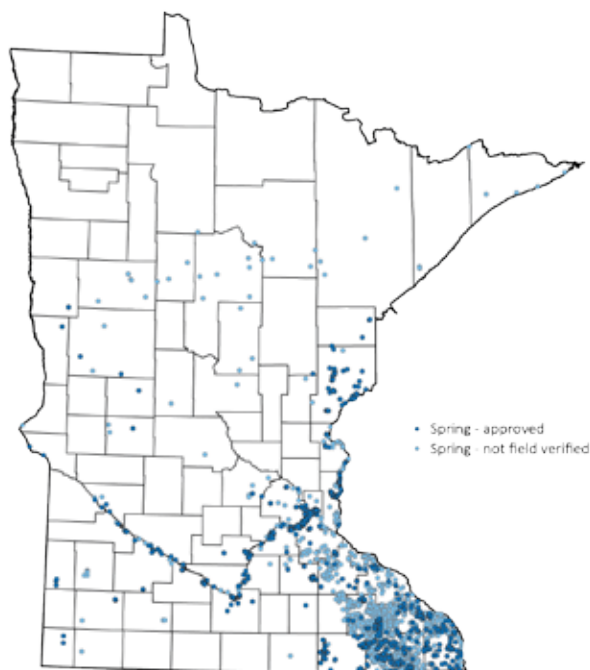


Figure 4. Mapped Minnesota springs.

trace information including links to reports and other documentation, and inferred groundwater flow vectors and springshed delineations developed by groundwater tracing specialists. These data will soon be incorporated into a web map service available for state and public use. Users will be able to query, select and view groundwater tracing data and associated reports synchronously alongside the KFD, CWI, and MSI.

Summary

Groundwater trace results combined with karst feature and spring location data have been used to improve land and water management decisions in southeast Minnesota (Larsen, 2015). Minnesota is one of few states to have this information available on-line in an accessible format. Increasing the availability of karst feature locations, spring inventory information, groundwater tracing data, reports and maps greatly improves access to important information allowing planners, researchers, and the general public to learn more about karst. Increasing the opportunities for this information to be used for environmental decision making will hopefully lead to more protected water quality in sensitive karst regions. These on-line data depositories also ensure that decades of fieldwork results and data analysis will be preserved for future use.

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STUDIES OF THE APPALACHIAN KARST: 1770 – PRESENT

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Abstract

The Appalachian region, extending from New England to Alabama, includes one of the most extensive regions of karst in the United States. It is a complex geologic terrain and has been studied for nearly 250 years. The history of karst study in the region is organized into eight frames of time: (1) Early American Notes and Records, (2) Age of Curiosity, (3) Exploration and Early Tourism, (4) Birth of Modern U.S. Speleology, (5) Landmark Speleogenetic Studies, (6) Organized Caving and Science, (7) Speleological Inflation, and (8) Applied and Environmental Science. Karst science has progressed from merely descriptive accounts to detailed scientific study. The beginnings of cave exploration, cave tourism, and development of organized speleology is rooted in this region. Environmental issues regarding karst in the Appalachians have intensified in recent decades, making the understanding of karst processes and historic perspective much more important.

Introduction

The fold belt of the Appalachian tectonic system includes one of the most extensive and contiguous regions of karst in the United States. It extends for over 2000 km (1240 mi), from the New England states in the northeast to Alabama in the southeast (Davies, 1970, Herak and Stringfield, 1972, Kastning, 1986, Weary and Doctor, 2014, Palmer and Palmer, 2009). Fourteen states have substantial areas of karst lying within this nearly linear zone: Vermont, Massachusetts, Connecticut, New York, New Jersey, Pennsylvania, Maryland, West Virginia, Virginia, Kentucky, North Carolina, Tennessee, Georgia, and Alabama.

This is the third Appalachian Karst Symposium (AKS) and is being held at the U.S. Fish and Wildlife Service National Conservation Training Center, Shepherdstown, West Virginia, 2–6 April 2018. The first symposium was convened at Radford University, Radford, Virginia on 23–26 March 1991. It convened in honor of the 50th anniversary of the National Speleological Society (NSS). All 31 papers and 2 abstracts were published by the NSS in a proceedings volume (Kastning and Kastning, 1991).

The second Appalachian Karst Symposium was held at the East Tennessee State University and General Shale Brick Natural History Museum and Visitor Center, Gray, Tennessee, on 7–10 May 2008. More than 30 papers were presented at the meeting. No proceedings volume was published, however, six papers were selected and subsequently published in the *Journal of Cave and Karst Studies* in the August and December 2009 issues (v. 71 nos. 2 and 3).

Significance of Appalachian Karst

One measure of the speleological importance of this region is the abundance of caves. Caves can be an important measure of karst (Curl, 1966, 1999). Approximately 30% of 1130 caves of the United States longer than one mile (1.61 km) are located within the Appalachian karst (as currently listed by Gulden 2018). This percentage is the same for sub-intervals of length (e.g., caves longer than 2, 3, 4, 5, 10 km).

The Appalachian region has a wide diversity of karst, providing a natural ‘laboratory’ for karst science (Palmer, 2007; White and White, 2009). The lithology and stratigraphy of soluble rocks (namely limestone, dolostone, and marble) varies considerably. Bedrock structure ranges from relatively flat-lying beds in the Appalachian Plateau sub-area, west of the mountain belt, to steeply dipping rocks characteristic of the intensely folded and faulted rocks of the fold belt itself. As expected, these factors have influenced the hydrogeology. Groundwater paths in the karst are complex, reflecting local geologic and topographic settings. Overall, the entire region lies within a humid-temperate zone and thus serves as a climatological type-locality.

Studies of the caves and karst of the Appalachian region began in the late 18th century. For some time, until the mid-19th century, speleological investigations in the United States were largely confined to this region, with few exceptions. Hence, the study of karst in the U.S. had its beginnings in the Appalachian region. Later, over the next 150 years, studies of karst spread westward to the rest of the country.

The history of karst science in the Appalachians can be divided into several periods to facilitate this overview. These are as follows: (1) Early American Notes and Records, (2) Age of Curiosity, (3) Exploration and Early Tourism, (4) Birth of Modern U.S. Speleology, (5) Landmark Speleogenetic Studies, (6) Organized Caving and Science, (7) Speleological Inflation, and (8) Applied and Environmental Science. The following is a concise summary of karst studies in the Appalachians. In the interest of space, the vast number of potential references in the literature are not included here; however, many can be found in those papers cited.

Early American Notes and Records

It is difficult to ascertain just when speleological study first began in the U.S. However, the earliest records are merely descriptions of caves and other karst features discovered during exploration, travels, and settling of new territories during Colonial times and after the founding of the U.S. Many early writings on American speleology have been listed by Speece (1981), including several that describe caves in the Appalachian region.

The first well-known accounts of karst in the region refer to features in the central part of the Shenandoah Valley of Virginia. The renowned Natural Bridge near Lexington, a substantial karst landform, was first described by the Marquis de Francois Jean Chastellux (1787), and a detailed map and views of the bridge were included in his book (reproduced in Kastning 2014). Thomas Jefferson, second president of the U.S., also described the bridge in his classic book (1787), *Notes on the State of Virginia*. Furthermore, editions of this book also included a map of Madison's Cave in Cave Hill, near Grottoes, Virginia (Jefferson, 1787; Kastning III, 1995; Kastning III et al., 1995). This is widely regarded as the first American cave map. It is interesting to note that Madison Cave has a large signature of George Washington on its wall. Washington was a land surveyor at Natural Bridge during his early years. Jefferson was an ardent scientist. One of his contributions was a study of bones of a giant ground sloth discovered in Haynes Cave, Monroe County, Virginia (Grady, 1997).

Age of Curiosity

Many caves and other karst features were described by writers during the early 19th century, in books, newspapers, and other early periodicals (see Speece 1981 and Kastning 1981 for citations). In general, these

are generally accounts of caves encountered during travels. A notable example is a description of Balls Cave in Schoharie County, New York that was published and republished in numerous newspapers in the early 1830s and in the *Monthly American Journal of Geology and Natural Science* in 1832 and the *American Journal of Science* in 1835 (Kastning, 1971; 1979). Hence, Balls Cave was one of earliest caves to appear in the Appalachian scientific literature.

Exploration and Early Tourism

Interest in caves surged during the mid-19th century as more caves were discovered and people frequented caves that were operated for visitation. The first three notable show caves in the U.S. were Mammoth Cave in central Kentucky, Weirs Cave in Grottoes, Virginia (within Cave Hill, and presently known as Grand Caverns), and Howe's Cave (known today as Howe Caverns) in Schoharie County, New York. Fountain and Madison caves, also in Cave Hill at Grottoes, Virginia, were shown to the public as well. Later, Luray Caverns in another Cave Hill in Page County, Virginia, was discovered in 1878 and joined the ranks of the most popular and documented show caves of the time. These caves received world-wide coverage in the literature and visitation grew in response. Concurrently, some scientists of the period were drawn to visit the caves and began to decipher the mechanisms of their origin. The history of Grand Caverns is discussed in Kastning III et al. (1995), that of Luray Caverns by Gurnee (1978) and that of Howe's Cave by Kastning (1978, 1979), Cudmore (2002), and Engel (2014). These sources provide numerous references to the early works.

In addition to these most celebrated caves, numerous accounts of smaller, yet important caves in the Appalachian region were also published during the mid-19th century. Many of these writings are listed in Northrup et al. (1998), a major resource to the literature of American speleology.

Birth of Modern U.S. Speleology

Perhaps the most important era in the origin of Appalachian karst science occurred during the late 19th and early 20th centuries. European studies of karst were well underway at this time, perhaps owing to a longer history in the discovery and exploration of caves. In the U.S. it is widely acknowledged that Horace Carter Hovey may rightfully be called the 'Father of American

Speleology.’ His popular book, *Celebrated American Caverns* (1882), stands out as a landmark publication in American speleology. It discusses the origin of caves and much of the book is dedicated to Mammoth Cave in Kentucky. However, two Appalachian caves that were considered in detail are Howe’s Cave in New York and Luray Caverns in Virginia. There is some information on other caves, including Balls Cave (New York) and caves of the Shenandoah Valley (Virginia), especially those in Cave Hill at Grottoes.

During this same period other descriptive studies of caves in various regions of the country were being published. Several came from the northeastern part of the Appalachian region, including works by Edwin Swift Balch, Lewis Caleb Beck, Herdman Fitzgerald Cleland, John Hawley Cook, Amos Eaton, James Eights, Ebenezer Emmons, Amadeus William Grabau, Edward Hitchcock, George Henry Hudson, W.H. Knoepfel, William Williams Mather, George Brubank Shattuck, and Charles Upham Shepard. Some of these authors were noted geologists of the day. A synopsis of these pioneer speleologists and their work is provided in Kastning (1981).

Significantly, this period marks the beginnings of systematic cave surveys and inventories. Among the pioneering scientists listed above, two stand out in this regard. Grabau (1906), a noted geologist of this era, described several caves in the Helderberg Plateau, just west of Albany, New York. Cook (1907), working in the same region for the New York State Museum (which includes the state geological survey), compiled what is arguably one of the most thorough descriptive and illustrated compilations of caves up to that time.

The early 1930s saw the publication of several cave inventories by other state geological surveys. Stone (1932) produced the first statewide survey of caves in Pennsylvania, and McGill (1933) authored a remarkable volume describing and illustrating the show caves of Virginia. Decades later these were later upgraded and published by the National Speleological Society and the two state geological surveys.

Alabama also began to inventory its caves (Varnedoe, 2008). Henry McCalley described about two dozen caves in Special Reports of the Geological Survey of Alabama in 1896. In 1930 the survey published Special

Report No. 16, titled, *Ground Waters of North Alabama*. A chapter by Walter B. Jones described 22 caves in detail. This is now recognized as the beginning of the present Alabama Cave Survey that has since published additional compilations.

Landmark Speleogenetic Studies

True karst science in the U.S. began and flourished with landmark papers on speleogenesis appearing in the geologic literature from 1930 to the early 1960s. Oddly, much of this work seems to have been done with little regard or knowledge of major contemporary karst research in Europe, particularly in the classic karst of central Europe and in France.

The American discourse on the origin of caves formed by dissolution began with considerable controversy as several competitive theories were advanced to explain the general origin of caves. Some of the most notable of the American theories advanced during this period were by J. Harlen Bretz, William E. Davies, William Morris Davis, James H. Gardner, Arthur M. Piper, Roger Rhoades and M.N. Sinacori, A.C. Swinnerton, and Herbert P. Woodward. In most cases, caves of the Appalachian region were included as examples or as case studies. Again, the Appalachian region was for some time the center of speleological activity, prior to extended exploration to other parts of the nation.

Most of these pioneering papers have been reprinted in Sweeting (1981). Reviews and discussions of the classic papers are found in White (1959), Halliday (1960), Davies (1966), Watson and White (1985), Feinberg et al. (2016), and many of the modern texts on speleogenesis and karst processes (cited in the following section).

Organized Caving and Science

The study of karst and the science of speleology made great strides during the last three decades of the 20th century. Three factors were in play. First, a plethora of regional and statewide cave surveys and inventories were compiled and published during the remainder of the 20th century. In addition to the forerunners in New York and Alabama (above), many surveys of Appalachian caves were formally published by state geological surveys as issues of their numbered series of reports. These include New Jersey, Pennsylvania, Maryland, West Virginia, Virginia, and Tennessee. Moreover, in other states, including Vermont, Massachusetts, Connecticut,

New York, Kentucky, North Carolina, Georgia, and Alabama, similar publications were produced by internal organizations (grottoes, regions, surveys, etc.) of the National Speleological Society (NSS, see below). Some of these groups continue to extend the previous work of the state geological surveys. The publications produced from these efforts are far too numerous to cite here; however, the reader can easily find them through bibliographical searches.

The published surveys and inventories, along with associated archived files have resulted in huge data bases. These have a high value to continued cave exploration. More importantly, these sources of information have had an immeasurable impact on the research of karst throughout the Appalachian region.

The second factor in the facilitation and expansion of karst science is the advent of organized caving. The National Speleological Society was founded in 1941 through the merger of two established caving groups, one in New England and the other in the national capital region. Beyond question, the NSS, through unifying the entire speleological community, has accelerated karst research in the U.S. All interests in caves, ranging from recreation to professional scientific study were now under a single umbrella. Information began to be disseminated among all parties. The NSS resources, including publications, internal organizations, meetings, gatherings, and other events at local, regional, and national levels benefitted all interest groups. Some of these resources and activities have been general in nature, but many became specialized, addressing specific needs, including a focus on science (such as studies of karst). Without the NSS and the caving community, karst science would not be at the level it is today. The history of the NSS and its effect on karst science have been well documented (Moore et al., 1966; Davies, 1966; Damon, 1991; 2016).

The third factor in fostering the phenomenal growth in karst science during this period has been the founding of other complimentary associations and sub-groups. Also, events and meetings dedicated to karst processes and issues have emerged significantly over the years.

In the Appalachian region, Pennsylvania, West Virginia, Virginia, Kentucky, Tennessee, Georgia, and Alabama have well-organized speleological surveys and data repositories. Caves in those states continue to be

documented in various publications including the Mid-Appalachian Region Bulletin, West Virginia Caver, Virginia Cellars, Western Kentucky Speleological Survey, Georgia Speleological Survey Bulletin. Caves in Vermont, Massachusetts, New York, and New Jersey are regularly reported in the regional Northeastern Caver.

Compilations of caves in specific regions are published often. These include guidebooks for the annual convention of the NSS and for semi-annual regional meetings and outings, including those of the Northeastern Regional Organization, Mid-Appalachian Region, Virginia Region, and Southeastern Regional Association.

Almost all grottoes (NSS chapters) regularly publish newsletters. Many include new discoveries, descriptions, and maps. These are archived in the NSS library in Huntsville, Alabama. Taken together, such newsletters and local guidebooks, published in low quantities, are a large data base for speleological research.

Another major development in Appalachian karst science has been the founding of several organizations that focus on karst research and sponsor meetings emphasizing scientific advances. The Karst Waters Institute, headquartered in West Virginia, regularly holds symposia on karst and publishes its proceedings. The National Cave and Karst Research Institute, in Carlsbad, New Mexico, sponsors meetings that often include presentations on Appalachian karst (including the present AKS). Since 1984, the Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst (commonly known as the ‘Sinkhole Conference’) meets approximately biannually. There have been 15 meetings to date including the one being held concurrently with the AKS in 2018. Many papers related to the Appalachian region have been presented and published in its proceedings. Typically, the annual and regional meetings of the Geological Society of America include papers, in some cases, entire sessions on karst. Each year the annual NSS Convention has a geology session and occasionally a session on local karst studies.

During the last few decades numerous significant and landmark papers on karst have appeared in established geoscience journals. Moreover, several major reference volumes on caves and karst have been published during this period (e.g., Klimchouk et al., 2000; Gunn, 2004;

Ford and Williams, 2007; Palmer, 2007; White and Culver, 2007, 2011). Martin and White (2008) identify the present state of karst research and the frontiers for further study.

Taken together these contributions have advanced karst science appreciably since the 1970s. Karst science in the Appalachian region has both contributed to and benefitted from these activities.

Speleological Inflation

A quick review of the speleological literature over the last few decades reveals an astounding trend: exploration of karst regions worldwide has been increasing at a surprising rate. New caves are being discovered in amazing numbers and records for the longest and deepest continually change. Some of the most awe-inspiring caves are coming to light and many existing caves have been significantly extended in length and depth. It had been thought that significant new finds in the Appalachian region would be on the decrease. On the contrary, new significant discoveries have also been the norm in most of the states in the region. Newly developed techniques of exploration, searching new areas for caves, and excavation for new entrances have all contributed to the discoveries.

Concomitant with accelerated exploration and documentation of caves and karst features has been a significant increase of professional contributions in the established geologic literature, including books, journals, proceedings volumes, and the like (White and White, 1998; Florea et al., 2005).

A number of sub-regions within the Appalachian karst area have seen a considerable explosion in exploration, mapping, and geologic study in recent years. Significant examples include (1) the marble zones of the Green Mountains of Vermont (various issues of the Northeastern Caver and guidebooks of the Northeastern Regional Organization of the NSS), (2) the Burnsville Cove Area in Bath County, Virginia (White, 2015), and (3) the Greenbrier Valley of West Virginia (White, 2018).

Applied and Environmental Science

A modern thrust of karst science is the application of principles and processes to environmental safety and protection. This has been a major thrust of the biennial Sinkhole Conferences (1984–present). Papers on

engineering and environmental problems regarding karst abound in the technical literature. This is because (1) the sensitivity of karst to human impacts is becoming much better understood, (2) industrial and economic development is increasingly encroaching on areas of karst, (3) sensitive areas must be identified prior to the design and implementation phases, (4) construction plans are more often required to consider hazards during planning, and (5) regulating agencies and governing bodies are under pressure to solve potential or occurring problems in a timely, efficient, and cost-effective manner.

Major environmental issues in the karst of the Appalachians are varied, largely governed by the complexity of karst systems in intensely deformed bedrock. Among the most important environmental considerations are (1) availability of adequate groundwater supplies, (2) chemical quality of groundwater, (3) sinkhole collapse and other ground instability, (4) protection of significant caves and karst features, and (5) preservation of sensitive subterranean biota.

Of all the major karst regions in the U.S., the Appalachian region has one of the highest population densities. Accordingly, environmental impacts will continue to be high and are likely to increase.

Conclusions

The Appalachian region includes one of the most significant karst areas in the United States. The historic development of karst science in the country is rooted here. From the late 1700s until the present, countless studies have addressed karst in the complex geologic setting of the region. This is supported by the wealth of published literature on the subject. Karst is an environmentally sensitive terrain. Not only is the historical context interesting, but as the region undergoes further economic development, it becomes increasingly necessary to understand the nature of the karst landscape, both above and below the surface, and the vast amount of information gleaned over the years.

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FACTORS AFFECTING KARST SPRING TURBIDITY IN EASTERN WASHINGTON COUNTY, MARYLAND

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Abstract

Infrequent and episodic turbidity events within the karst spring at the Albert Powell Trout Hatchery in Maryland's eastern Great Valley threatened late winter fry populations. Turbidity events in early winter 2016–2017 prompted detailed geologic, dye tracing, and resistivity studies. The hatchery spring lies at the juncture of a northeast trending thrust fault and a northwest trending cross strike fault. Dye tracing study along these structures produced mixed results. Fluorescein tracing, injected 1,500 m north, and upstream of the spring was used to test the conductivity along the Beaver Creek fault and Beaver Creek. This dye was not conclusively identified at any of the surrounding recovery sites. Rhodamine WT injected more than a kilometer northwest of the spring, and along the trend of the cross fault, was detected at both the hatchery spring and surrounding recovery sites after about one week. 2D resistivity studies attempting to identify subsurface voids along the cross-fault trend show a high resistivity anomaly possibly indicating an air-filled void and warrant further investigation. The study suggests that while faulting plays a role in direction of ground water movement, turbidity events appear to be most prone during periods of lowered flow.

Introduction

The Albert Powell Hatchery (APH), located along Beaver Creek near the eastern edge of Maryland's Great Valley, raises over 250,000 rainbow trout each year for stocking of the State's freshwater streams. A karst spring that is the main water supply for the hatchery has a flow of up to 4000 gallons per minute (~908 cubic meters per hour) (James and others, 1999). Since

its founding in 1949, infrequent and episodic turbidity events have killed or threatened several late winter fry populations. Two such episodes, in November 2004, resulted in significant mortality to young fish. Following these events, the Maryland Geological Survey (MGS) conducted a study to determine the possible catchment area that might contribute water, as well as sediment, to the spring (Duigon, 2009). That study indicated that the groundwater divide doesn't coincide with the surface-water divide, and that the contributing area is partly controlled by faulting. On December 5, 2016, the hatchery spring again experienced a major turbidity event that did not result in fish mortality. A second smaller turbidity event was recorded on January 16, 2017. Following the December 2016 event the Maryland Geological Survey and the Maryland Department of the Environment (MDE) identified two possible surface sources of sediment input nearby. The dye tracing portion of this study was conducted to evaluate if either of the sites was hydrologically connected to the hatchery spring. Additionally, an electrical resistivity study along the northwest trending cross fault was conducted to identify any subsurface voids along that structure.

Location and Geology

The spring that supplies water to the APH is located near the eastern edge of the Hagerstown Valley. The Hagerstown Valley is the largest karst region in Maryland and is a segment of the Great Valley Section of the Ridge and Valley Province (Reger and Cleaves, 2008) (Figure 1). The geology of the area surrounding the APH spring has been mapped in (Brezinski and Fauth, 2009; Brezinski and Bell, 2009) (Figure 1).

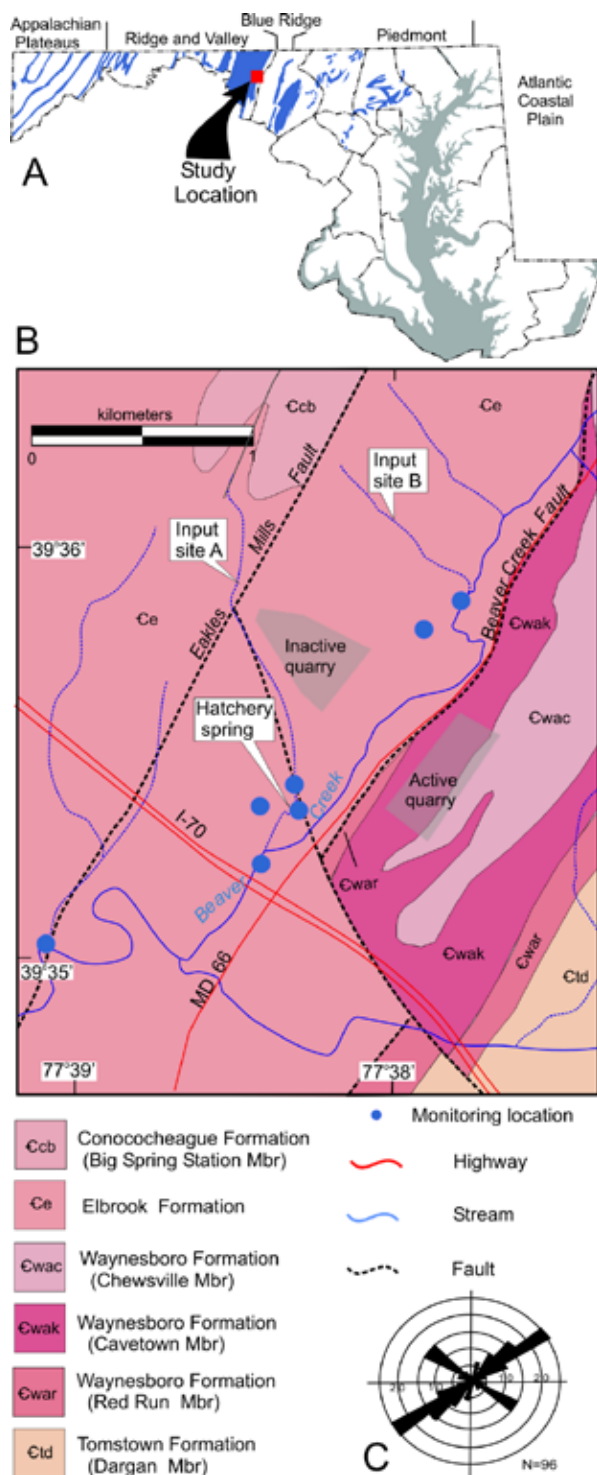


Figure 1. A, Location map of karst regions of Maryland (blue), the study area (red square) and the Hagerstown (Great) Valley. B, Geologic map of study area at the Albert Powell Trout Hatchery with locations of dye injection and monitoring. C, Rose diagram showing fracture orientations for measured joints at the Beaver Creek West Quarry.

The spring lies at the junction of two mappable fault traces. Stretching northeast from the spring, a thrust fault termed the Beaver Creek fault (Brezinski, 1992), places Lower Cambrian carbonate and clastic rocks of the Waynesboro Formation over shaly limestone of the Middle Cambrian Elbrook Formation. Near APH the Beaver Creek fault is truncated by a northwest trending unnamed high-angle cross strike fault that offsets the Waynesboro outcrop belt by approximately 900 m. This cross-strike structure has been portrayed as passing directly through the APH spring and continuing up a karst valley to the northwest of the spring (Brezinski and Bell, 2009). Near the western edge of the study area a high angle fault termed the Eakles Mills fault (Brezinski, 1992) has been interpreted as intersecting the cross fault, and was initially believed to be in karst connectivity with both the cross fault and Beaver Creek to the southwest of APH (Brezinski and Bell, 2009) (Figure 1). Based on these structural factors dye tracing and resistivity studies were conducted to determine if either of these structures influenced turbidity within the APH spring.

Two quarries, Beaver Creek West and East, lie approximately 0.5 km northeast and east of the APH, respectively. Beaver Creek West has been inactive since 2008. Beaver Creek East, although currently operating, lies east of a groundwater divide that follows the trace of the Beaver Creek Fault, which is believed to act as a barrier to groundwater flow (Water level monitoring data, 2004, unpublished).

Methods

To determine background levels of fluorescence, water samplers and charcoal traps were placed prior to dye injection. Two injection sites were chosen for the dye tracing study. At one of the injections sites fluorescein was injected and at the second rhodamine WT was used (Figure 1B). The automatic water samplers (ISCO™ samplers) were placed at three locations for six days and activated charcoal traps were placed, in pairs, at eight sites for approximately one month.

Dye was injected at the two study sites on Monday, February 27, 2017, after background water samples and charcoal traps had been collected. At the first site, fluorescein dye was injected in recently formed holes within a field 1,500 m NNE of the main spring. At this site, reclaimed earth was being used to make the field easier to farm. The injection hole was flushed with water. After

observing the water sink into the ground, approximately 1 kg of fluorescein disodium salt (also called fluorescein or uranine) was mixed with several gallons of water and poured into the injection hole. Afterwards approximately 600 gallons (~2.3 cubic meters) of water was used to flush the dye down the hole.

At the second site, the rhodamine WT dye was injected into a pool along a dry streambed 1,000 m NNW of the main spring. Water was flushed into this pool, followed by approximately 1 gallon (~0.004 cubic meters) of rhodamine WT. Additional water was placed in the pool, causing it to overflow and follow the stream channel so that the dye would sink where it could along the channel. A total of approximately 600 gallons (~2.3 cubic meters) was also used at this site.

All water samplers and eluted charcoal-traps were analyzed with a Turner Designs Trilogy™ Fluorometer with modules for fluorescein and rhodamine WT. The fluorometer was calibrated with 0.1 parts per billion (ppb), 1 ppb, and 10 ppb standards for both dyes. Calibrations were checked every day prior to analysis; the fluorometer was recalibrated as necessary. Water samples were pipetted directly into cuvettes, which were placed in the fluorometer for analysis. Charcoal traps were emptied into plastic cups and rinsed with deionized water. Approximately 12 mL of a solution of 95% isopropyl alcohol, 5% ammonium hydroxide, and supersaturated with potassium hydroxide flakes was placed in each cup with the charcoal to desorb the dye from the charcoal. The cups were capped to prevent evaporation, and then allowed to sit for approximately one hour. The resulting solution was pipetted into cuvettes to be analyzed. Each pipette and cuvette was used for only one sample before being disposed. Additionally, pairs of charcoal traps were left overnight in the lab in beakers containing 100 mL of known concentrations of dye before being eluted and analyzed as normal samples. This was done to note variability in readings and a relationship between dye concentrations in water and in the solution eluted from charcoal traps.

Results

There were no certain detections of fluorescein in the four recovery sites (Beaver Creek on hatchery property, the well on hatchery property, the well on farmhouse property, and the seep near Doub's Mill). Fluorescein readings at the other four sites (the main spring on

hatchery property, the seep on hatchery property, and the two Beaver Creek sites on farmhouse property) were inconclusive.

The lack of certain detections of fluorescein from both the water samplers and charcoal traps indicates that under the conditions present during the study, the holes in the drainage swale NNE of the main spring do not appear to be hydraulically connected to Beaver Creek at the fish hatchery entrance, the fish hatchery well, the farmhouse well, or the seep near Doub's Mill. Results were inconclusive for the main spring and seep on hatchery property, and Beaver Creek upstream and downstream at the farmhouse.

Rhodamine WT was detected in the charcoal traps at the main spring of the hatchery, and in the well of the farmhouse. The rhodamine WT readings in the well of the hatchery are inconclusive. No evidence of rhodamine WT detection was observed from the charcoal traps at the Fish Hatchery seep, Beaver Creek on hatchery property, Beaver Creek upstream or downstream on farmhouse property, or the seep near Doub's Mill.

Background rhodamine WT readings for the charcoal traps set in the main spring on hatchery property range from ~1.5–4 ppb. The charcoal traps set on March 6 and collected on March 9 returned an average rhodamine WT reading of 10 ppb. The traps set in the hatchery spring on March 9 and collected on March 13 returned an average rhodamine WT reading of 11 ppb. The rhodamine WT readings then decreased gradually until returning to the normal background range for the traps set on March 20 and later (Figure 2).

Charcoal traps set in the toilet tank fed by a well on hatchery property had background rhodamine WT readings of ~1–3 ppb. The charcoal traps set on March 9 and collected on March 13 returned an average rhodamine WT reading of 5 ppb. The traps set on March 13 and collected on March 16 returned an average rhodamine reading of 5 ppb. Later readings were in the background range (Figure 2). This peak is somewhat low, compared to both background levels and to levels recorded in lab tests. Additionally, there is a wide range between the readings for the two traps placed at this site from March 9 to March 13. Therefore, these readings were inconclusive.

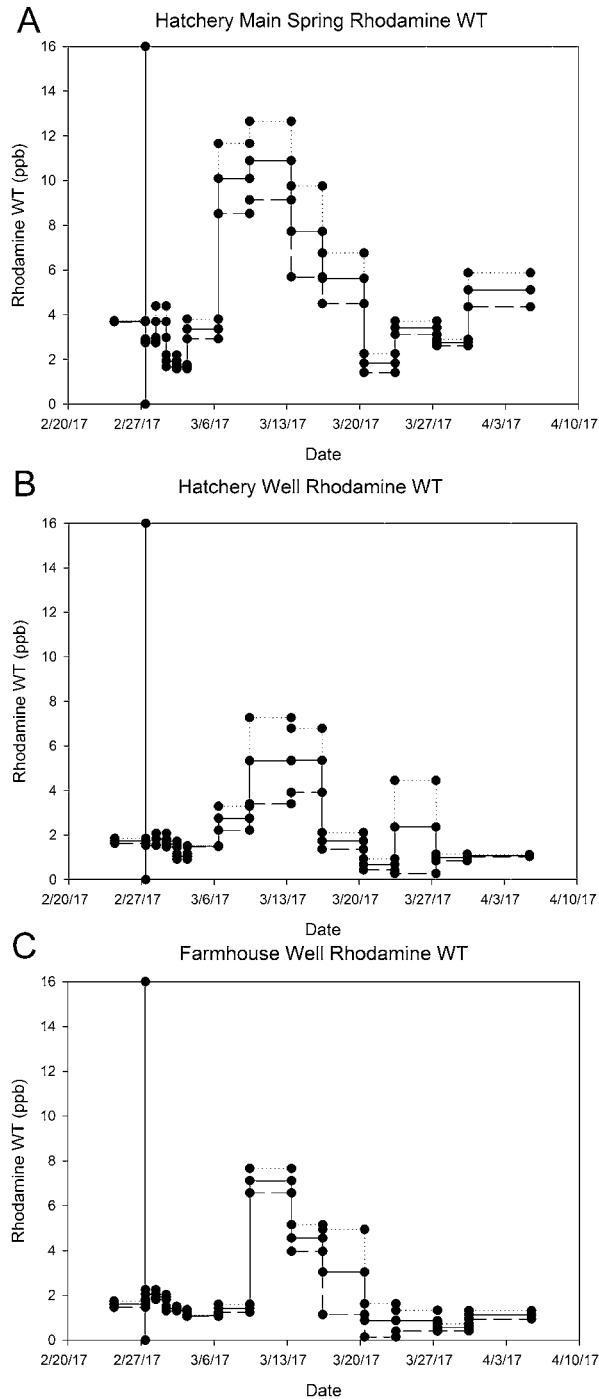


Figure 2. Timing of concentration levels of rhodamine WT recorded from charcoal traps placed in the main spring on hatchery property (A), toilet tank fed by a well on hatchery property (B), and well on farmhouse property (C). The dotted and dashed lines represent the upper and lower readings, respectively, while the solid line represents the average. The vertical lines on February 27 indicate date of dye injection.

The traps set in the toilet tank fed by a well on farmhouse property had background rhodamine WT readings of ~1–2 ppb. The traps set on March 9 and collected on March 13 returned an average rhodamine WT reading of 7 ppb. The traps set on March 13 and March 16 returned decreasing but still elevated rhodamine WT readings. Traps set on March 20 and later returned readings of rhodamine WT in the background range (Figure 2).

The rhodamine WT results for the charcoal traps tested in 100 mL of known dye concentrations are shown in Table 1. In general, low levels of rhodamine WT in water below 1 ppb do not lead to definitive detections of rhodamine WT in the eluted solution. However, higher levels of rhodamine WT in water lead to noticeably increasing levels of rhodamine WT in the eluted solution. The average difference in rhodamine WT readings between two traps placed in the same solution was 1 ppb. The average difference in rhodamine WT readings between two traps placed at the same field site for the same time period was 1 ppb.

The results indicate that under the conditions present during the study, the karst valley that trends northwest of the hatchery main spring is hydraulically connected to the main spring on hatchery property, to the farmhouse well, and possibly to the hatchery well (Figure 3).

RESISTIVITY AND KARST AT APH

An electrical resistivity study was conducted near the APH to evaluate the potential for bedrock voids along the northwest trending cross fault. Electrical resistivity (ER) imaging can be an effective method for identifying subsurface water- and air-filled voids when there is a strong contrast in conductivity with the surrounding bedrock (Zhou and others, 2002; Zhu and others, 2001). ER injects a direct current into the ground between

Solution	Sample 1 (ppb)	Sample 2 (ppb)	Average (ppb)
Blank (deionized water)	0.8	1.0	0.9
0.1 ppb rhodamine WT	1.0	2.5	1.8
0.5 ppb rhodamine WT	0.7	1.6	1.2
1 ppb rhodamine WT	0.9	3.2	2.0
10 ppb rhodamine WT	3.3	3.2	3.3
100 ppb rhodamine WT	19.7	18.9	19.3

Table 1. Concentrations of rhodamine WT measured in solution eluted from charcoal traps left overnight in 100mL of water with known initial dye concentration.

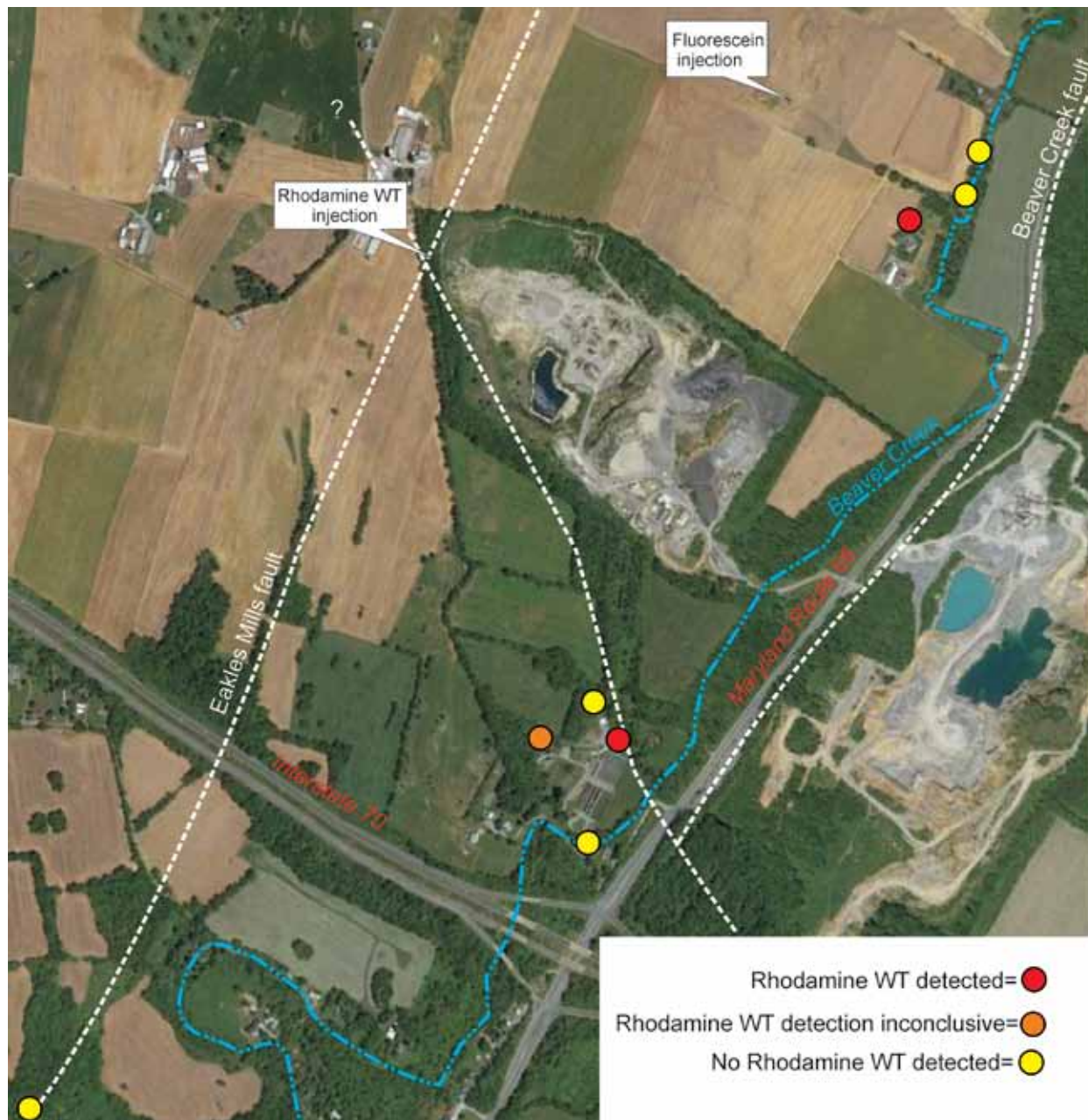


Figure 3. Summary results of dye tracing study surrounding the Albert Powell Hatchery, Washington County Maryland. Google Earth base image date 5/25/13.

two metal electrodes and then measures the potential field between additional nearby electrodes to model changes in resistivity around subsurface targets. The measured potential depends on the resistivity of the materials through which the current is conducted, which varies with geologic factors such as lithology, porosity, and saturation (Table 2). Modeled resistivity profiles then allow geologic and hydrologic interpretation and comparison with ground truth data.

Material	Resistivity from wet to dry (Ohm-meters)
Sandstone	10-6000
Shale	30-3000
Limestone	70-7000
Dolomite	500-7000
Clay	1-100
Groundwater (fresh)	10-100
Sea water	0.2
Air	>10,000 (Theoretically infinite)

Table 2. Typical resistivity values of earth materials in the APH study area. Adapted from Loke, 2016.

ER surveys employ an array of electrodes connected with electrical cable and arranged either in a straight line (2D surveys and quasi-3D surveys) or a grid (3D surveys). Electrode pairs are automatically measured by means of a switchbox and resistivity meter. The depth of investigation is approximately 20% of the maximum length of survey, while resolution is estimated to be

one half of the electrode spacing. MGS staff initially conducted electrical resistivity surveys perpendicular to the line projected for the cross-fault (Figure 4), using 28 electrode arrays at a 3-m electrode spacing, for a maximum length of 81 m, a depth of investigation of approximately 23 m, and resolution of 1.5 m. The electrode spacing and maximum survey length were

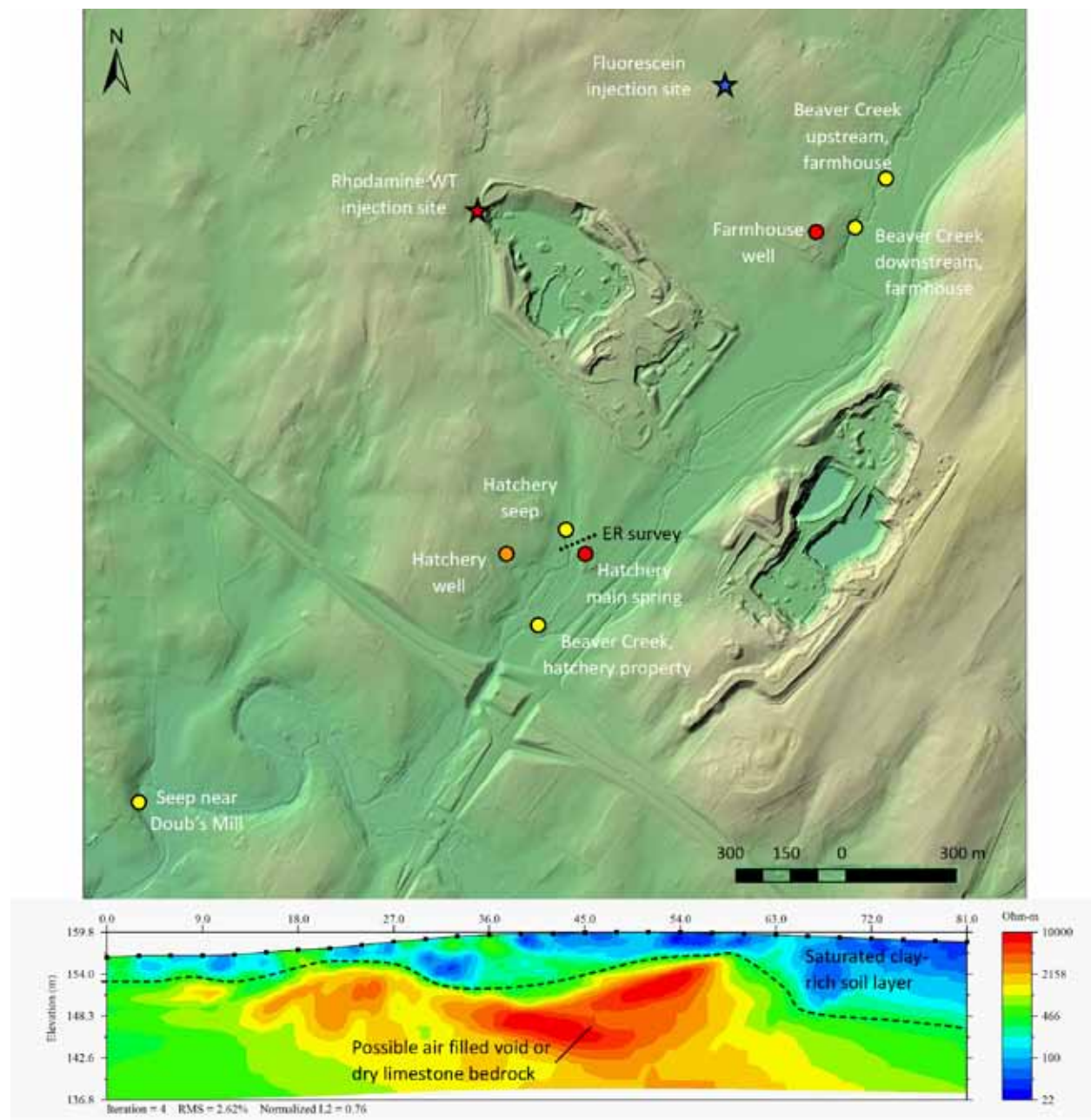


Figure 4. Location of ER survey relative to APH main spring and dye tracing sites on background LiDAR-derived hillshade image. Beneath it is inverted resistivity profile from the ER survey showing highly resistive anomaly.

chosen to strike a balance between maximizing the exploration depth while maintaining a degree of resolution able to define both small and large voids in the bedrock. A dipole-dipole array was chosen for the electrode configuration as it has been shown effective in mapping both air and water-filled karst voids (Zhou and others, 2002; Zhu and others, 2011). While resistivity data were collected, a survey-grade global positioning system (GPS) survey was conducted of all electrode positions for each array. The elevation data were used for advanced processing to correct for variations in topography along the survey line. An Advanced Geosciences, Inc. (AGI) SuperSting R8/ IP/SP electrical imaging system was used to collect the data and EarthImager-2D™ software was used to process the data. Results of the ER survey (Figure 4) showed a thin low resistivity layer near the surface corresponding to values for a saturated clay-rich soil. A highly resistive area occurred in the middle of the profile from 6–14 m in depth and may indicate an air-filled void, dry limestone and dolomitic bedrock, or a combination of the two. Further ER surveys using expanded 2D, quasi-3D, and 3D arrays will increase the depth and width of the imaging and may better constrain the location and orientation of this anomaly.

DISCUSSION

Rhodamine WT readings in charcoal traps at the main spring of the hatchery and the toilet tank fed by well-water on the farmhouse property both increased to several times background levels in early March 2017, with the increases being greater than the usual variability between charcoal traps set at the same site. While the dye trace conducted for this study established a connection between the spring and the rhodamine WT injection site, this does not necessarily establish that site as the source of the turbidity observed at the spring. However, it may implicate the northwest trending cross fault as a possible course along which some of the dye migrated.

The Maryland Geological Survey also reviewed precipitation data and the quarry blasting schedule, and found no evidence to associate the turbidity events with either precipitation or blasting events.

The fact that the 2004 and 2016–17 turbidity events all occurred within the late fall and early winter may reflect a proclivity of these events at that time of the year. The lowest monthly mean spring flow occurred in November (3074 gallons per minute / ~698 cubic meters per hour)

based on a period of record from 1987–1997 whereas the highest monthly mean spring flow was in April (4187 gallons per minute / ~951 cubic meters per hour) (James and others, 1999). The lowered water table at that time of the year may have increased the potential of these presumably subsurface sedimentation events. Due to the complexity of karst terrain, connections between sinkholes and springs may vary depending on water level. During times of high flow, hydraulic pathways that are dry at low flow may be active (Kentucky Natural Resources and Environmental Protection Cabinet, 1991).

As a proxy for determining water levels in the shallow aquifer, stream flow for eastern Washington County was examined. The stream flow, as recorded by a gauging station downstream from the hatchery (Figure 5), illustrates that the October 2016 through January 2017 records suggest diminished surface water flow. Concomitantly, the hatchery spring was flowing at approximately 1900 gallons per minute (~432 cubic meters per hour).

If it is assumed that low water table and greatly reduced subterranean flow affects karst conduit character, any slumping or widening within the conduits might have had a greater effect on the reduced level of karst flow. Because of the complexity of karst systems, additional and different hydraulic pathways could be in effect during higher flow regimes. Groundwater divides in karst areas are known to change with different conditions, and operate as three-dimensional flow systems where overflow routes can convey water to different discharge

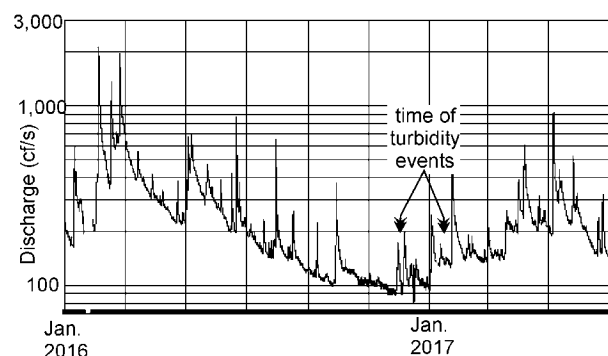


Figure 5. Timing of turbidity events at APH and stream flow of nearby Antietam Creek for the period from January 2016 to July 2017. USGS gauging station 01619500 is approximately 18 km southwest and down-stream from main hatchery spring.

points depending on the hydrologic conditions (White, 1993; Meiman and others, 2001).

ACKNOWLEDGEMENTS

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PATTERNS OF HETEROGENEITY WITHIN PHREATIC KARST AQUIFERS OF THE GREAT VALLEY, VIRGINIA AND WEST VIRGINIA: EVIDENCE FROM TIME SERIES HYDROLOGIC MONITORING, GROUNDWATER CHEMISTRY, AND STYGOBITE SITE OCCUPANCY

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Abstract

Phreatic karst waters in the Central Appalachian Great Valley are the subject of an ongoing habitat monitoring project across the geographic range of the federally threatened Madison Cave Isopod (MCI, *Antrolana lira*), a stygobitic crustacean previously documented at each monitoring site. Eight caves and five wells were monitored, via instrumentation, hourly from June 2016 thru October 2017 for water level (WL), temperature (T), and specific conductivity (Cs.) Sites were visited quarterly to download data, collect water samples, and deploy baited traps to assess occupancy by stygobitic fauna. Samples were analyzed for major ions, inorganic carbon, and stable water isotopes. Precipitation data from National Climate Data Center stations were used to evaluate response to precipitation events. There is significant variation between sites in water chemistry, in baseline WL, Cs, and T values, and in the response of these parameters to precipitation. Median temperatures varied from 11.6 to 13.8°C, with ranges within sites of 0.7 to 15.5°C. Median Cs values varied from 442 to 726 uS/cm at 25°C, with ranges within sites of 16 to 573 uS/cm. Ranges of WL within sites varied from 0.9 to

9.6 m. Ten sites exhibited rapid WL increases following precipitation, accompanied by spikes and/or dips in Cs. Six of these sites exhibited significant T changes. Sites with negative Cs response typically exhibited T changes reflecting precipitation temperature, with several exhibiting a compound response to larger events. Samples analyzed as calcium-magnesium-bicarbonate type waters, with Ca:Mg ratios from 9 to 5.5:1 and Ca + Mg values from 1.8 to 4.1 mmol/l. Geochemical parameters grouped more by site than by season. Chloride, nitrate, sulfate and sodium levels at some sites suggest significant land use influence from agricultural and stormwater management practices. Average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ compositions suggest winter-dominated (Nov-April) recharge. Over the course of the study, site occupancy of these known MCI sites ranged from 0 to 100%, both for MCI and other stygobitic invertebrates. Occupancy rates appeared unrelated to geochemical or hydrodynamic patterns. Data are consistent with a complex, compartmentalized phreatic aquifer, reflecting the folded, faulted, and fractured bedrock structure. Water levels determine inter-compartment connectivity, facilitating episodic migration of stygobitic species.

Characterization of such a system to support groundwater and habitat management decisions would require a much higher spatial density of monitoring stations than presently exists in the Great Valley.

Introduction

The Madison Cave isopod (*Antrolana lira* Bowman 1964) is a freshwater, stygobitic cirolanid isopod of marine lineage. The only species in the genus *Antrolana*, it is known exclusively from phreatic groundwater in the karst aquifer developed in the Cambro-Ordovician aged carbonate rocks of the Great Valley of Virginia and West Virginia (Bowman, 1964; Holsinger et al., 1994; Hutchins et al., 2010.) The Madison Cave isopod is documented from 20 survey sites (12 caves, 8 wells) representing 12 distinct occurrences (Holsinger et al., 2013; Holsinger et al., 1994; Fong, 1996; Orndorff and Hobson, 2007; Hutchins and Orndorff, 2009; Orndorff and Hobson, 2010.) *A. lira* was listed as threatened over its entire range under the United States Endangered Species Act in 1982 (Fong, 1996). Based on analysis of CO1 mitochondrial DNA from a subset of sites within its range, Hutchins et al. (2010) separated *A. lira* into three distinct evolutionary lineages: a southern clade from the type locality at Madison Saltpetre Cave, a western clade just north of Harrisonburg (VA) (3-D Maze, Linville Quarry caves), and a northern clade from sites along the main stem of the Shenandoah River. Hutchins et al. (2010) concluded that the approximate 9.5 to 11.3% divergence between any two of these clades reflected long term genetic isolation on the order of millions of years, and recognized that DNA analyses of specimens from other sites may identify additional genetic clades. Holsinger et al. (1994) hypothesized that colonization of the Great Valley karst by *A. lira* may have occurred as early as the Cretaceous period.

Prior investigations of the Madison Cave isopod and its habitat have addressed distribution (Fong, 1996; Orndorff and Hobson, 2007; Orndorff, 2008; Orndorff and Hobson, 2010), population estimates based on mark-recapture methods (Fong, 2007; Orndorff, 2012, 2014a, 2014b; Hutchins and Orndorff, 2009), site occupancy and sampling methodology (Hutchins and Orndorff, 2009), molecular genetics (Hutchins et al., 2010,) natural history (Holsinger et al., 1994; Hutchins et al., 2010), population ecology (Collins and Holsinger, 1981; Hutchins and Orndorff, 2009), and habitat characterization and monitoring (Printz, 1999; Orndorff, 2014a, 2014b). Orndorff (2014a, 2014b) showed that hydrological and geochemical characteristics varied significantly between three sampling locations, both

in terms of base level values and in responsiveness to precipitation events, even between monitoring locations in close proximity.

This study addresses physical hydrology, geochemistry, and species site occupancy at 13 of the known confirmed survey sites (Figure 1. Study area – site abbreviations listed in Table 1. Karst bedrock distribution from Weary and Doctor (2014).) for *A. lira*, including eight caves and five wells, in an attempt to better define the range of hydrological and geochemical parameters that characterize its habitat and affect its presence at a specific site. Table 1. Monitoring sites of this study. Locations shown in Figure 1. lists the monitoring sites for this study.

Materials and Methods

Time series data were collected using automatic data loggers deployed at each site to record specific conductivity, water levels, and temperature at hourly intervals over the course of the study. Instruments in caves were deployed in vertically oriented or steeply sloping stilling well enclosures comprised of 1.5 inch PVC pipe perforated with 1/8" holes (4 per inch), open on the bottom to discourage sediment buildup, and capped on the top to prevent entry of material into the well from above the water level. Instruments were deployed free-hanging in wells, and were secured with independent

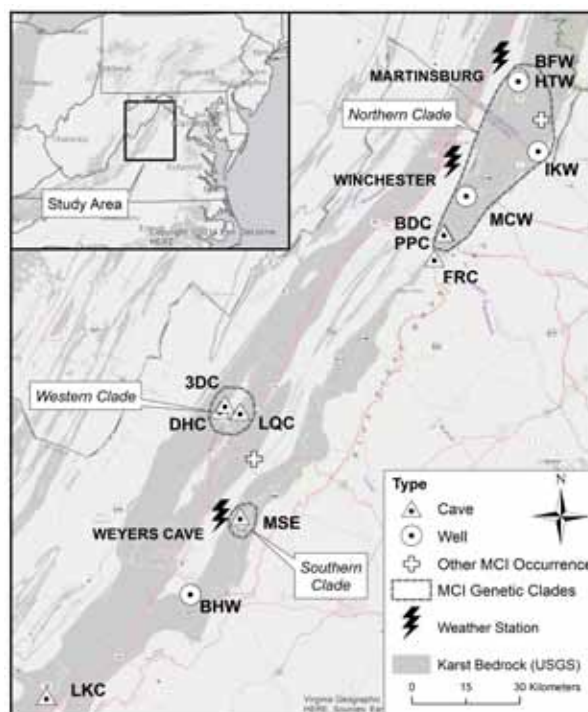


Figure 1. Study area – site abbreviations listed in Table 1. Karst bedrock distribution from Weary and Doctor (2014).

Site	Abbr.	Type
3-D Maze Cave	3DC	Cave
Brother Daves Cave	BDC	Cave
Devils Hole	DHC	Cave
Front Royal Caverns	FRC	Cave
Lime Kiln Cave	LKC	Cave
Linville Quarry Cave	LQC	Cave
Madison Saltpetre Cave (East Lake)	MSE	Cave
Power Plant Pit	PPC	Cave
Ballfield Well	BFW	Well (drilled)
Blue Hole Well	BHW	Well/cave
Howard Tabb Well	HTW	Well (dug)
Irvin King Well	IKW	Well (drilled)
Meade Church Well	MCW	Well (dug)

Table 1. Monitoring sites of this study. Locations shown in Figure 1.

and redundant nylon cord and/or plastic coated steel wire. Depth was recorded using Onset® HOB0® U20L-01 Water Level Data Loggers specified for use up to 10 m depth and accurate to 0.5 cm. These loggers also record temperatures to within 0.44°C. These loggers were placed at arbitrary depths below the water surface, at elevations below which it appeared the water table rarely (if ever) recedes. U20 Water Level Data Loggers were also deployed above maximum water level to log barometric pressure facilitating calculation of sensor depth using Onset® Hoboware® software. Specific conductivity was measured using a HOB0 Freshwater Conductivity Data Logger - U24-001, factory calibrated for the range of 0 to 1,000 µS/cm accurate to within the greater of 3% of the reading or 5 uS/cm. Data were corrected using Onset Hoboware software to specific conductivity to eliminate temperature effects (~2% per °C) so that all changes in conductivity could be attributed to changes in ionic composition of the groundwater. Hourly precipitation data were downloaded from National Climate Data Center weather stations proximal to study sites to facilitate analysis of time series data response to precipitation events.

Water samples were collected in December 2016, March 2017, and July 2017, and were filtered to 0.2 microns to remove sediment and microorganisms. Major cation samples were acidified and analyzed using an inductively-coupled mass spectrometer (ICP-MS), and anion samples were analyzed by ion chromatography (IC) at Virginia Tech. Samples for total inorganic carbon analysis were collected in gas-tight glass vials without headspace, and analyzed by a total carbon analyzer interfaced with an isotope ratio mass spectrometer (IRMS) at the U.S. Geological Survey (USGS) in

Reston according to methods described in Révész and Doctor (2014). Samples for oxygen and hydrogen stable isotope analyses were analyzed at the USGS Reston Stable Isotope Laboratory. All samples were refrigerated until analysis. Approximately 10% of the samples were collected in duplicate for cross-comparison among analytical results.

Site occupancy was assessed using a combination of stygobite traps (caves and wells) and visual observation (caves). Traps baited with raw shrimp or salmon eggs (Hutchins and Orndorff, 2009) were deployed quarterly for approximately 24 hours. Specimens were counted and identified to the extent possible then returned to habitat, except in cases where taxonomic uncertainty existed or additional specimens were required for ongoing genetic investigations pursuant to Hutchins et al. (2010). Collections were performed under permits issued by Virginia DGIF and West Virginia DNR.

Results

Time series data statistics are summarized in Table 2 and expressed graphically in Figure 2. A complete set of time series data are available upon request from the first author.

Water level values are reported as meters above minimum recorded levels. Three sites in close proximity – 3-D Maze, Linville Quarry, and Devils Hole – spent a significant portion of the study period dry when water levels receded below the instruments, so relative water levels and ranges are underestimated for these sites. Among the remaining sites, the highest range of water levels was observed at Power Plant Pit at 9.55 m, and the lowest at Madison Saltpetre Cave (East Lake) at 1.06 m. Highest median water level was at Meade Church Well (1.80 m) and the lowest at Brother Daves Cave (0.03 m).

Temperatures reported are those collected by submerged pressure transducers. The highest median temperatures observed were at Power Plant Pit (13.6°C) and Meade Church well (13.9°C). The lowest median temperatures were at Devils Hole (11.9°C) and Front Royal Caverns (11.7°C). The highest (22.5°C) and lowest temperatures (7.0°C) observed were at Power Plant Pit, defining a range of 15.5°C. Madison Saltpetre Cave (East Lake) exhibited the smallest range of temperatures at 0.1°C.

The highest median specific conductance values reported were from Howard Tabb Well (794 µS/cm), Power Plant Pit (726 µS/cm), and Meade Church Well (717 µS/cm.) Lowest median values were reported for Madison

Site name	Site Abr.	Level (m)			Temp (°C)				Specific Conductance (μS/cm)			
		med	R	SD	med	max	min	SD	med	max	min	SD
3-D Maze Cave	3DC1	0.21	3.71	0.68	12.4	13.7	11.2	0.30	702	733	519	19
Brother Daves Cave	BDC	0.03	5.01	0.21	12.2	13.3	12.1	0.11	607	668	439	18
Devils Hole	DHC1	2.15	4.79	1.4	11.9	12.0	10.2	0.54	724	776	556	47
Front Royal Caverns	FRC	0.25	7.34	1.1	11.7	12.3	10.9	0.11	693	984	574	69
Lime Kiln Cave	LKC	0.04	4.93	0.33	13.1	15.8	11.8	0.14	450	492	233	14
Linville Quarry Cave	LQC1	2.63	5.99	2.1	12.6	13.1	12.0	0.09	639	680	600	14
Madison Saltpetre Cave (East Lake)	MSE	0.25	1.06	0.23	12.2	12.2	12.1	0.04	468	477	458	5
Power Plant Pit	PPC	0.77	9.55	1.1	13.6	22.5	7.0	0.47	726	765	192	54
Ballfield Well	BFW	0.76	1.64	0.32	12.5	13.4	11.5	0.41	660	688	630	11
Blue Hole Well	BHW	0.96	2.81	0.62	13.0	13.1	12.2	0.10	442	449	439	2.6
Howard Tabb Well	HTW2	0.61	1.64	0.40	Influenced by well pump				794	1093	101	81
Irvin King Well	IKW	1.39	6.43	1.41	12.5	14.3	12.4	0.02	590	618	137	45
Meade Church Well	MCW	1.80	6.75	1.40	13.9	14.2	13.4	0.18	717	825	622	34

Table 2. Water level and temperature time series statistics. 1–water receded below loggers during significant portion of study period; 2–water level affected by pumping (med=median, max=maximum, min=minimum, R= range, SD= standard deviation). Site abbreviations listed in Table 1.

Saltpetre Cave (East Lake, 468 μS/cm), Lime Kiln Cave (450 μS/cm) and Blue Hole Well (442 μS/cm). The highest ranges in specific conductance values were at Howard Tabb Well (992 μS/cm) and Power Plant Pit (573 μS/cm.) The lowest ranges in specific conductance were at Madison Saltpetre Cave (19 μS/cm) and Blue Hole Well (10 μS/cm).

Time series data were plotted over time against precipitation to assess and compare parameter responses to precipitation events. Figure 3 displays the responses of the Northern sites, while Figure 4 shows those of the Southern sites. Howard Tabb Well was excluded from these plots due to strong suspected influence from pumping and well maintenance activities.

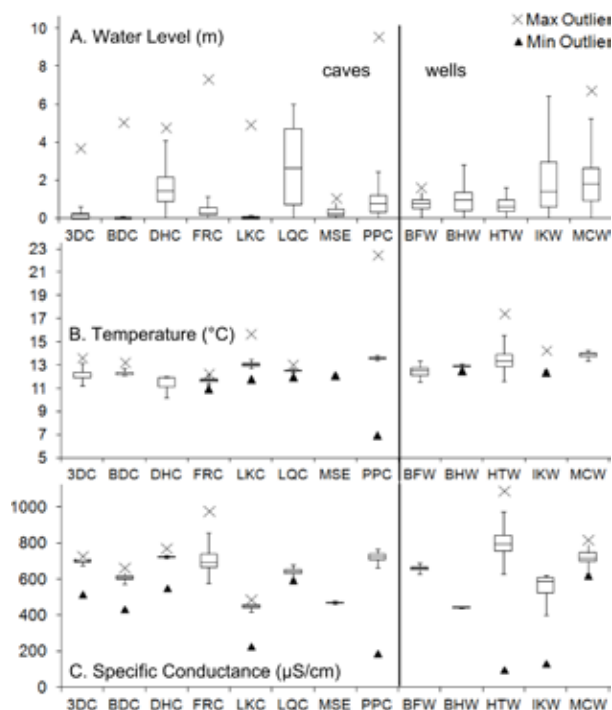


Figure 2. Box plot summaries of time series data (A. Water level, B. Temperature, and C. Specific conductance)

Water level was the only parameter responsive to precipitation across all study sites. Power Plant Pit, Front Royal Caverns, and Meade Church Well respond immediately to most precipitation events over ¼ inch, while the remaining sites respond to larger events typically exceeding ½ inch. Ballfield Well level response is irregular. Blue Hole Well and Madison Saltpetre Cave show slow responses to larger precipitation events, with an increase in base level values subsequent to the events. Power Plant Pit, Irvin King Well, and Meade Church Well also show increases in base trends after storm flows recede. The largest level response observed was approximately 9 m over 14 hours at Power Plant Pit on September 30, 2016.

Temperature was the parameter that was responsive to precipitation events at the lowest number of sites. Power Plant Pit exhibits a pronounced temperature response to nearly all precipitation events reflecting seasonal precipitation temperatures. 3-D Maze cave showed temperature changes in response to larger precipitation events that reflected seasonal temperatures. Brother Daves Cave exhibited increases in temperature after larger precipitation events, regardless of the season.

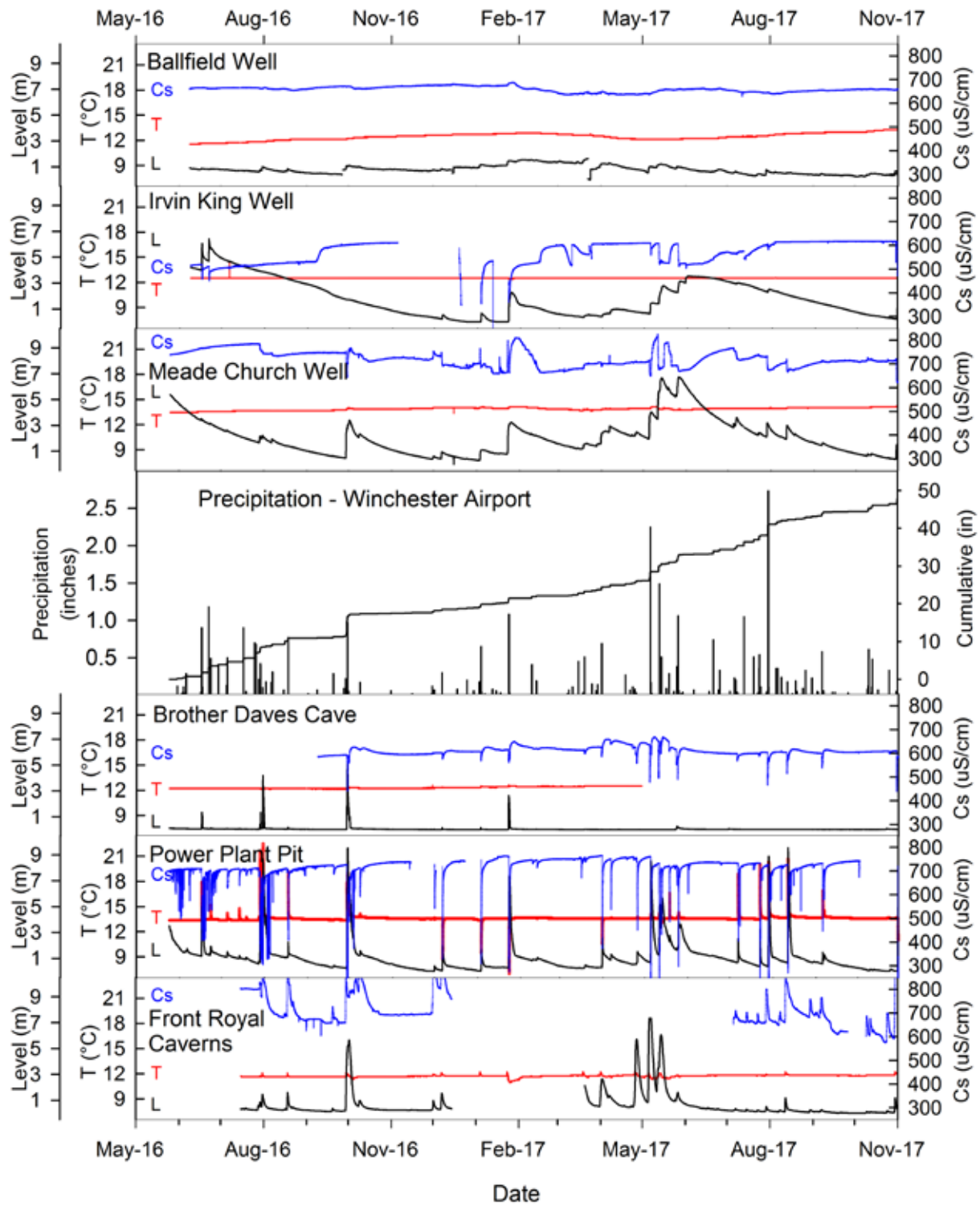


Figure 3. Time series data responses to precipitation events, Northern sites.

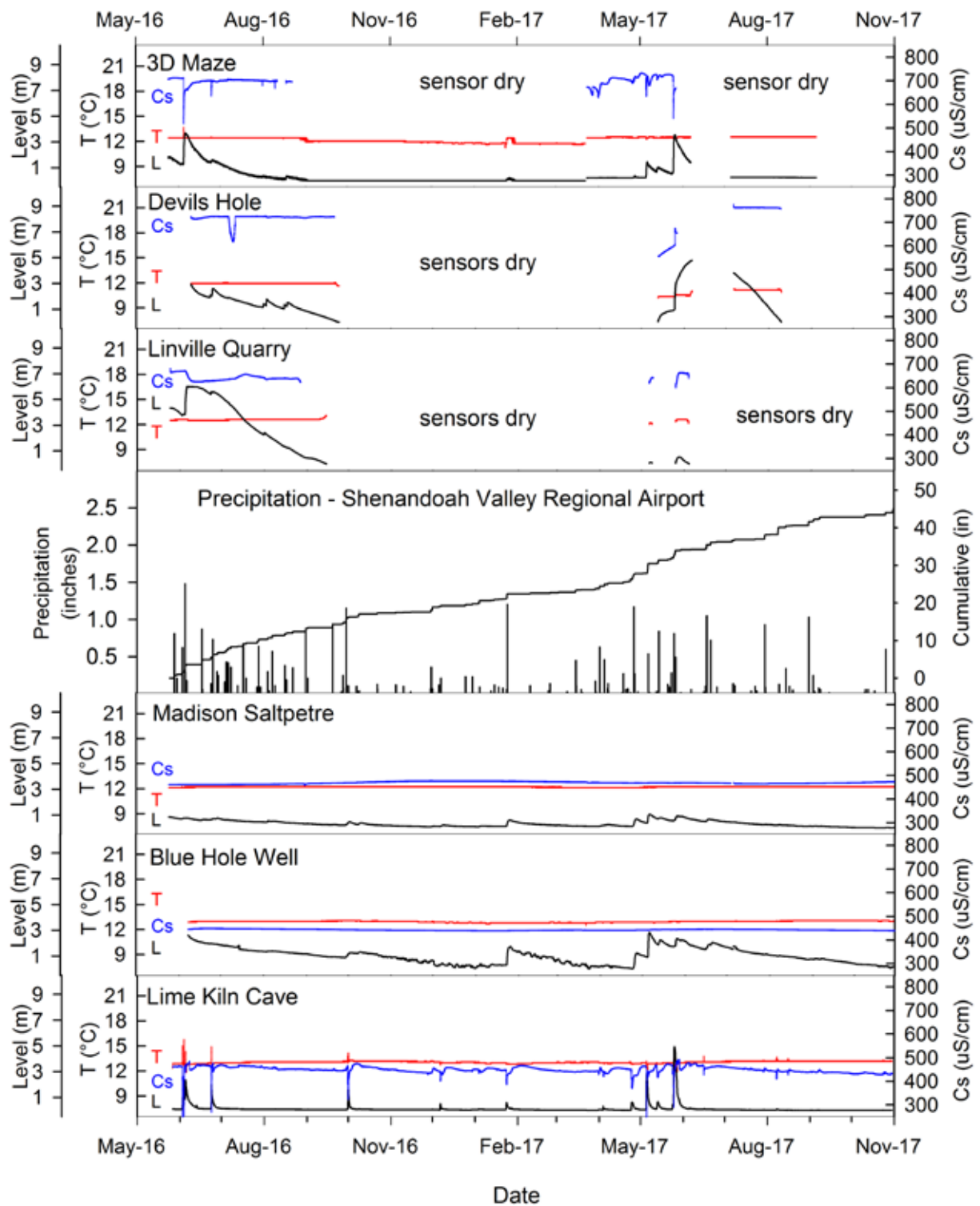


Figure 4. Time series data responses to precipitation events, Southern sites.

Front Royal Caverns exhibited temperature increases in response to precipitation events regardless of the season, but these increases were followed immediately by decreases in response to larger precipitation events during the cold season. Lime Kiln Cave exhibited a similar hybrid response to that of Front Royal Caverns. Meade Church Well showed a minimal response to a handful of the larger precipitation events, while Madison Saltpetre Cave, Blue Hole Well, Irvin King Well, and Ballfield Well showed no temperature response to any precipitation events. Incomplete datasets at Devils Hole and Linville Quarry caves showed no clear temperature response to precipitation events. The largest temperature increase response to a precipitation event was at Power Plant Pit, ~9°C on July 31, 2016. The largest temperature decrease was also at Power Plant Pit, ~7°C on January 23, 2017.

Specific conductance values responded to precipitation events at all but two sites, Madison Saltpetre Cave and Ballfield Well. Groundwater in Power Plant Pit significantly decreased in specific conductance in response to precipitation events, as did Irvin King Well and 3-D Maze Cave. Both Lime Kiln Cave and Brother Daves Cave reacted to most precipitation events with a negative spike followed by a small increase in specific conductance. Front Royal Caverns generally showed a spike in specific conductance after precipitation events, followed by decay to a different conductance value than prior to the event. Meade Church Well responded irregularly to precipitation events, generally decreasing after precipitation, but increasing after some of the larger, winter events. Ballfield Well exhibited only very small changes (<30 $\mu\text{S}/\text{cm}$). Data was insufficient to evaluate response at Devils Hole and Linville Quarry caves, though both show evidence of some response. The largest change at a site following a precipitation event was a decrease of 530 $\mu\text{S}/\text{cm}$ at Power Plant Pit on September 30, 2016, while Front Royal Caverns (9/30/2016) and Meade Church Well (1/23/2017) both showed increases of ~200 $\mu\text{S}/\text{cm}$ after larger precipitation events.

Table 3 summarizes responsiveness characteristics of monitoring sites. Devils Hole and Linville Quarry had insufficient data to characterize overall response to precipitation, while Howard Tabb well was excluded due to apparent influence from well pumping and maintenance. All ten remaining sites showed water level changes in response to precipitation, seven exhibiting rapid rises, and three more moderate rises. Of the rapidly rising sites, three had levels return quickly to pre-event levels while another three showed more gradual water level falls after events. Seven sites showed changes in specific conductance, three negative, one positive,

and three with compound responses. Six sites showed temperature changes: three seasonal, two positive, and one compound.

Geochemical analyses are displayed graphically on the Piper diagram in Figure 5. Raw water analyses are available from the author upon request. All samples plot as calcium-magnesium-bicarbonate type waters. Samples from Front Royal Caverns, Meade Church Well, Linville Quarry Cave, and Power Plant Pit exhibit slightly elevated chloride, sodium and sulfate levels. Total dissolved $(\text{Ca},\text{Mg})^{2+}$ concentrations ranged from 1.8 to 4.1 mmol/L, with dissolved organic carbon ranging from 4 to 9 mmol/L. Figure 6 shows dissolved organic carbon (DIC as HCO_3^-) plotted against $(\text{Ca},\text{Mg})^{2+}$. Molar ratios were generally grouped by site, with several sites exhibiting variation across sampling events. The more alkaline waters were observed at Devils Hole Cave, 3-D Maze Cave, and the Howard Tabb Well. Samples from Blue Hole Well, Lime Kiln Cave, and Madison Saltpetre Cave exhibited consistently lower alkalinity values.

Chloride and nitrate levels are depicted in Figure 7. Chloride and nitrate concentrations in the sampled groundwater sites.. Chloride levels ranged from 2 to 63 mg/L, grouped by site with some sites exhibiting seasonal variation. Higher chloride values were measured at Front Royal Caverns, Linville Quarry Cave,

Site	Water Level	Temperature	Specific Conductance
3DC	fast	seasonal	Strong -
BDC	Fast rise, fast decay	+, larger events	- then +
DHC	fast	Insuff data	Insuff data
FRC	Fast rise, fast decay	+ then -	Strong +
LKC	Fast rise, fast decay	seasonal	- then +
LQC	fast	Insuff data	Insuff data
MSE	Rise then slow decay	none	none
PPP	Fast rise, slow decay	seasonal	Strong -
BFW	Rise then slow decay	none	negligible
BHW	Rise then slow decay	none	none
IKW	Fast rise, slow decay	none	Strong -
MCW	Fast rise, slow decay	Weak +	variable

Table 3. Site groundwater responses to precipitation. Site abbreviations listed in Table 1.

Meade Church Well, and Power Plant Pit. Lower chloride values were observed at Madison Saltpetre (East Lake), Brother Daves, and Lime Kiln caves. Nitrate (N) levels ranged from 1 to 12 mg/L, grouped by site with some sites exhibiting seasonal variation. Higher nitrate values were Irvin King and Howard Tabb wells in spring and summer, respectively. Nitrate values were consistently low (<2 mg/L) at Madison Saltpetre (East Lake), Lime Kiln, and Front Royal Caverns.

Variability in the water isotope compositions of the phreatic ground water samples collected in this study is small. The average $\delta^2\text{H}$ and $\delta^{18}\text{O}$ compositions of all the sites overlap with the winter season (Nov-April) amount-weighted precipitation measured at Grottoes, Virginia (Figure 8. Stable isotope composition of precipitation collected at Grottoes, Virginia in 2016 compared to the groundwater samples collected in this study.,) and the mean $\delta^{18}\text{O}$ value of -7.9 ± 0.3 per mil coincides with the mean value of drip waters collected in Grand Caverns (see Benton and Doctor, 2018, this volume.)

Precipitation samples fall on a local meteoric water line (LMWL) that closely parallels the global meteoric water line (GMWL). The average value of mean annual amount-weighted precipitation, and the value of amount-weighted precipitation for the late winter and early spring months of January, February, March, and April (JFMA) are plotted on Figure 8. Stable isotope composition of precipitation collected at Grottoes, Virginia in 2016 compared to the groundwater samples collected in this study. for reference.

Site occupancy results are displayed in Figure 9. Site occupancy over the duration of this study of known *Antrolana lira* sites by taxon, habitat access (cave or well), and method of sampling (t – trapping, v – visual observation or collection).. Results expressed as percent of events when taxon was detected $\pm$ standard error. Source data is displayed in the table below the histogram as number of sampling events during which taxon was observed. Overall, *A. lira* was more likely to be detected in a cave using trapping and visual surveys (50%) than in

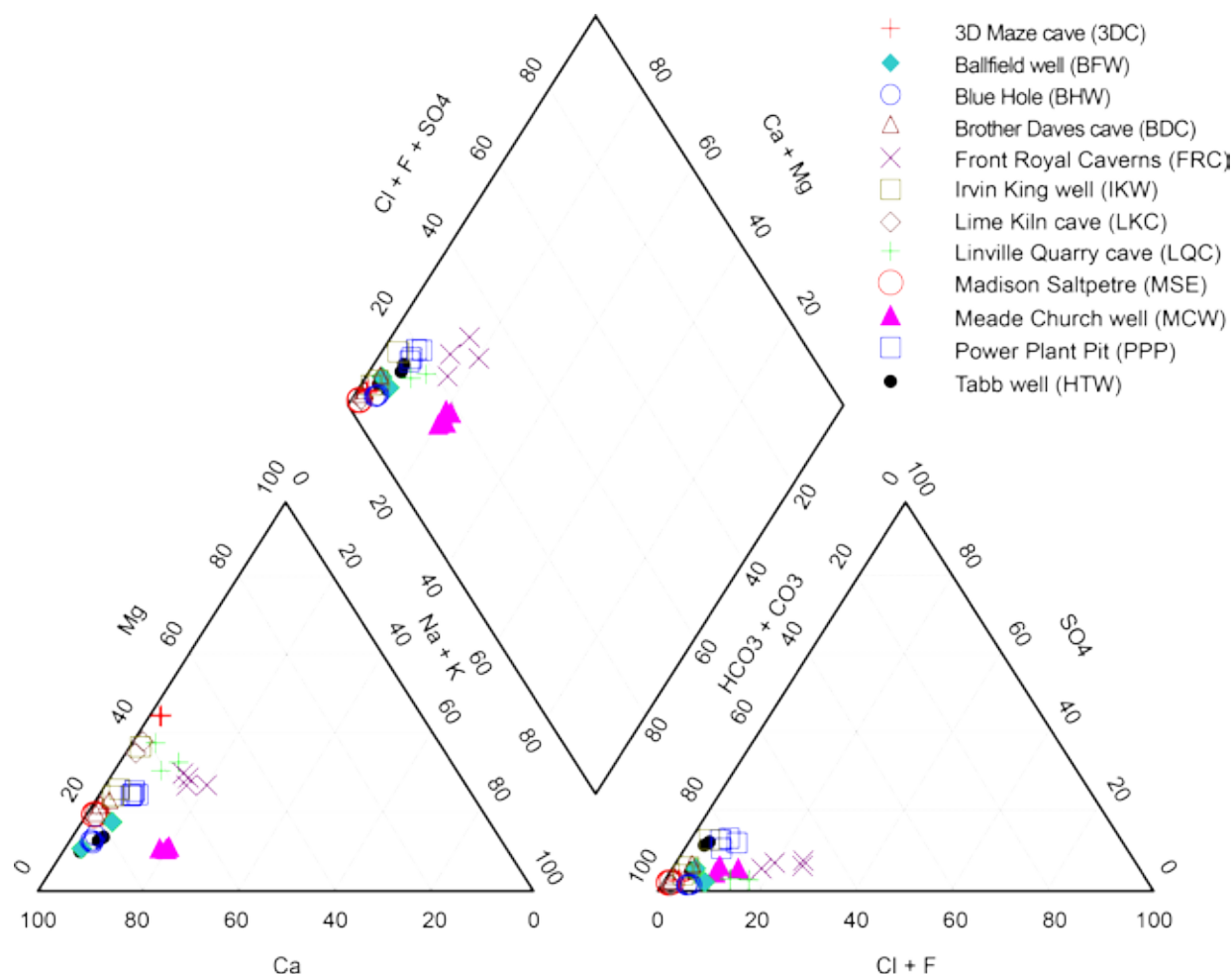


Figure 5. Piper diagram illustrating the distribution of the groundwater samples according to major ion chemistry.

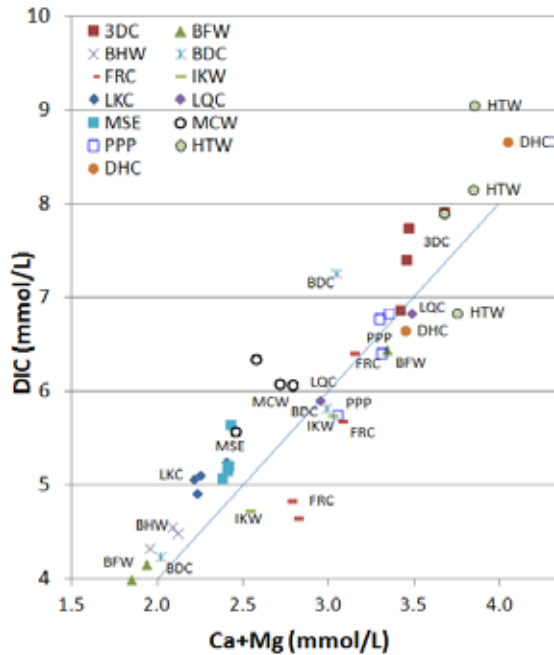


Figure 6. Concentrations of dissolved carbonate minerals for each sample.

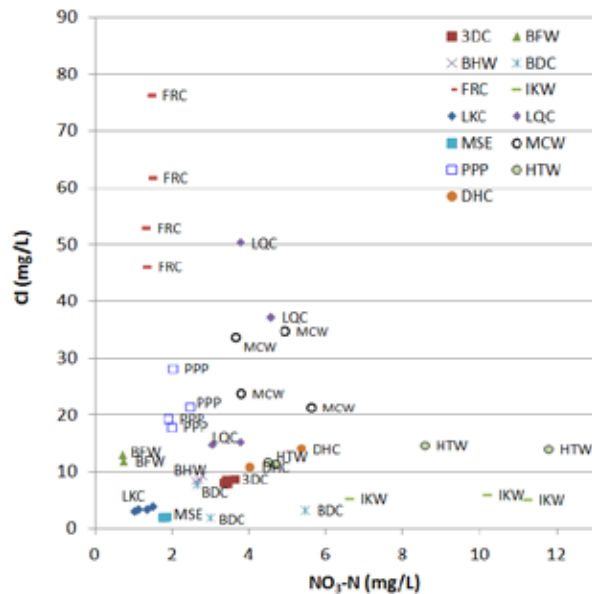


Figure 7. Chloride and nitrate concentrations in the sampled groundwater sites.

wells using baited traps (14%). Baited traps were more effective capturing *A. lira* in caves (32%) than in wells (14%). Both large and small specimens of the amphipod genus *Stygobromus* exhibited similar site occupancy patterns. Asellid isopods of the genus *Caecidotea* were detected visually in many caves near the intersection of vadose and phreatic waters, but were only trapped successfully 5% of the time. Groundwater planaria were collected in a single trapping event.

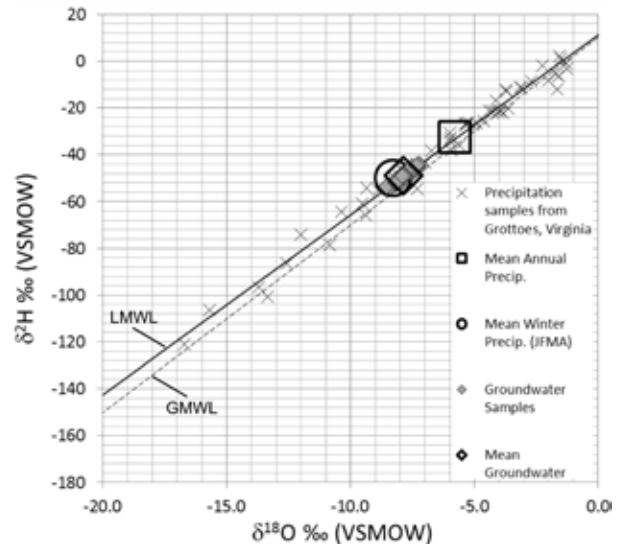


Figure 8. Stable isotope composition of precipitation collected at Grottoes, Virginia in 2016 compared to the groundwater samples collected in this study.

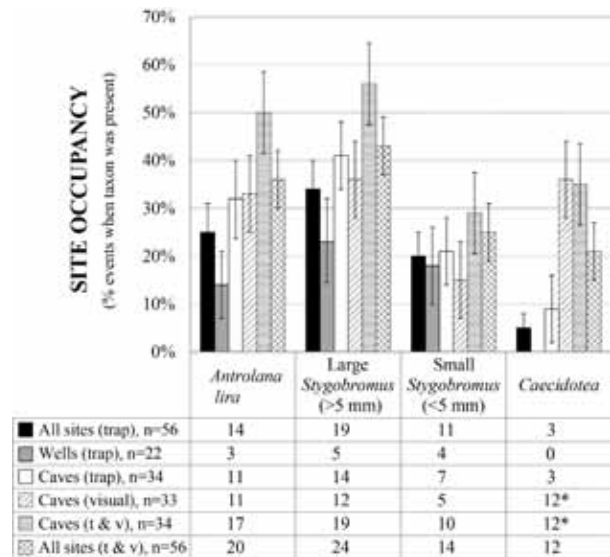


Figure 9. Site occupancy over the duration of this study of known *Antrolana lira* sites by taxon, habitat access (cave or well), and method of sampling (t – trapping, v – visual observation or collection).

Table 4. Site occupancy by site and species (0* indicates previously known from site but not present over the duration of this study; **includes vadose zone observations.) *Stygobromus* species are 1–gracilipes, 2–biggersi, 3–stegerorum, 4–baroodyi, ?–undetermined; C are *Caecidotea* species isopods. Site abbreviations listed in Table 1. presents a breakdown of stygobitic crustaceans observed by site and species. Stygobitic crustaceans were detected at least once from all sampled

Site	N	A. lira	Stygobromus species					C
			1	2**	3	4	?	
Caves:								
3DC	5	0*	2	NA	NA	NA	1	0
BDC	3	0*	3	0	NA	NA	NA	3
DHC	3	3	3	NA	NA	NA	1	1
FRC	5	2	3	?	NA	NA	1	0
LKC	5	0*	NA	NA	NA	1		4
LQC	5	4	3	NA	NA	NA	0	0
MSE	4	4	1	NA	4	NA		0
PPP	4	4	3	1	NA	NA		4
Wells:								
BFW	3	2	1	0	NA	NA		0
BHW	5	0*	1	NA	0*	NA		0
HTW	5	0*	2	0	NA	NA		0
IKW	4	1	0	1	NA	NA		0
MCW	5	0*	1	3	NA	NA		0

Table 4. Site occupancy by site and species (0* indicates previously known from site but not present over the duration of this study; **includes vadose zone observations.) Stygobromus species are 1–gracilipes, 2–biggersi, 3–stegerorum, 4–barodyi, ?–undetermined; C are Caecidotea species isopods. Site abbreviations listed in Table 1.

sites. Madison cave isopods were observed at seven of the sites, one or more amphipod species were observed at all thirteen sites, and *Caecidotea* species isopods were observed at four of eight cave sites. *Caecidotea* species are benthic and difficult to trap in wells, so the lack of capture should be interpreted as a failure to detect rather than as absence from the habitat. Madison Cave isopods were detected at all sampling events at Madison Saltpetre Cave, Power Plant Pit, and Devils Hole. Highest species diversity was observed at Devils Hole (4) and Power Plant Pit (4.) No more than two crustacean species were observed from any of the wells during this study, though a total of three species are known from Meade Church Well (Orndorff and Hobson, 2007).

Discussion

Time series data for level, temperature, and specific conductance portray a high degree of variability among sites in terms of the immediate influence of surface water on phreatic habitat. Madison Saltpetre Cave, Blue Hole Well, and Ballfield well exhibit relatively slow rises in water levels after precipitation events, with zero to negligible changes in temperature or specific conductance. These sites are highly isolated from immediate surface water influences and were geochemically and thermally stable over the course of

the study. By contrast, Power Plant Pit, 3-D Maze, and Lime Kiln caves showed seasonal temperature responses and negative changes in specific conductance indicating direct and rapid connection to surface drainage. The remaining sites exhibited more complex responses, suggesting that multiple flow paths delivered a combination of surface water and displaced groundwater to these monitoring locations. The displacement component in particular resulted in such seemingly paradoxical responses as the increase in temperatures at Brother Daves Cave and Front Royal Caverns following precipitation events, even in winter. The temperature increases were accompanied by decreases then increases in specific conductance at Brother Daves Cave as water from different flow paths arrived at the monitoring site.

Baseline temperatures across the study area show no obvious geographic trends, suggesting that variations are likely due to differences in depth and rate of groundwater circulation across sites.

The variability in baseline temperature and conductivity values, water chemistry, and response to precipitation events, even over short distances, supports the notion of a highly compartmentalized phreatic zone. For example, the water filled fissure passages in Brother Daves Cave and Power Plant Pit, separated by ~100m horizontally, have respective median temperature values of 12.2 and 13.6°C and conductivity values of 607 and 726 $\mu\text{S}/\text{cm}$. Water chemistry is distinctly different between the sites as well (Figure 5, Figure 6, Figure 7. Chloride and nitrate concentrations in the sampled groundwater sites.) A physical survey performed in 2002 showed the water level in Brother Daves Cave to be approximately four meters higher than that in Power Plant Pit (Orndorff, 2016a, 2016b). Such thermal, chemical, and physical gradients could not be supported over such a short distance within the phreatic zone, requiring that any connection between these two sampling locations is highly circuitous and intermittent. The difference in patterns of response to precipitation between these two sites is further evidence of their isolation under most conditions. An alternative hypothesis to explain these observations is that the sump lake in Brother Daves Cave is the result of rising phreatic waters trapped in a vadose passage following larger recharge events, stranding stygobitic fauna from the phreatic zone and mixing with local epikarstic recharge and direct recharge from smaller precipitation events. However, temperature increases in the Brother Daves Cave sump in response to most precipitation events, regardless of season, support a more continuous connection to deeper, phreatic water, favoring the hypothesis of compartmentalized phreatic zones.

As shown in Figure 5, waters in the study area are typical of karst groundwaters around the world. Major carbonate mineral ions at all sites plot near the $(\text{Ca,Mg})^{2+}$ versus HCO_3^- line.

Chloride and nitrate levels reflect nearby land-use activities affecting the groundwater at the sampling sites (Figure 7. Chloride and nitrate concentrations in the sampled groundwater sites.). Those sites that show higher chloride levels (>15 mg/L) are likely affected by salt in road runoff or other sources of chloride from land use activities. These sites include Front Royal Caverns, Meade Church well, Power Plant Pit, and Linville Quarry. Front Royal Caverns lies directly beneath and adjacent to US Route 340 just south of Front Royal. Meade Church well is in the hamlet of White Post immediately adjacent to US Route 340 in Clarke County. Power Plant Pit lies along a swale that receives discharge from several industrial stormwater management facilities. Linville Quarry Cave has no obvious connection to a source of elevated chloride.

The nitrate data help to identify sites with some possible agricultural contamination. Only two sites, Irvin King well and Tabb well, exceeded the drinking water standard of 10 mg/L nitrate as N. Irvin King well lies immediately adjacent to a several hundred acre cornfield, and Tabb well is ~100 meters down gradient along a swale from an active barnyard. Background nitrate concentrations of most groundwater in the carbonates of the Appalachian Great Valley aquifer vary between 2.0 to 5.0 mg/L nitrate as N (Lindsey et al., 2009). Sites that fall consistently below that level are likely to be unaffected by local surface agricultural activities. Such sites include Lime Kiln Cave, Madison Saltpetre Cave (East Lake), Front Royal Caverns, and Ballfield well.

The consistent isotope composition results across sites and sampling events indicate that cool-season precipitation supplies the majority of recharge to the greater aquifer at large, supporting previous conclusions about the strong seasonality of epikarstic recharge from work done at James Cave (Eagle et al., 2015), and in Grand Caverns (Benton and Doctor, 2018, this volume). This suggests that the majority of the water in the aquifer in long-term storage originated as precipitation stored in and subsequently discharged from the epikarst. The influence on overall recharge by surface water bypassing the epikarst and directly entering the phreatic zone, as documented at several sites in the time series data during summer months, appears relatively minor. However, such bypass flow can introduce disproportionate amounts of contamination into the aquifer locally as a function of land use practices.

No relationships of site occupancy or stygobitic crustacean diversity to time series data or geochemistry were apparent in this study. Two of the three sites with 100% site occupancy by the Madison Cave isopod were Madison Saltpetre Cave and Power Plant Pit, which comprise the two end members of study sites in terms of degree of variability and surface water influence. However, caution should be used in interpreting this result. Abundance was not considered as part of this study, and greater numbers of Madison Cave isopods are regularly present at Madison Saltpetre Cave than at Power Plant Pit. Furthermore, in prior studies isopods exhibited much lower site occupancy at Power Plant Pit than at Madison Saltpetre Cave (Orndorff, 2014a, 2014b). While Madison Saltpetre Cave should still be considered the highest quality and best protected site for the Madison Cave isopod, this study clearly shows that it and other associated stygobionts tolerate a wide range of geochemical and hydrological conditions, and continue to persist at sites with ongoing negative impacts from land use practices.

This study demonstrates the value of combining high resolution time series data with geochemical analyses and biological monitoring to characterize karst groundwater systems. Phreatic karst aquifers developed within the carbonate bedrock of the Great Valley exhibit complexity and heterogeneity both in terms of baseline chemical and physical parameters and the nature and degree of response to precipitation events. Increased collection and analysis of such data would facilitate better decisions in regards to both aquifer management and habitat conservation.

Acknowledgements

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COLD-AIR TRAP TEMPERATURE RECORDS SUPPORT SIMPLE HIGH-DENSITY AIR-FLOW MECHANISMS AT AN APPALACHIAN LIMESTONE CAVE ENTRANCE SINKHOLE

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Abstract

Many Appalachian caves act as cold-air traps, widely open systems chilled by high-density cold air during chilly weather that evolve into density-stratified, nearly closed systems in warm weather. Like algific talus slopes, rock cities, and other cold-air traps in the region, these caves appear to function in accordance with a simple natural refrigeration model popularized by Balch (1900), in which circulation is dominated by static, thermally stratified conditions episodically disrupted by sinking cold air. Crowder Cave, in Monroe County, West Virginia, hosts two separate cold-air traps, a small room and a large room, both contiguous to an entrance pit, a ~12,000 m³ sinkhole surrounded by 6 to 18 m high limestone cliffs. The sinkhole and both cave rooms are poorly connected to surface runoff and subsurface water flow. Davies (1958) reported historical accounts of seasonal ice in the small room as late as July, but our temperature monitoring indicates ice regularly has disappeared by late April in five of the last six years. The entrance pit functions as a relatively open cold-air trap system with a mean annual temperature of ~7°C, well below mean annual air temperatures of ~10°C recorded at nearby weather stations. In summer, both cave rooms are virtually closed systems with gradual (<0.1 to 0.2 C°/day) temperature increases; neither had a reading >9.2°C during our monitoring. In stark contrast, both rooms often experience winter episodes of rapidly plunging (4 to 8 C°/day) temperatures, dipping as low as -13 to -15°C. Icicles, columns, frozen lenses, and other ice accumulations have been observed in the small ~350 m³ room at the northeast end of the cave, where five-year mean temperature was ~2.6°C. Ice stalagmites and other ice forms have been seen on the floor of the large ~12,000 m³ room on the south end of the pit, where the mean temperature was ~3.4°C.

Entrance pit temperatures respond very quickly when atmospheric conditions are appreciably colder than existing air in Crowder Cave; temperature trends in the two rooms seldom lag more than 1–3 hours behind. Despite similar timing, the amplitude of temperature response in the large room is markedly less than in the small room, presumably because of a 35-fold difference in room volume. The amplitude of temperature change decreases and mean temperature increases with distance from the mouth of the large room. More characteristic of typical cave conditions, temperatures near the end of a narrow 85 m long side passage varied little (9.8° to 10.6°C) over the last 4.5 years. Crowder Cave data show the interplay between density-driven cold-air flow, karst topography, and cave geometry lead to variability in winter conditions that may give rise to very different bat hibernacula conditions in a single cave. The ecological significance of cold air traps associated with sinkholes may be profound, both as climate change indicators and for a potential role they may play in the course of the ongoing white-nose syndrome (*Pseudogymnoascus destructans*) epidemic.

Introduction

Edwin Swift Balch (1897, 1900) introduced the phenomenon of freezing caverns, or *glacières naturelles*, to the American speleological community, describing examples of caves he observed in Europe and over a dozen freezing sites in the Northeastern United States and Iowa. Although most of Balch's American sites were "freezing talus", his discussion of a freezing mechanism focused on caves (Balch, 1900). After dispelling other proposed mechanisms, he championed "The Winter's Cold Theory" in which "cold air of winter sinks into and permeates the cave" leading to the formation of ice, which, sheltered from summer heat by the cave, long

outlasts ice in the surrounding landscape. Balch (1900) continued “The only effect of the heat of summer is to melt the ice.”

Balch (1900) noted that other scholars had put forth similar mechanisms for cold air traps as early as the 16th Century. An intriguing forerunner was C.B. Hayden (1841, 1843), who advocated a similar model for ice formation in Ice Mountain talus, Hampshire County, West Virginia. Hayden explained the Ice Mountain freezing mechanics as the “familiar principle upon which is constructed the common refrigerator”, enhanced by poor thermal conduction properties of the sandstone talus.

Balch (1897, 1900) differentiated between static freezing caves, dominated by thermal stratification of cold air, and dynamic cold-current caves, a.k.a. wind-holes, from which dense cold air pours out in the summer, followed by a reversed flow of cold air drawn into the cave because of chimney effects during the winter. Balch recognized “wind-holes do not seem to necessitate the presence of ice”, and thus, they were not considered freezing caves.

Studies of freezing caves continued after Balch, but discovery of a “living fossil”, the Iowa Pleistocene Snail (*Discus macclintoki*), drew attention to the ecological significance of freezing talus and freezing caves (Frest, 1981, 1991). The snail was known from Pleistocene deposits in the Midwest, but Frest (1981) recognized living *Discus macclintoki* and other cold-adapted plant and animal species survived in relict boreal refugia on cold-air producing hillslopes, which Frest named algific talus slopes. Frest (1991) documented >300 sites in

Iowa, Wisconsin, Illinois, and Minnesota, and noted they occur where talus accumulations cover *glacières* created by “mechanical karst” developed on carbonate bedrock last glaciated >130,000 years ago. Frest (1981, 1991) championed an algific talus circulation model similar to the dynamic two-way flow system Balch (1900) proposed for wind-holes, wherein the partial vacuum created by a chimney effect is responsible for drawing cold air into the slope during winter.

A long-term goal of our research has been to assess whether Central Appalachian cold-air traps follow the largely one-way static cave/natural refrigerator air-flow model of Hayden (1843) and Balch (1900) or the seasonal two-way model favored by Frest (1981). Studies (Edenborn et al., 2012; Kite and Tudek, 2014, 2017) show static thermal stratification by cold air density best explains low temperatures and ice formations at several Appalachian talus and an ice mine site in Pennsylvania. The main goal of this study is to examine which airflow model best applies to Central Appalachian freezing caves, specifically a relatively simple limestone cave system with a large open sinkhole entrance.

Crowder Cave

Crowder Cave (Figure 1) is a periodically freezing cave with two separate cold air-trapping rooms connected to a single ~12,000 m³ sinkhole in Monroe County, West Virginia (Balfour, 2011). Davies (1958) reported: “Ice has been collected by local residents as late as July” in the small room, but we saw no ice in visits on 9 July 2016 or 8 July 2017. We saw substantial ice in both rooms during visits on 8 January 2013 and 24 February 2014, a few melting ice accumulations in both rooms on

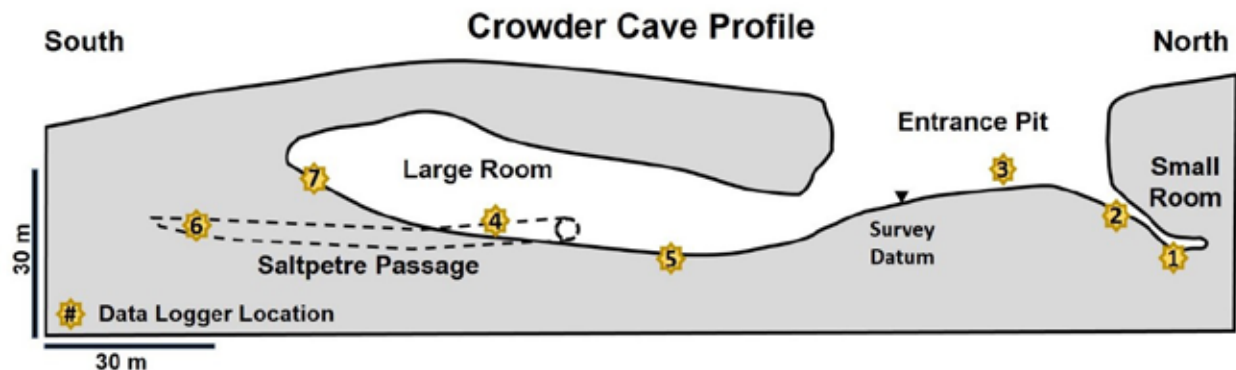


Figure 1. Crowder Cave profile showing data logger locations. Saltpetre Passage connects to large room, but aligned 30 to 90 degrees east of profile line. Cave profile is from Balfour (2011) elevation and ceiling height data; surface topography is based on Google Earth elevations.

25 April 2015, and tiny ice stalagmites in the small room on 13 November 2011. The upper rim of the sinkhole lies at about 632–633 m (~2075 ft) altitude, on a hillcrest ~100 m (330 ft) above Second Creek, the nearest perennial stream.

The cave lies in the lower Mississippian Greenbrier Group, but which subunit is uncertain. Davies (1958) reported the cave is developed at the top of the Patton Limestone, but Ogden (1976) mapped it at the contact between the Patton and the underlying Sinks Grove Limestone. Cherty layers in lower levels of the cave are typical of the Sinks Grove (White, 2018) suggesting cliffs that form the walls of the sinkhole and the ceiling of the cave may be in the lower Patton Limestone, whereas lower parts of the cave extend down into the upper Sinks Grove.

Limestone cliffs around the sinkhole perimeter vary from 6 to 18 m high. The sinkhole floor is covered by breakdown that slopes in opposing directions toward the two rooms. Extending northeast of the sinkhole, the small room has a volume of ~350 m³, while the large room southwest of the sinkhole has a volume of 12,000 m³ (Figure 2). The small room has a relatively flat floor that terminates in a 2 m high bedrock wall; the southern end of the large room rises to elevations higher than most of the entrance pit floor (Figure 1).

The ~1,000 m³ Saltpetre Passage runs ~85 m south from the large room, but the two rooms have no other substantial side passages (Balfour, 2011). No active stream channels are evident anywhere in the cave, although woody debris suggests occasional ponding at



Figure 2. Eight to 12 m high entrance to the large room, viewed from the sinkhole entrance pit. J. Tudek Photo

the lowest points in the two rooms. The most abundant cave sediment is breakdown, including fallen and toppled speleothems; intact speleothems are abundant in the small room. A dissected accumulation of oxidized chert-rich cobble-pebble gravel near the back of the large room show stream flow was once active within cave, but this through-flowing drainage system has been long-abandoned.

Both rooms are well connected to the atmosphere via the sinkhole entrance pit, but receive water largely through downward vadose flow through over-lying roof rock, with lesser influx near their entrances via indirect runoff from the sinkhole, ice fall and ice melt from the cliff faces, or drifting snow and errant precipitation. Compared to most caves in the region, the hydrology and thermal energy flux in Crowder Cave is only very weakly connected to groundwater.

Methods

Onset Computers Hobo Pendant 64 kb (UA-001 and UA-002) temperature loggers were installed in seven different Crowder Cave locations (Figure 1), based on local caver guidance, Davies's (1958) cave description, and field observations. Loggers were deployed on seemingly stable surfaces, wired to a fist-sized angular rock fragment to avoid displacement, flotation, or pilfering by caching animals, hidden from plain view to elude discovery by curious cavers. Measurement interval was 60 minutes. UA-002 light intensity data yielded little insight besides non-stop 0.0 readings at five sites.

Temperature loggers were installed at locations 1 through 5 on 11 November 2011. Initial deployment was planned to collect data from the entrance pit sinkhole (location 3) and locations very near the lowest points in the two cave rooms (locations 1 and 5). Location 2 was picked to assess air entering the small room, while location 4 was selected to assess temperatures a few meters above the floor, well away from the large room entrance. An on-site surface weather station was deemed unfeasible because of intense cattle grazing and unchaperoned recreational caving. Anomalous temperature readings led to two new logger deployments: location 6, near the back of the narrow, 85 m long Saltpetre Passage, on 8 January 2013; and location 7, at the highest readily accessible stable surface in the large room, on 24 February 2014.

All data loggers were most recently downloaded on 18 July 2017, except for a logger at location 3, last downloaded on 25 April 2015, which was inaccessible during our last two visits because of a downed tree. Location 2 was abandoned in July 2017 because of instability on its steep slope, but loggers are deployed at the other six Crowder Cave locations, adding to >350,000 temperature measurements made so far.

Loggers were exchanged at each deployment to avoid potential malfunctions inherent in optically down-loading data and servicing loggers in the cave environment. Loggers were later downloaded and serviced in an office environment. One logger at location 7 failed for >9.5 months, but records are otherwise continuous except for 1 to 2 hour periods of equilibration after each deployment for which anomalous readings were excluded from analysis. Manufacturer's data show measurements are accurate to $\pm 0.7^\circ\text{C}$, with resolution of $<0.2^\circ\text{C}$ over the temperatures seen in the cave. Time is accurate to ± 1 minutes/month. Lab calibration experiments show some loggers regularly read a few tenths of a $^\circ\text{C}$ above

or below others, so our protocol of switching loggers with each deployment adds to potential measurement inaccuracy. Differences between locations of $<1^\circ\text{C}$ may not be significant. Logger contact with rock surfaces may delay or reduce response to short-lived cold-air incursions, but probably by similar amounts for all of the similarly deployed loggers. Hence, we contend our data provide informative records of the timing and magnitude of responses to the thermal phenomena in the entrance pit sinkhole and Crowder Cave.

Site-to-Site Temperature Variations

The Crowder Cave temperature record (Figure 3, Table 1) is complex. Site to site variation is apparent, but partly obscured by seasonal trends aligned with (October to September) water-year cycles). Most locations responded quickly and similarly during autumn and winter, but much more gradually and disparately during spring and summer. The small room (location 1) and large room floor (location 4) are the coldest locations, with mean temperatures and standard deviations of $2.6^\circ\text{C} \pm 3.2^\circ\text{C}$ and $3.1^\circ\text{C} \pm 3.8^\circ\text{C}$, respectively. Neither

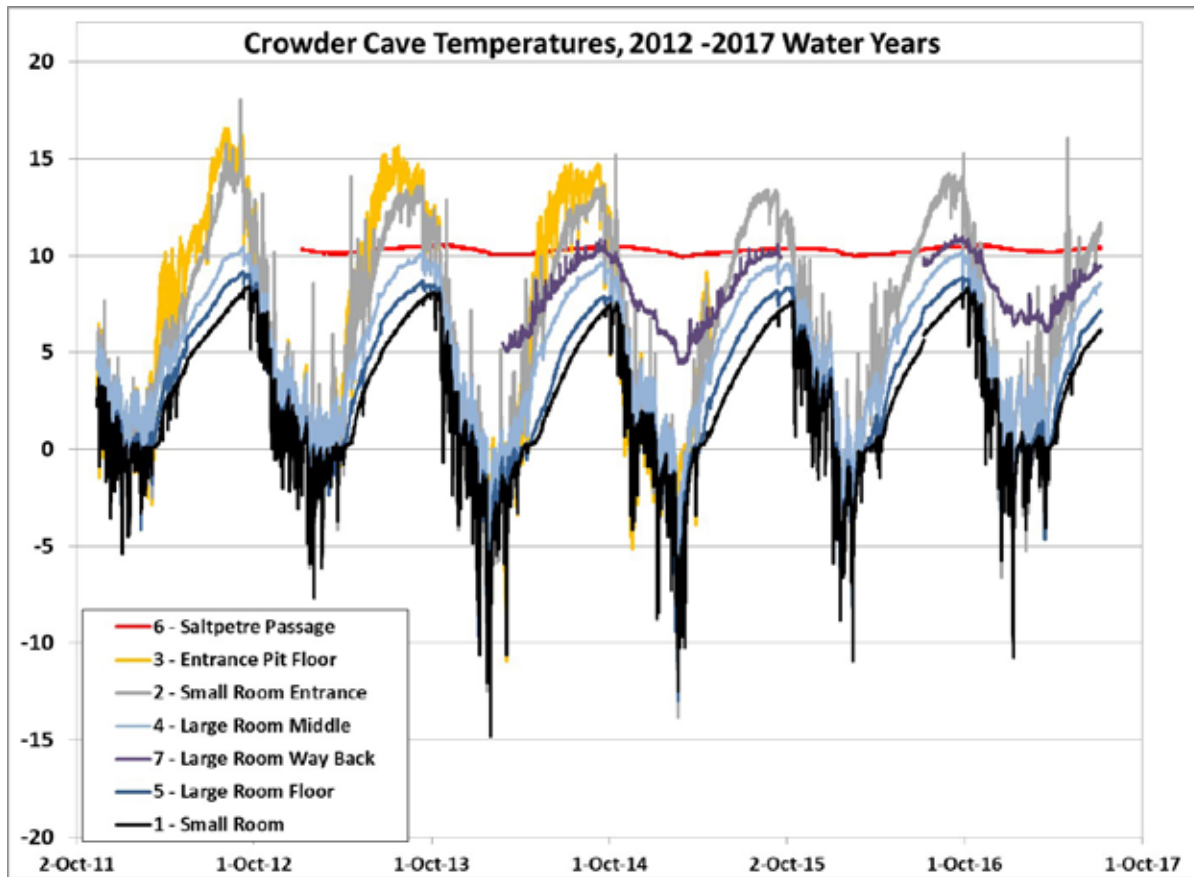


Figure 3. Crowder Cave temperatures, November 2011 to July 2017. Records at four locations are continuous over the period, but locations 3, 6, and 7 are less complete.

Location #	Temperatures °C			
	Mean	Max	Min	StDev
Small Room 1	2.6	8.4	-14.8	3.58
Small Rm Entr. 2	6.2	18.0	-14.5	5.22
Sinkhole Floor 3	6.2	16.5	-14.6	5.94
Large Rm Floor 5	3.1	9.2	-13.0	3.84
Large Rm Mid 4	5.0	10.5	-9.1	3.56
Large Rm Back 7	8.1	11.0	4.4	1.69
Saltpetre Passage 6	10.3	10.6	9.9	0.15

Table 1. Crowder Cave summary statistics. Location numbers match Figures 1 and 3.

site experienced a reading $>9.2^{\circ}\text{C}$, remaining below the 10.0°C mean annual temperature at a nearby Lewisburg NOAA weather station during every hour for ~ 5.7 years. (The Lewisburg station lies only 21 km north-northeast of, and about ~ 62 m higher than, Crowder Cave.) The entrance pit floor and small room entrance rose above 10°C for prolonged periods in late spring and summer and infrequently recorded temperatures $>15^{\circ}\text{C}$ during warm rainfall, but both had long-term mean temperatures of only 6.2°C . Variability decreases and mean temperatures

increase in the large room with distance from the entrance. The remote Saltpetre Passage recorded a mean of $10.3^{\circ}\text{C} + 0.15^{\circ}\text{C}$. Measurements ranged only from 9.8° to 10.6°C during the last 4.5 years, a pattern more typical of local caves.

The two colder locations lie in roof-sheltered, low-lying sites near a cave entrance adjacent to the entrance pit sinkhole. Although the sinkhole and small room entrance experienced similar minimum temperatures, they are higher on the landscape and much more exposed to wind, sun, and precipitation; thus, these exposed locations recorded temperatures approaching – but not reaching – ambient warm weather conditions. Data show the sinkhole acted as a discernable cold-air trap, but one more open and less stable than nearby low-lying cave locations.

Seasonal and Annual Variations

Data from the warmest and coldest years in our record for the small room and the large room floor (Figure 4) reveal the mechanics of these two cold-air traps,

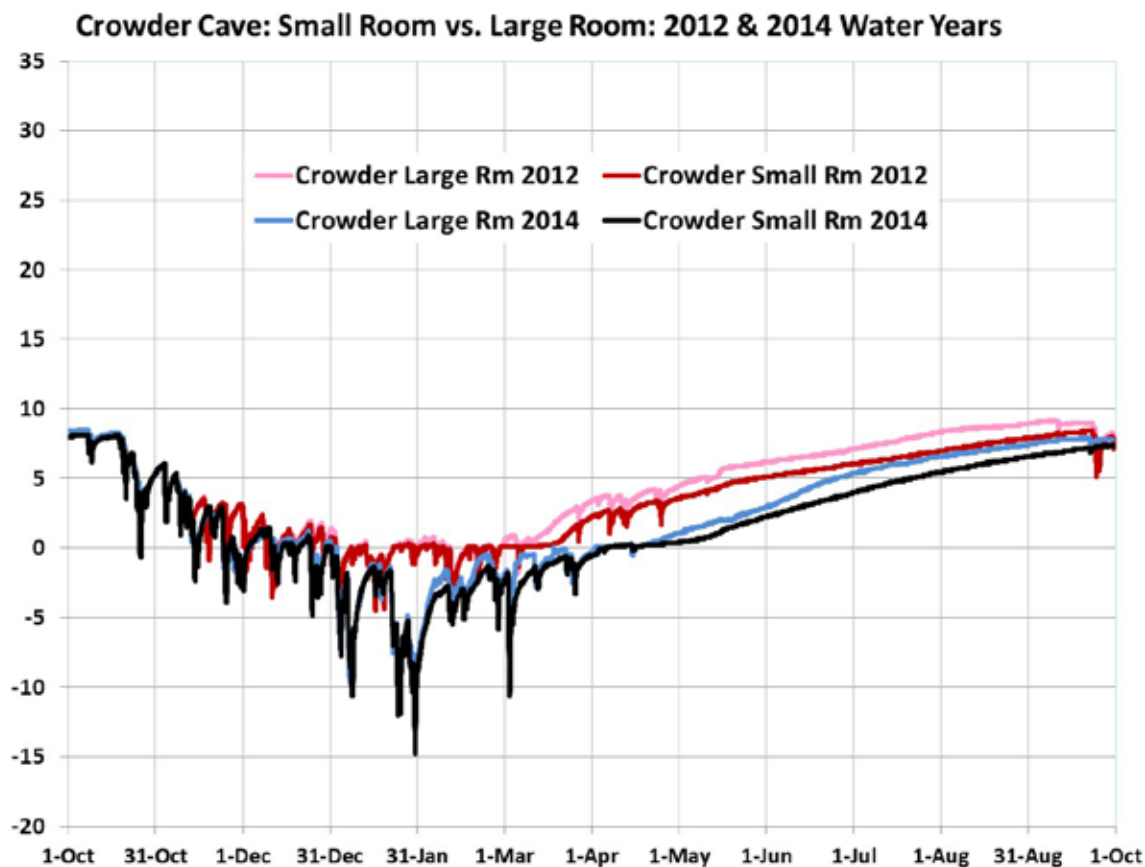


Figure 4. Temperatures at the two coldest Crowder Cave locations in an exceptionally warm early melt-out year (2012) and a colder late melt-out year (2014).

including ways these mechanics vary from season to season, year to year, and location to location. The timing of day-to-day fluctuations aligned well, but differences between the two locations were apparent both years. Each water year commenced with generally falling temperatures punctuated by sharp declines of up to 5 C° when cold outside temperatures triggered dense air flows into the cave entrances. Air circulation was an open system for much of this period, which continued well into both winters.

During the warmest year, 2012, winter minimum temperatures were nearly 10 C° above those of the coldest year, 2014, and very few cold snaps occurred after mid-January. Temperatures at the small room and large room floor locations hovered near 0°C for most of winter 2012, suggesting an unknown amount of ice moderated temperatures. An unprecedented heat wave began 1 March 2012 (Borth et al., 2012) and the large room floor temperatures began to rise immediately, but slowly, interrupted by very brief incursions of cool air over the next eight weeks.

The immediate warming of the large room coincident with warm weather suggests winter ice in the large room had already melted. The small room held ~0°C temperatures until ~20 March, when, apparently depleted of winter ice, it began an unusually early temperature climb. The next two months saw temperature rises of ~0.1 C°/day, which decreased to ~0.03 C°/day after 15 May. Both rooms remained closed stratified systems until cool air incursions near the end of the 2012 water year in September.

In the colder 2014 winter, both rooms were generally open systems, dropping to -15°C in late January and -11°C in early March. Our 24 February 2014 visit revealed significant ice in various forms in the small room (Figure 5) and numerous melting ice stalagmites in the large room (Figure 6). Icicles in the large room clustered on low ceiling near the entrance pit, while most ice stalagmites formed below unfrozen high-ceiling drip sources, >10 m above the floor.

Verifying IR temperature data and sensory perception during our visit, stabilized logger data two hours later showed location 7 was 6.0 C° warmer than location 5. A 4.4°C minimum temperature shows location 7, far back in the cave and 16.5 m above the low point in the room, never froze. With temperatures 2 to 18 C° warmer at location 7 than at location 5 during 2.5 years

of overlapping data, thermal stratification in the large room was incessant. Substantial ice in the cave probably helped maintain low temperatures later than usual during 2014. The large room floor rose above 0°C and began to increase significantly around 15 April, while a similar rise occurred about three weeks later in the small room, despite the latter's sunnier aspect. Thereafter, the two systems remained a thermally stratified, nearly closed system with an average rise of <0.05°C/day.

Relative to the large room, its delayed rise above 0°C during all years of record suggests the small room is a more effective cold-air trap, or its ice persistence is more dominant in its seasonal thermal progression. These two explanations are not mutually exclusive.

Short-Term Temperature Variations

Two four-day late-winter temperature plots (Figures 7 and 8) show how temperatures at cave locations respond to short-term outside temperature declines. A March 2014



Figure 5. Icicles and other ice growths in the Crowder Cave small room. J. Tudek photo.



Figure 6. Ice stalagmites in the large room. J. Tudek photo.

cold front triggered a straight-forward cave temperature response (Figure 7). Lewisburg NOAA data show a 12°C high temperature on 3 March, falling to -20°C on 4 March and -16.7°C on 5 March. No snow cover was reported until 5 cm fell on 3 March, growing to a 10 cm cover for the next two days. Six of seven Crowder Cave locations had temperature declines between 16:00 EST 3 March and 09:00 EST 4 March. Magnitude of change varied widely, but timing was similar at all locations. The open sites, the entrance pit and small room entrance, fell 11.1 and 9.5 C°, respectively, with daily minima 1 to 3 hours before other sites. Though temperatures at the two best cold-air trap locations were both -2°C on the afternoon of the 3rd, location 1 in the small room dropped 8.8 C° in the next 13 hours, outpacing location 5 on the large room floor, which declined only 5.7 C° to reach an event minimum an hour later. Farther from the big room entrance and slightly above the floor, location 4 began the period at +2 C° but dropped a similar 5.8 C° at nearly the same time as the lowest point in the big room. By 12:00 on the 4th, temperatures at locations 4 and 5 were

almost identical, and remained so for the next 24 hours. This equilibration suggests mixing of newly introduced air. Location 7, far back from the entrance and near the top of the large room had a mere 0.2 C° dip, but it occurred simultaneously with large temperature declines in parts of the cave directly linked to the atmosphere. Meanwhile, the remote Saltpetre Passage appeared unaffected by this cold front.

Modest cave temperature shifts occurred 5 March 2014, despite the fact that low outside temperatures at Lewisburg were >10 C° colder than any location in Crowder Cave. We are unsure why this was the case.

A succession of cold fronts led to a prolonged cold spell between 16 and 22 February 2014, with Lewisburg low temperatures reaching -17°C on the 18th, -20°C on the 19th, and -22°C on the 20th, a date when the high was only -17°C. A 23 cm snowfall on the 17th led to snow depths ranging from 20 to 23 cm over the period. Cold antecedent conditions meant this four-day period began

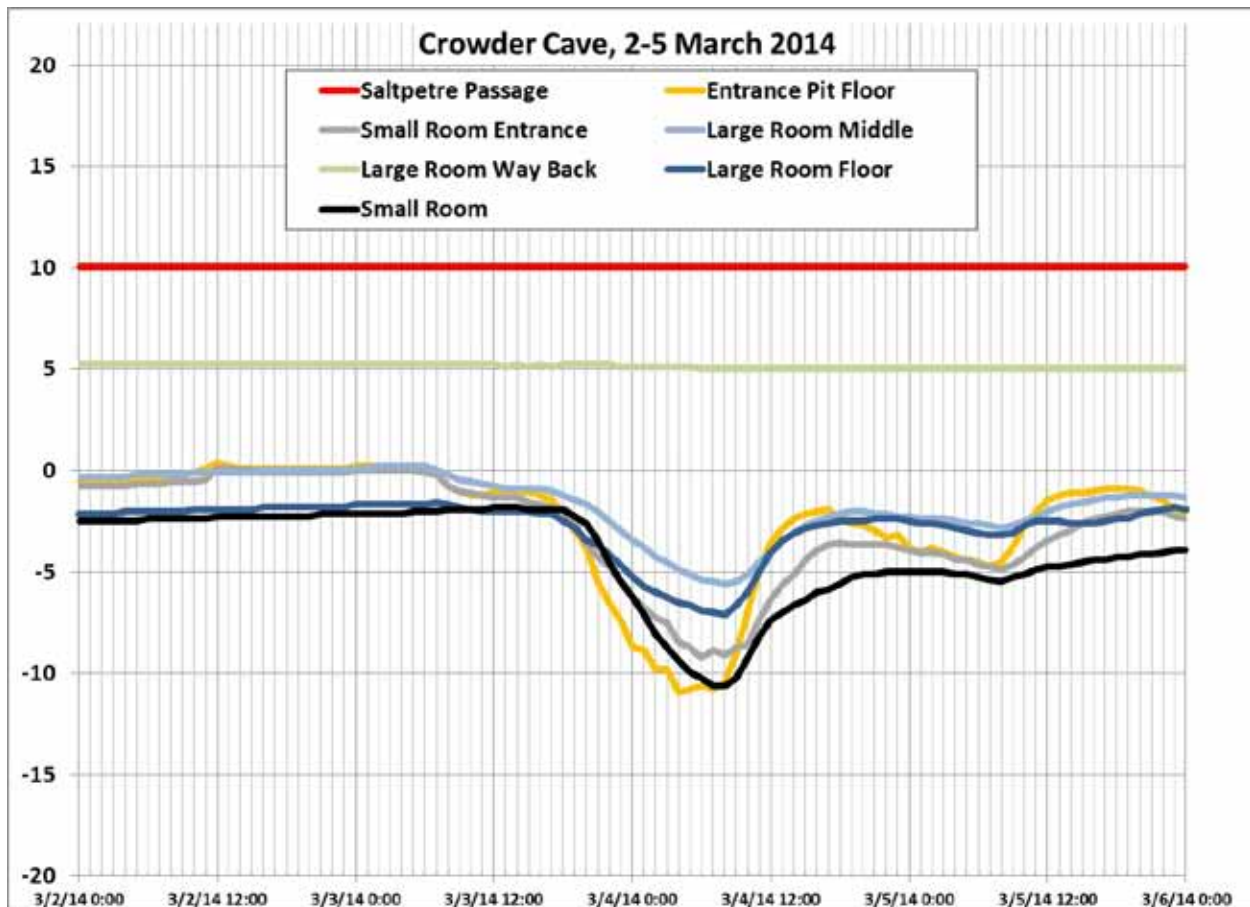


Figure 7. Crowder Cave response to two consecutive nights with unusually cold temperatures.

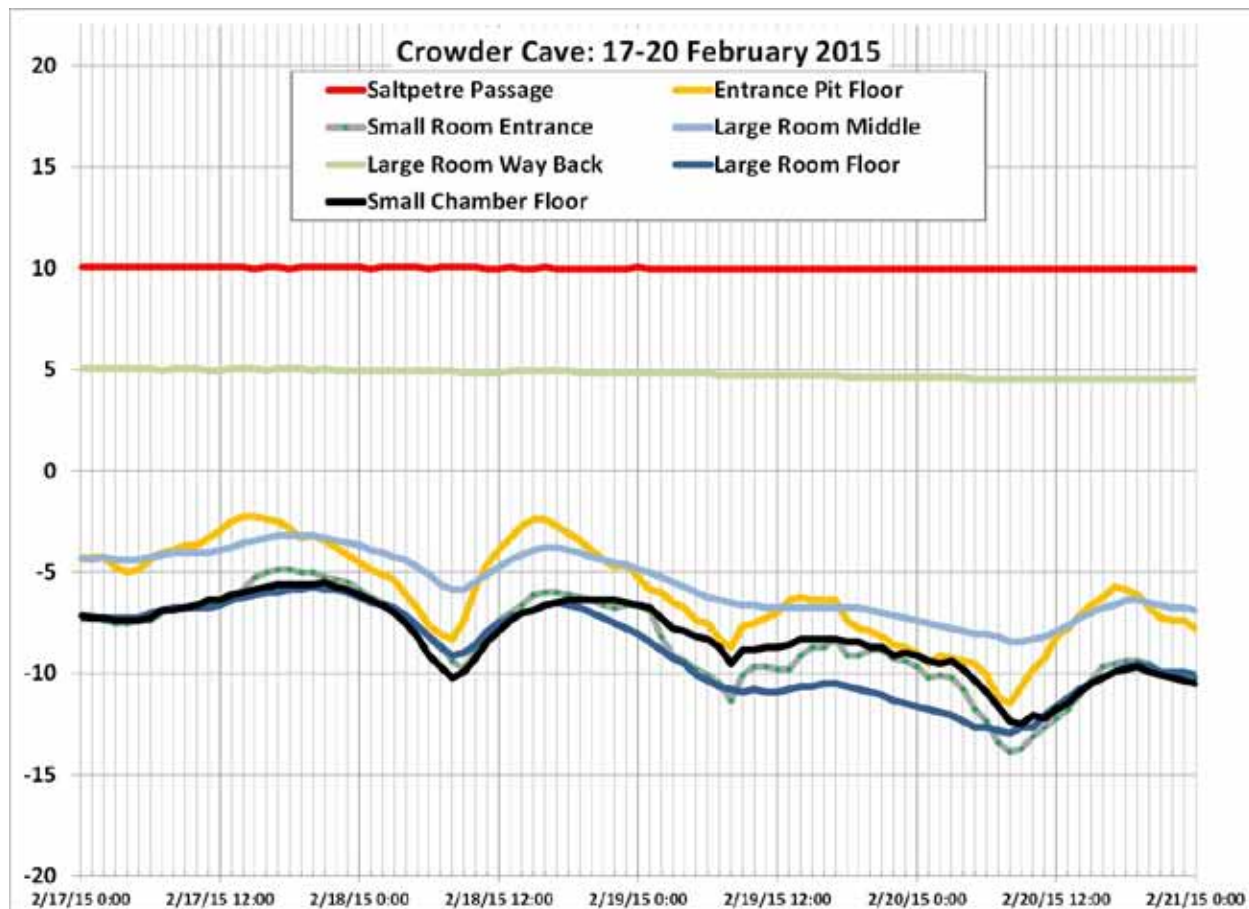


Figure 8. Crowder Cave response to a prolonged cold spell when highs did not exceed freezing.

with most of the cave about 5 C° colder than the March 2015 event, decreasing the potential for heat exchange from cave surfaces and sediments to fuel diurnal temperature rebounds.

The snow cover may have insulated the data logger in the unsheltered entrance pit from the coldest early morning conditions. The sinkhole experienced a 9.7 C° decline, but unlike most cold snaps, this location was warmer than three other locations for the entire four-day period. The small room entrance and the small room declined 9.0 and 7.0 C° over the period, vacillating in relatively similar patterns, which were more erratic than the locations in the large room. Location 5 temperatures declined only 6.6 C°, but were lower than the other sites for almost all of a 38 hour period, at times nearly 3 C° below that of the ordinarily colder small room. Unlike the March 2015 event, locations 4 and 5 temperatures had almost no convergence, suggesting strong thermal stratification and little mixing of air throughout the room. The thermal stratification increased as the outside

temperature hovered near –20°C on February 20th. Back in the cave, near the top of the large room, location 7 saw a 0.5 C° decline over 57 hours, while the normally constant temperature in Saltpetre Passage fell 0.1 C°.

Discussion

Crowder Cave is an example of a freezing cavern, or *glacière naturelles*, as described by Balch (1897, 1900). Its two chambers are connected by a sinkhole that acts as a cold air trap in its own right. The redundancy of the 15–18 m deep entrance pit sinkhole to provide significant shelter to the two cave entrances and serve as a first chamber for cold-air density stratification may explain why the thermal behavior of Crowder Cave differs so remarkably from most other caves in the region.

Cave temperatures, viewed over various timescales, point to density-driven cold-air flow into the cave as the key mechanism leading to cold temperatures and the formation of ice in the two Crowder Cave rooms. Shelter provided by the cave favors the persistence of thermal

stratification through subsequent warm atmospheric conditions, allowing the air to warm slowly and ice to last into warm weather. Continuous above-freezing conditions at upper levels of the large room show there is no seasonal chimney effect operating to draw cold air into the room entrance. Crowder Cave temperature data are consistent with the natural refrigeration model proposed by Hayden (1841, 1843) and the compatible Winter's Cold Theory widely articulated by Balch (1897, 1900).

The two four-day winter cold episodes (Figure 7 and 8) reveal that the two rooms act somewhat differently in spite of a similar refrigeration mechanism. The differences relate to chamber volume and the heat-sink role that ice provides in maintaining cold air. Although its opening to the sinkhole is smaller, the small room's ~350 m³ volume is more quickly filled by cold-air density currents during a cold episode. The ceiling in the room is only 2–3 m high, providing too little vertical space for distinct thermal stratification, so ice can form anywhere in the room once cold conditions are established. No space in the room is >25 m from the entrance, so there are opportunities for drifting snow or freezing rain to enter the chamber. A substantial fraction of the room may be occupied by ice during winter, and this ice may persist in the shelter of the cave for weeks or months after warm weather onset. The greatest limitation on the small room functioning as a freezing cave is that deep snow or seasonal ice buildup may partly block the flow of cold air into the room.

The huge large room entrance would be virtually impossible to block with snow and ice under any climate likely to have existed in the region since the end of the Younger Dryas, 11,500 years ago. The 12,000 m³ volume, considerable length and shape of the large room makes it very difficult to fill with cold air during a brief cold spell, although the February 2014 data show longer events effectively mantle lower portions of this room with very cold air. The 15 to 22 m ceiling heights, which rise well above the top of the cave entrance, provides an excellent chamber for density-driven thermal stratification, and make it very unlikely for ice to form on high surfaces in the room. Proportional to volume, there will always be less ice in the large room, providing less of a latent heat sink to maintain ice into warmer seasons.

Insights into Changing Cave Ecosystems

Davies's (1958) statement that ice has been collected from the small room as late as July contrasts with our July field observations and temperature records showing melt out typically occurs by late April. It is uncertain whether folklore about late-persisting ice reflects low winter temperatures, delayed seasonal warming, high snowfall, high winter precipitation, human ice management, or possible imprecise memory. Dated historical temperature measurements, photographs, and ice observations recorded in diaries or field notes may provide insights into whether or not Crowder Cave and other Appalachian freezing caves serve as bellwethers of changing climate.

Traditions of ice lasting much longer in the historical past compared to recent decades exist at many well-known freezing caves in the Central Appalachians. At face value, these traditions could be evidence of climate warming in the region (US Environmental Protection Agency, 1998). Although concerns exist over their scientific rigor, the abundance and wide geographic distribution of these accounts suggest there is something of substance to these traditions.

The ecological consequences of a reduction in the persistence of cave ice or the complete disappearance of freezing caverns would be unfortunate. Atypically cold caves may be refugia for relicts of Pleistocene ecosystems, similar to the manner in which some algalic talus slopes provide refugia for boreal flora and fauna (Frest, 1991; Lendemer et al., 2009). The density current and thermal stratification processes that lead to freezing caves may be highly important in numerous cave passages that are atypically cold, but not to the point of freezing. Such caves may provide temperature diversity in bat hibernacula, which may enhance conditions favorable to a variety of species, some of which have seen drastic declines from the ongoing white-nose syndrome (*Pseudogymnoascus destructans*) epidemic (Perry, 2013). White-nose syndrome isolates grow between 5 and 20°C, growing optimally at 12–13°C (Perry, 2013), so atypically cold caves may provide hibernacula in which some bat species may avoid extirpation and stage a recovery.

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INVESTIGATING VADOSE ZONE HYDROLOGY IN A KARST TERRAIN THROUGH HYDROGRAPH AND CHEMICAL TIME SERIES OF CAVE DRIPS AT GRAND CAVERNS, VIRGINIA

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Abstract

Caves provide useful access points for sampling and monitoring of vadose groundwater to better understand the hydrologic conditions controlling the timing and magnitude of critical recharge events. In this study, two cave ceiling drips within a single room at Grand Caverns, Virginia have been monitored simultaneously for changes in drip rate, electrical conductivity, and geochemistry from February 2014 to July 2017.

The results show distinctly different behavior in the discharge between the two drip sites. One site exhibits seasonal changes in flow rate while the other site has remained nearly constant at 0.018 L/h. The dynamic site has a lower flow regime during the summer, fall, and winter (0.004 L/h–0.008 L/h) until precipitation or snow melt events in the early spring triggered a sudden increase in discharge up to 0.328 L/h. There is an apparent volumetric soil moisture threshold of approximately 30% that must be exceeded before there is a response in the drip rate within the cave. Both the peak discharge rate and duration of the annual recharge period depends upon what time of year it occurs, with larger recharge events beginning in February and March and smaller recharge events occurring as late as April and May. This higher flow regime continues until the summer when an increase in evapotranspiration on the surface creates a soil moisture deficit that corresponds to a drop in discharge within the cave. This moisture deficit is usually not fully recharged again until winter and early spring when surface precipitation continues and evapotranspiration is low.

Stable oxygen and hydrogen isotopes of the drip water and of precipitation above the cave were measured as potential tracers for determining the seasonality of

recharge to the cave drips. Despite there being large seasonal shifts in the isotopic composition of rain waters collected above the cave, the oxygen isotope composition for both drip sites have remained nearly equal and constant at $-8.0 \pm 0.1\text{‰}$. This value is similar to the cool-season amount-weighted average of precipitation collected at the surface, and thus supports the hypothesis of a cool-season recharge bias to the drips.

Introduction

Monitoring groundwater within the vadose zone enhances the understanding of how aquifer recharge changes throughout each hydrologic season. Understanding rates of recharge into an aquifer is important for resource management and regional water budget calculations (Mathias et al., 2017). The flow rate of vadose waters in karst terrains can change quickly resulting in a sudden flux of water into the aquifer system. Cave drip water studies provide insights into processes controlling the characteristics of groundwater flow in karst terrains (Doctor et al., 2015). Many of the temporal changes in the discharge and chemistry of drip waters are the result of biological, chemical, and physical processes occurring above the cave within the soil zone and the soil-to-bedrock transition zone called the epikarst. The carbonate bedrock within the epikarst is highly weathered being subject to chemical dissolution from undersaturated, meteoric waters that are not only enriched in CO_2 from the atmosphere, but also from microbial respiration in the soil zone (Williams, 2008).

As a result, there is an abundance of secondary and tertiary porosity and a decrease in hydraulic conductivity at the transition from highly weathered bedrock to less weathered bedrock allowing for the temporary storage and mixing of waters within the epikarst (Eagle et al.,

2016). These features make the epikarst an important control on the physical and chemical characteristics of downward-penetrating vadose waters that ultimately take part in recharge to the regional karst aquifer (Schreiber et al., 2015). Below the epikarst the water either diffuses slowly through primary porosity and small fractures within the bedrock or transmits at a faster rate through enlarged conduits and caves (Lachniet, 2009). The purpose of this study is to use the chemical and physical changes of drip waters in a cave to learn more about the dynamics involving water transmission from the epikarst to the aquifer below. Specifically, this project tested the hypothesis of highly seasonal recharge to cave drips in the Great Valley of Virginia (Eagle et al., 2016).

Location, Geology, and Climate

Grand Caverns is a tour cave located in the central Appalachians on the eastern side of the Great Valley in the town of Grottoes, Virginia (Figure 1). Grand Caverns is within a prominent ridge called Cave Hill that contains several other large caves. The Great Valley is part of the Valley & Ridge physiographic province which primarily consists of folded and faulted Paleozoic sedimentary rocks with minor, late igneous intrusions. Grand Caverns is completely within the Cambrian Conococheague Limestone, a shallow-marine carbonate that consists of interbedded limestone and dolostone, and minor beds of quartz sandstone (Gathright et al., 1978).

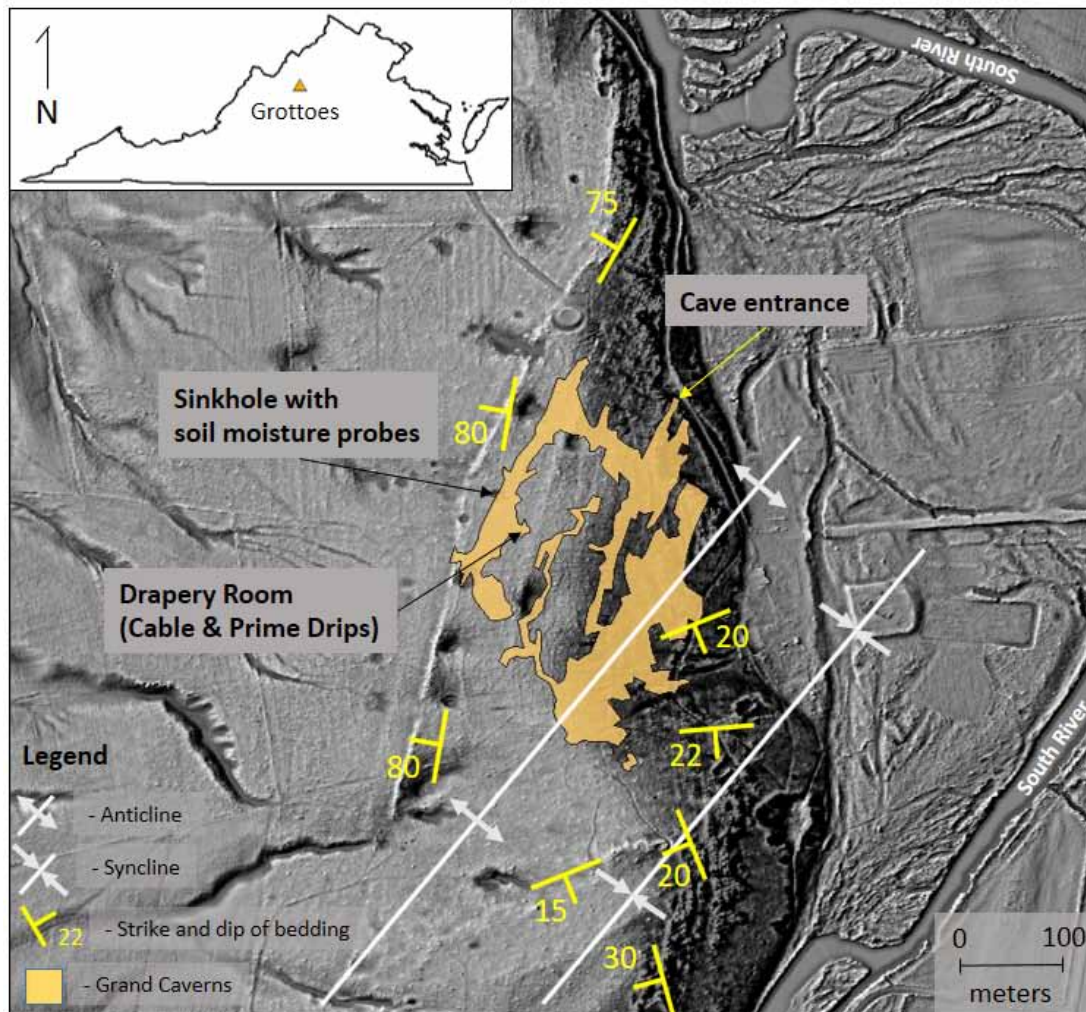


Figure 1. A map of Grand Caverns overlying a hill-shaded LiDAR-derived elevation image of Cave Hill. Bedrock structure data is also shown highlighting the axis of an anticline that extends through the eastern portion of Grand Caverns. Both of the sampling locations within the cave (Cable & Prime Drips) are located within the Drapery Room, and the sinkhole where the soil moisture probes are installed is visible within the LiDAR image.

The carbonate rocks in the Valley & Ridge have a low primary porosity due to diagenetic alteration of the bedrock, and secondary and tertiary porosity created by fractures and conduits play a more important role in groundwater flow and storage. The long axis of Grand Caverns is parallel to the strike of bedding (Figure 1), which also correlates to a regional NE/SW strike of many geologic structures in the mid-Atlantic portion of the Appalachian fold belt. Structurally, this section of the Great Valley is part of the Massanutten Synclinorium, and the cavern is on the eastern limb of this broad syncline.

Cave Hill has a steeper, east facing slope that is flanked by the South River flood plain (Figure 1). It has been questioned as to whether the formation of Grand Caverns relates to the incision of the South River and the corresponding drop in the water table; however, the lack of alluvial deposits and the absence of flowing water within the cave implies Grand Caverns is a hypogenic, phreatic cave system that formed much deeper below the water table (Doctor et al., 2014).

Grand Caverns is located within a temperate climate zone at an elevation of approximately 340 meters above sea level. The outside temperature range throughout the course of the study period (2014–2017) was a high of 36°C in July, 2017 and a low of –22°C in February 2015, and Grottoes received an average of 882 mm/year of precipitation (<https://www.wunderground.com/personal-weather-station/dashboard?ID=KVAGROTT2>, accessed January 8, 2018).

Site Description

The two drip sites monitored in this study, named Cable and Prime, are on the western side of Grand Caverns in a chamber called the Drapery Room (Figure 1). Both drips feed actively growing stalagmites and are located within 5 meters of each other. The drips are 0.4 kilometers from the entrance of the cave and approximately 52 meters at depth below the surface of Cave Hill. The Drapery Room is 10 meters above the elevation of the South River which is the approximate elevation of the water table in Cave Hill.

The bedding within the Conococheague is vertical to sub-vertical on the western side of Grand Caverns where the Drapery Room is located and then flattens out to become horizontal to sub-horizontal on the eastern

side of the cave. This is because Cave Hill is part of an anticline/syncline pair where the axis of the anticline extends through the larger, eastern portion of the cave (Figure 1). Since discontinuities created by bedding planes act as preferential flow paths for water, the nearly vertical bedding at the drip site can have an important influence on the pathways for vadose water flow that have developed above the Drapery Room.

Although agriculture is prevalent throughout this portion of the Great Valley, the surface of Cave Hill is completely forested. The soil above Grand Caverns is mapped as the Frederick-Christian silt loam and the Christian gravelly fine sandy loam (websoilsurvey.sc.egov.usda.gov, accessed September 20, 2017) that transitions to primarily clay below a depth of 33–36 cm. The total soil depth varies from zero to more than a meter.

Methods

Cave Monitoring

For each site the drip rate was monitored using an Onset® HOBO® tipping bucket rain gauge stationed directly below each drip (Schreiber et al., 2015). The volume of the tipping bucket is 3.73 mL which partially controlled the resolution at which changes in drip rate were observed. Directly on top of the rain gauge was a Nalgene® reservoir that temporarily stored the drip water until it spilled over into the rain gauge below (Figure 2). On top of the reservoir was a funnel that captured the drip water, and within the funnel was a HOBO® conductivity data logger that measured the electrical conductivity of the water at 15 minute intervals.

Water samples were collected from the Nalgene® reservoir for analysis of major ions and stable isotopes of water. Water sampling frequency ranged from weekly to monthly with higher frequency targeted towards recharge events. All of the samples were filtered on site through a 0.20 µm filter to remove any bacteria from the water. Samples for cations and anions were stored in 15 ml polypropylene bottles. Samples for dissolved inorganic carbon (DIC) were stored in clear, 20 ml glass vials with black butyl rubber septa and were filled to a positive meniscus leaving no head space. Samples for stable isotopes of water (^{18}O and ^2H) were stored within clear, 4 ml glass vials with polyseal conical inserts in phenolic caps to prevent evaporation. CO_2 concentration in the air was recorded using a Vaisala® handheld CO_2 meter, and the temperature and relative humidity was

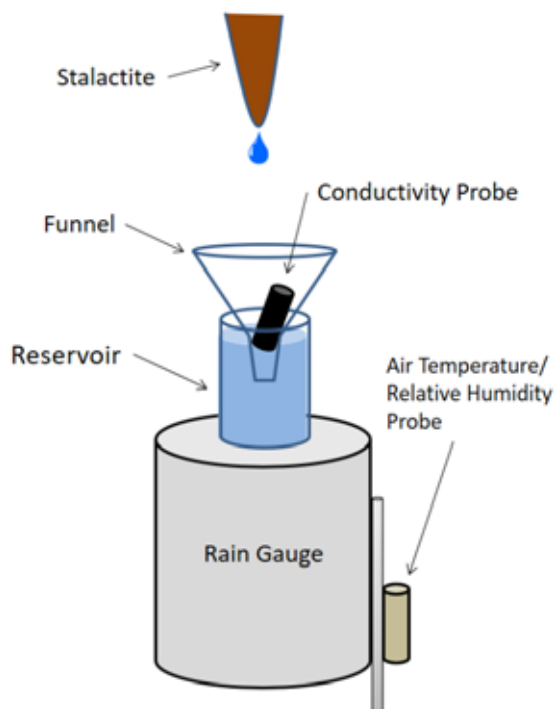


Figure 2. A diagram showing the drip monitoring instrumentation.

continuously measured using a HOBO® temperature/relative humidity data logger.

Surface Monitoring

Three capacitance-based soil moisture probes were installed in November 2015 at the surface of Cave Hill to measure changes in volumetric water content above the cave. The probes were installed at depths ranging from 0.58 meters to 0.98 meters within a sinkhole that was closest to the location of the Drapery Room as if it were projected to the surface (Figure 1). Water content was recorded at 15 minute intervals, and the probes were connected to a HOBO® Micro Station Data Logger where the data was retrieved on a monthly basis.

Precipitation samples were collected on a bi-weekly to monthly basis for the analysis of stable isotopes of water. Samples were collected from a sealed, plastic rain sampler that was located at the surface of Cave Hill within the sinkhole where soil moisture was being monitored. The volume of water within the bucket was recorded and the samples were stored within 4 ml glass vials with polyseal caps. Once all of the samples were transported back to the laboratory, they were refrigerated until analysis. The meteorological data used in this paper was from a weather station located 1 km from the cave at the Grottoes fire station.

Results

The two drip sites showed marked differences in discharge throughout the study period of March 2014 to July 2017. The Cable drip exhibited seasonal changes in flow rate while the Prime drip showed a nearly constant drip rate at 0.018 L/h (Figure 3). The Cable drip had a lower flow regime (0.0037 L/h–0.0075 L/h) during the summer, spring, and early winter until a precipitation event triggered a sharp increase in drip rate to values as high as 0.328 L/h. This sudden change in drip rate by at least two orders of magnitude occurred within a 4–7 day period, and corresponded to a sudden increase in electrical conductivity of the water by 80–100 $\mu\text{S}/\text{cm}$ (Figure 3). Every year starting in the fall there was a consistent drop in electrical conductivity at the Cable site from values as high as 438 $\mu\text{S}/\text{cm}$ to as low as 290 $\mu\text{S}/\text{cm}$ during the winter and early spring. Major ion results show that the conductivity is primarily driven by changes in the concentration of calcium plus magnesium cations and corresponding bicarbonate anions (Figure 4).

The soil moisture above the cave ranged from 12%–31% with higher values occurring during the spring at 27%–31% until it began to drop during the summer months and reached low value of 12%–15% in the fall (Figure 5). This dry period persisted until winter, and the soil moisture began to rise back to spring time values. Throughout 2016, there was an apparent soil moisture threshold of approximately 30% before a drip rate response to precipitation was recorded within the cave (Figure 5).

Despite the observed flow variability between the two sites, the oxygen isotope composition of both drip sites remained nearly equal and constant at $-8.0 \pm 0.1\text{‰}$, with a positive excursion of $\sim 0.5\text{‰}$ over the course of about 4 months after a large storm event in early October 2015 (Figure 2). Unfortunately, precipitation from 2015 was not collected, thus its isotopic composition is unknown; however, the isotopic composition of rainfall typically peaks in the late summer and early fall, thus we surmise that the excursion in drip water composition was caused by the large rainfall events during a time period of low drip rate in the late summer/early fall.

The oxygen isotope composition for precipitation collected above the cave in 2016 had an amount-weighted mean annual value of $-5.8 \pm 0.1\text{‰}$. In comparison, the amount-weighted winter season precipitation (November–April) was $-8.3 \pm 0.1\text{‰}$, a value similar to

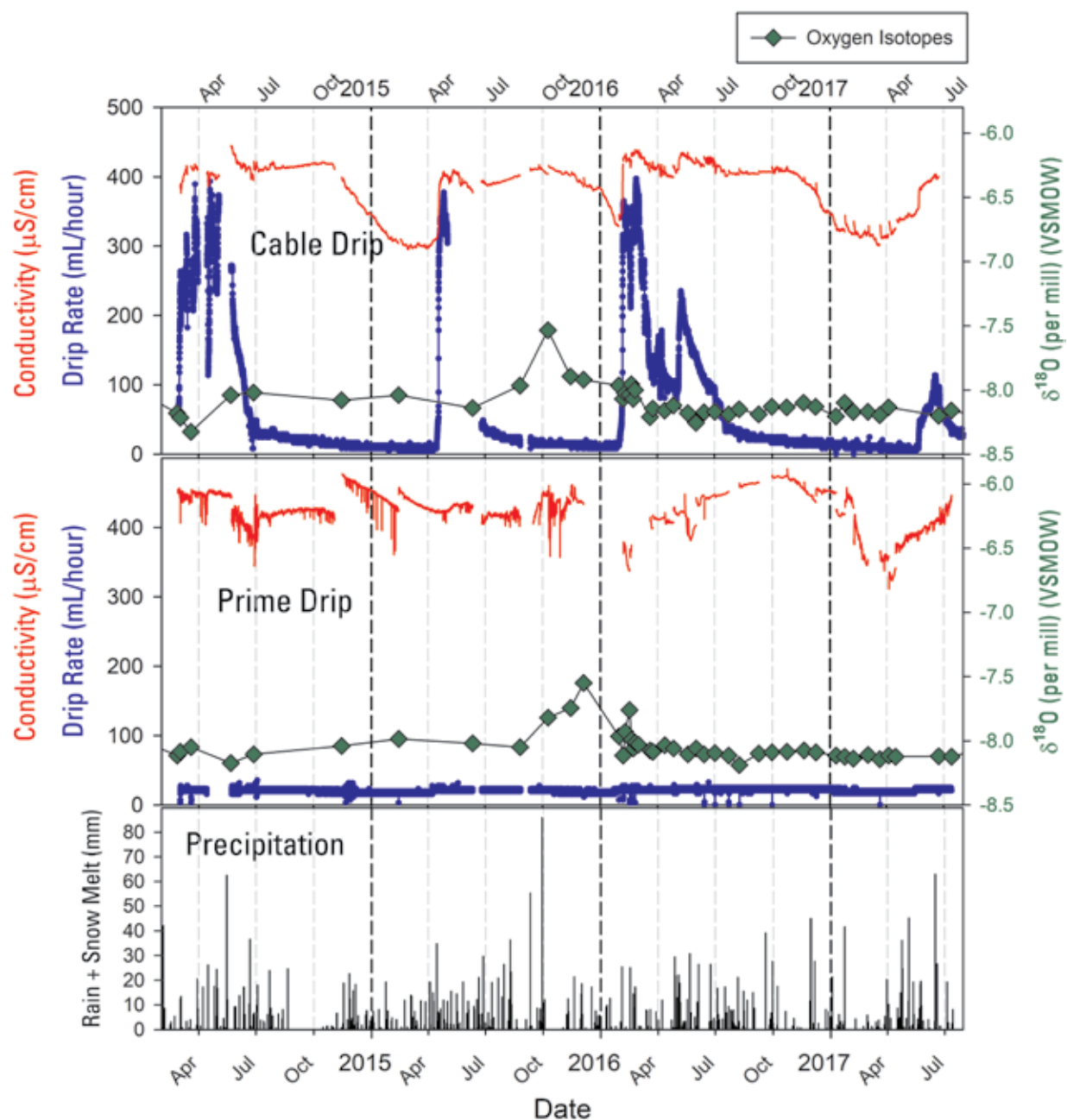


Figure 3. A time series showing the drip rate, electrical conductivity, and the oxygen isotope composition of both drip sites along with precipitation data collected from a nearby weather station in Grottoes, VA (<https://www.wunderground.com/personal-weather-station/dashboard?ID=KVAGROTT2>, accessed Jan 08, 2018). Gaps in conductivity and drip rate data are from instrument failure.

the mean oxygen isotope composition of the drip waters (Figure 6).

Discussion

The annual decrease in discharge at the Cable site corresponds to a drop in soil moisture as observed in

2016 (Figure 5). It is assumed this is a response to an increase in evapotranspiration at the surface during the spring and early summer. Despite there being 524 mm of precipitation from May 1 to October 31 in 2016, the soil moisture and drip rate continued to drop, and there were no responses in drip rate to precipitation

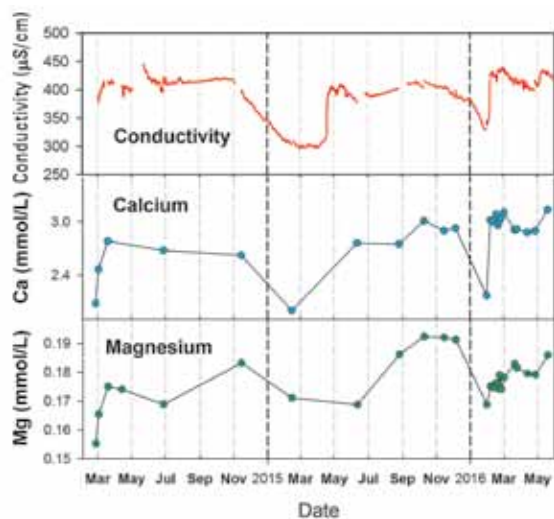


Figure 4. Electrical conductivity of drip water from the Cable site plotted with calcium and magnesium concentrations.

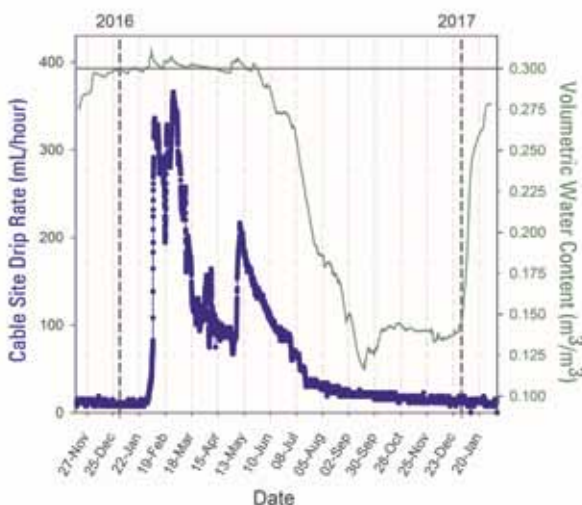


Figure 5. A time series showing the drip rate for the Cable site and the volumetric water content of the soil above Grand Caverns. A 30% soil moisture threshold is emphasized by the solid, horizontal line.

events throughout this period. The lower flow regime of the Cable site continued throughout the fall and winter; however, the soil moisture began to increase by December as the rate of evapotranspiration dropped and precipitation continued, allowing for the infiltration of water through the soil zone as expressed in the soil moisture record (Figure 5). This increase in soil moisture is interpreted to be the onset of the recharge period above the caverns which continued throughout the winter

and early spring. The isotopic composition of the drip waters collected within the cave supports the observed cool season bias towards recharge as the weighted mean oxygen isotope composition of the drip waters is approximately equal to the cool-season weighted mean isotopic composition of precipitation collected above the cave (Figure 6). The relatively constant $\delta^{18}\text{O}$ values observed at both drip sites supports the presence of a perched aquifer within the epikarst that would allow for the mixing and homogenization of vadose water before percolating downward into the cave.

The lower flow regime of the Cable site continued until late winter or early spring when a series of precipitation events triggered the epikarst aquifer to drain into the cave causing a spike in drip rate. After the initial spike in discharge, the Cable drip appears to have a persistent hydraulic connection with the surface, responding to subsequent precipitation events (Figure 3).

The initial waters flushed into the cave at the beginning of each recharge event had greater concentrations of calcium and magnesium which is interpreted to be the result of the waters having reached a higher degree of chemical saturation with carbonate minerals due to storage within the epikarst during the dry season.

The timing and magnitude of the initial annual recharge events varied significantly (Figure 3) with larger

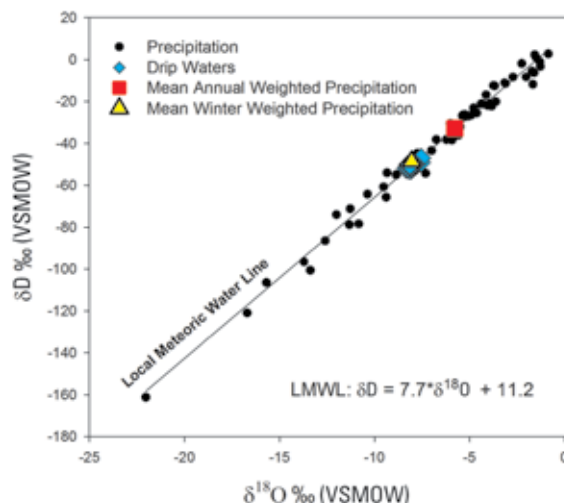


Figure 6. The local meteoric water line plotted with the isotopic composition of the drip waters. Notice the mean winter amount-weighted precipitation value is approximately equal to the composition of the drip waters.

recharge events beginning as early as February (2014, 2016) and smaller events beginning during April or May (2015, 2017). There is no apparent relationship between the amount of precipitation that occurs during the winter season and the magnitude of recharge that occurs during the spring season; however, an apparent volumetric soil moisture threshold of 30% needs to be overcome in order to initiate a drip response in the cave to precipitation. The temporal extent of the recharge period for the epikarst is also regulated by evapotranspiration rates throughout the fall, winter, and spring which will vary depending upon climatic conditions. Nonetheless, continuous soil moisture measurements are superior to calculated estimates of evapotranspiration for determining periods of excess precipitation necessary to initiate and sustain recharge into the epikarst; however, a multi-year record is needed before modeled predictions can be made between changes in soil moisture, and the timing and magnitude of recharge to the drips.

Summary

Based upon soil moisture records for 2016 and the isotopic composition of drip waters, results from this study support the hypothesis that the winter season is the crucial recharge period for vadose waters that ultimately take part in recharge to the aquifer. Also, waters sampled during spring recharge events had higher concentrations of dissolved ions compared to waters sampled under lower, winter flow regimes. A longer, multi-year record of soil moisture is needed before definite connections and correlations can be made between rates of precipitation, and the timing and magnitude of recharge events.

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GEOLOGIC FRAMEWORK OF KARST AQUIFER SYSTEMS IN ALABAMA

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Abstract

Extreme droughts in recent years have highlighted the need to enhance management and protection actions for the water resources of Alabama. The Groundwater Assessment Program (GAP) of the Geological Survey of Alabama investigates the availability and quality of the states' groundwater resources working in cooperation with other state and federal agencies, local governments and water systems, industry, educational institutions, and citizens.

Alabama is located in the humid region of the United States, with numerous karst features, such as caves, sinkholes (dolines), and springs occurring in carbonate (limestone and dolomite) rocks, which underlie about 25% of the state. In the Interior Low Plateaus (Western and central part), Appalachian Plateaus, and Valley and Ridge Physiographic Provinces, which are in the northern half of the state, carbonate rocks underlie many areas and groundwater is contained mainly in karstified aquifers with high secondary porosities. The southern half of the state is situated in the Coastal Plain physiographic province, where around 7.5% of the aquifers are located in carbonates rocks.

All wells installed in carbonate rocks and karst springs obtain water from solution cavities in these strata or the regolith above them. These solution cavities are not uniformly distributed, making prediction of their occurrence extremely difficult. To better understand the geologic framework of karst aquifer systems in Alabama, a series of hydrogeological cross-sections were constructed depicting stratigraphy and aquifers in the area. The selection of cross-section lines and wells were based on their geographic location, with preference given to wells having a greater total depth and with supporting geophysical and sampling logs. These cross-sections were used to identify geologic structure, aquifers (depth and elevation) and their production intervals, and determine where deeper aquifers might be located.

The economic future and quality of life for Alabamians, as well as sustainable ecosystem functions and services,

are dependent upon the availability and protection of the state's water resources. Therefore, future water source development will require significant scientific research, substantial logistical planning, and infrastructure development to find and manage water sources.

Introduction

Alabama's climate is humid subtropical with warm, summers and typically mild winters. Precipitation generally occurs year round, except during drought periods, varying from 1,270–1,372 mm in the Tennessee Valley to 1,524–1,651 mm along the coast. (Stringfield et al., 1974; Evans, 1998).

Alabama, with an area of 135,765 km², is located in the southeastern United States and has a karstifiable area of about 34,051 km² (approximately 25%).¹

Karst

The karstifiable rocks (limestones, dolomite) of the northern half of Alabama (approximately 17.5%) are mostly Paleozoic deposits, while rocks in the southern part of Alabama belong mainly to Mesozoic or Neogene deposits representing 7.5% (Figure 1).

The Alabama karst landscape was generated mainly in the Quaternary. The most karstified deposits belong to the Paleozoic sedimentary cycle. The largest exposed carbonates region in the state, and the most karstified area is in Appalachian Plateaus Province. Based on the geomorphological and structural aspects, there are two types of karst landscapes specific to Alabama:

- Plateau type karst characterized by large limestones, dolomite or chert plateaus with surface karstic features like dolines (sinkholes), closed depressions, dry valleys and streams with elevation ranging between 100 m to 300 m. The

¹All areas in km² or percent were estimated based on the Szabo et al. (2006) Digital Version of the Geologic map of Alabama.

most important plateaus are in the Interior Low Plateaus and Appalachian Plateaus Provinces.

- Bar/Ridge type karst features are ridges derived from carbonate deposits alternate with non-soluble rocks, which dip at over 45°. Very prominent ridges appear because of the differential erosion processes. The strike of these is controlled by northeast southwest longitudinal faults with regional extension, and is cut by transverse faults, on which the karst aquifer is opened and emerges to the surface through springs. The most representative ridges are in the Valley and Ridge Province.

The main karst features present in Alabama and discussed briefly in this paper are: sinkholes, caves and springs. In Alabama, the most common causes of land subsidence are the development of sinkholes in areas underlain by soluble carbonate rocks that are susceptible to dissolution and the formation of caves and sinkholes. More than 6000 sinkholes are recorded (based on the 7.5' USGS topographic maps >10 m across or larger), developed mainly in the northern half of the state, with the highest concentration in the Appalachian Plateaus Province (Ebersole and Tavis, 2010; Ebersole and Hill, 2016).

Over 4,386 caves² are known in Alabama, developed in limestones and dolomite. Most of the caves are in the Bangor Limestones (1369), about 211 caves in the Monteagle limestones, and 141 caves in the Tusculumbia limestones. The largest numbers of caves (3422) are located in Appalachian Plateaus Province, the longest one is 25,153 m and the deepest one is -184 m. In the Valley and Ridge Province are recorded 513 caves, the longest one is 5.4 km and the deepest is -95 m. In the Interior Low Plateaus province are known 216 caves, the longest is 3.34 km and the deepest is -60 m. In the Coastal Plain Province there are 113 known caves, with a maximum length of 417 m and -15 m vertical range. Overall, the longest cave is over 25 km long and the deepest one is -184 m.

The Alabama karst landscape was generated mainly in the Quaternary. The most karstified deposits belong to the Paleozoic sedimentary cycle. The largest exposed carbonates region in the state, and the most karstified area, is in Appalachian Plateaus Province.

²All cave numbers are from Alabama Cave Survey database, as April 9, 2017.

About 40% of public water supply by volume is derived from groundwater sources, and 70% of the geographic area of Alabama is supplied by groundwater sources. Karst springs are numerous in the state, several being used as public or domestic water supply (Hutson et al., 2009). On Figure 1 are shown 109 springs, which are measured (discharge) and sampled periodically. Because of the high number of sinkholes and caves in the state, they are not shown on our figures. The distribution and density of the sinkholes and caves is comparable with those of the springs.

Cross Sections

In order to understand the geologic framework of karst aquifer systems in Alabama, a series of geological cross sections were constructed depicting the stratigraphy of the study area. The selection of wells included along a particular cross-section line was based on the availability of sample logs and associated electric logs.

The Geological Survey of Alabama (GSA) has a large water well record file (more than 125,000), and geochemical data dating to the early 1900s. Because geophysical well logs were completed only in a small number of the water wells and test holes drilled in the area, well-log data from oil and gas wells were used to generate the cross sections. The State of Alabama Oil and Gas Board (OGB) has a large oil and gas well database (more than 17,000 wells). These water well data will be critical to Alabama's water future and are managed using the GSA RBDMS-ENV (Risk Based Data Management System-Environmental) database (GSA, 2017).

Use of these cross sections allows rapid determination of which aquifer is screened. These cross sections are also important in planning for the exploitation of an aquifer. The cross sections will be critical in further exploitation of an existing aquifer or future exploration for new resources as well as in aquifer contamination risk assessments (GSA, 2017).

Due to space restriction, only one cross section (A-A') will be presented in this paper (Figure 2). The others will be available online in the near future, at www.gsa.state.al.us.

Geology and Karst Features Distribution in Physiographic Provinces

Five major physiographic provinces are recognized in Alabama: the Interior Low Plateaus, Appalachian

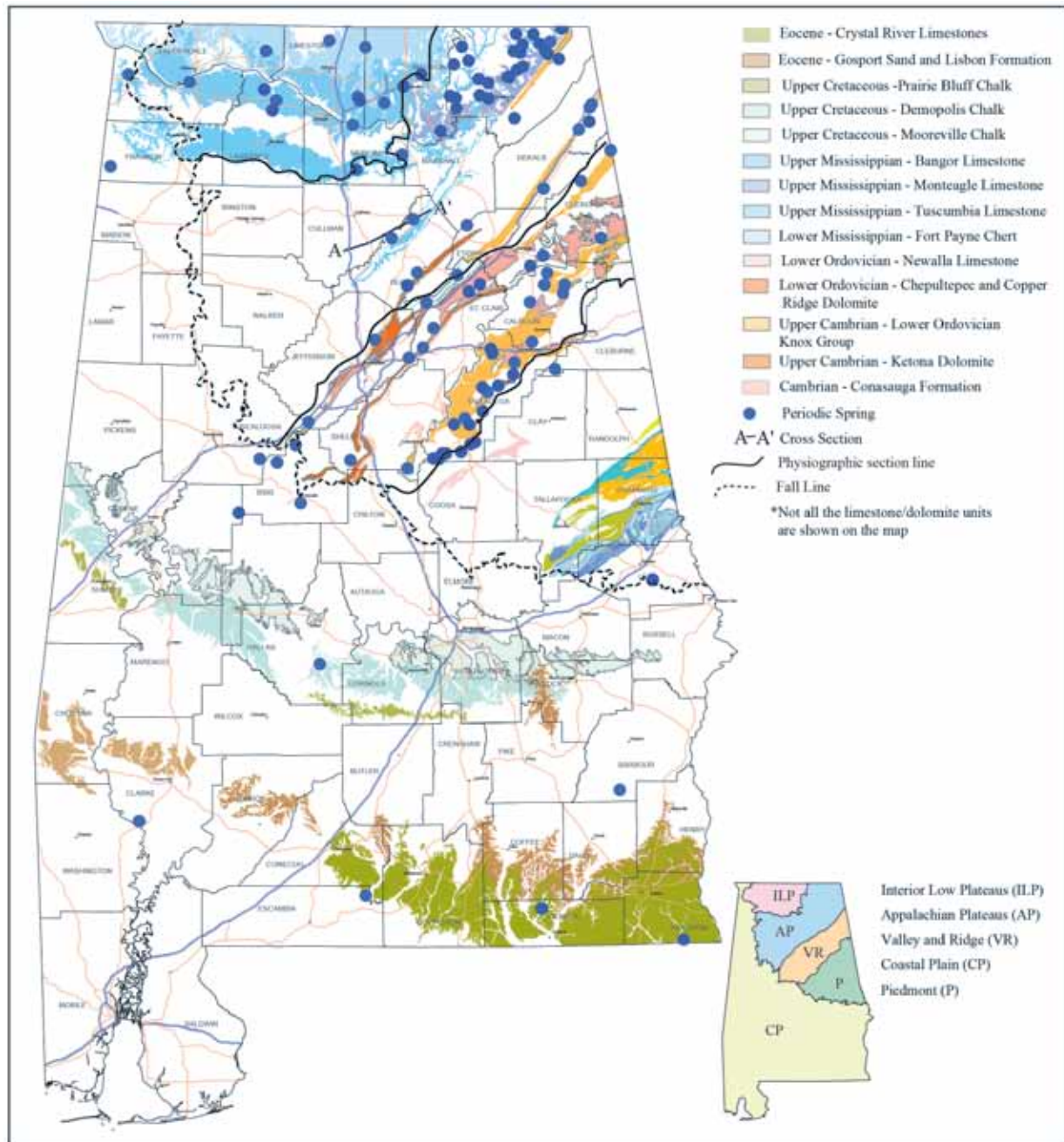


Figure 1. Karst areas of Alabama. Geology modified after Osborne et al. (1989). Not all limestones/dolomites units are shown on the map.

Plateaus, Valley and Ridge, Piedmont, and Coastal Plain (Harper, 1920, 1942, 1943, Johnson, 1930, Fenneman, 1938, Pierce, 1966, Sapp and Emplainscourt, 1975, and Mettee et al., 1996).

Interior Low Plateaus Province – Mississippian Age Limestones/Chert/Dolomite Deposits

The Interior Low Plateaus Province is located in the northwest part of the state and is traversed by the

Tennessee River from east to west. The Tuscumbia Limestone and Fort Payne Chert are predominantly present along the Tennessee River, outcropping in the area at elevations around 120 m to 170 m. South of Tennessee River, the Tuscumbia Limestone is overlain by the Bangor Limestone which outcrops as an east-west strip. In the eastern side of the section the Monteagle Limestone is present in small exposures.

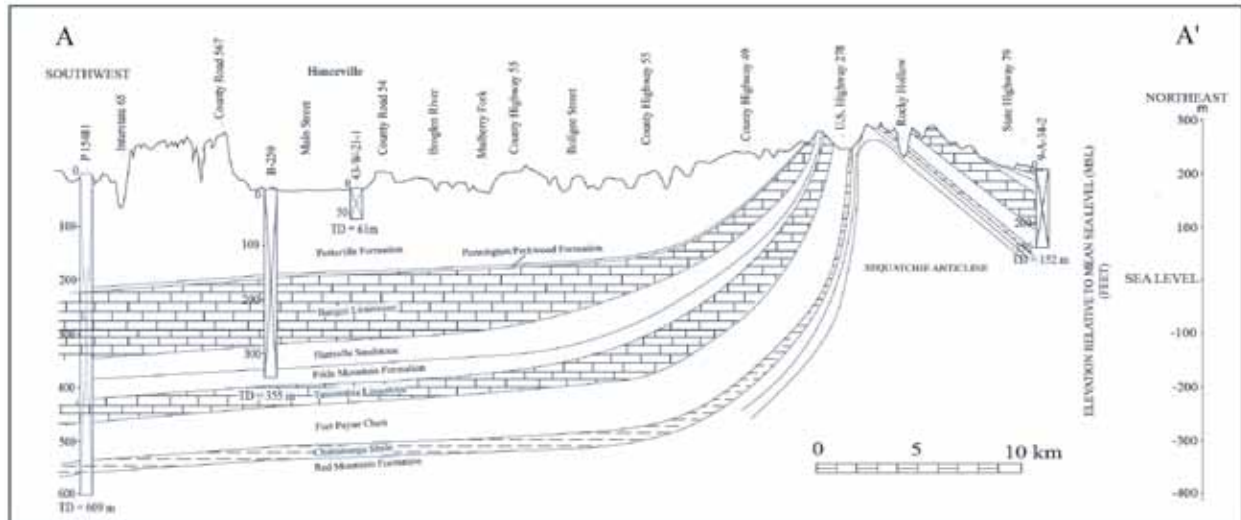


Figure 2. Cross section A—A'. Location of cross section line shown on Figure 1.

The Tuscumbia Limestone is a light-gray bioclastic or micritic, partly oolitic limestone in beds that generally are more than 30 cm thick. Thickness ranges from 0 to 75 m (Thomas, 1972).

The Fort Payne Chert consists of limestone with abundant irregular chert nodules and beds. The Tuscumbia Limestone and Fort Payne Chert overlie the Chattanooga Shale, which is an aquiclude that can reach a thickness of up to 25 m (Butts, 1926).

The Monteagle Limestone consists of limestone, dolomite, and shale, and the Bangor Limestone consists primarily of medium to light gray, bioclastic, and oolitic limestone and overlay the Tuscumbia Limestones. Thickness range between 60 and 90 meters.

The Bangor Limestone is an unconfined karst aquifer in the Interior Low Plateaus Province. Groundwater movement is through secondary porosity conduits and solution enhanced fractures, which discharges to springs. The thickness of the Bangor Limestone in the Interior Low Plateau Province can range up to 150 m. The Bangor aquifer is unconfined throughout the entire Interior Low Plateaus Province area. Plateau-type karst dominates the region and numerous sinkholes are identified in the area, some large in diameter and a few meters deep.

About 216 caves are known in the area, the longest one being Key Cave (Lauderdale County) with over 3 km of passages disposed in a labyrinthic maze. The deepest cave is Craigs Mill Bluepond—60 m located in Cherokee County. Numerous springs are present, the largest

one being Tuscumbia Spring (Colbert County) with a discharge of 1,700 L/s.

Major aquifers in the Interior Low Plateaus Province are the Tuscumbia Limestone and the Fort Payne Chert. However, there are several minor aquifers including the Bangor Limestone, and Monteagle Limestone (GSA, 2017).

Appalachian Plateaus Province - Cambrian through Mississippian Age Limestones/Dolomites/Chert Deposits

The Appalachian Plateaus Province, located in north central, northeastern, and west Alabama is an undulating surface frequently dissected by valleys. Elevations range from around 200 m at Tuscaloosa to near 500 m in the Jackson Mountains northeast of Huntsville and Lookout Mountain near Mentone.

The limestones and dolomites outcropping in the Appalachian Plateaus in Alabama include the Conasauga Formation, Brierfield Dolomite, Ketone Dolomite, and Knox Group (Copper Ridge Dolomite, Chapultepec Dolomite, Longview Limestone, and Newalla Limestone), Chickamauga Limestone, Tuscumbia Limestone, Fort Payne Chert, Monteagle Limestone, and the Bangor Limestone. The Pottsville Formation is considered to be the major aquifer and the Conasauga Formation is the oldest unit in the Appalachian Plateaus Province.

The Tuscumbia Limestone and Fort Payne Chert overlies the Chattanooga Shale in the southern and northeastern

sections of the Appalachian Plateaus Province. These units serve as a minor aquifer in the area and wells are primarily public and domestic supply wells.

Cross Section A-A' is located in the eastern part of the Appalachian Plateaus Province and ends in the Valley and Ridge Province, showing the relationship between the Tuscumbia Limestone and Bangor Limestone with the non-carbonaceous rocks. In the southwestern end of the cross section, the wells are screened/opened in the karst aquifers of Tuscumbia Limestone, Fort Payne chert, and Bangor Limestone. At the northeastern end of the cross section, wells are completed in the Valley and Ridge Province and karst aquifers are the primary sources of water. Spring discharge is generally less than 100 L/s with some springs used as public water supply. About 3422 caves are known in the area, the longest one being Fern Cave (Jackson County) with over 25 km of passages disposed in labyrinthic maze. The deepest cave Obscure Magnificence is -184 m, and is located in Jackson County.

Valley and Ridge Province - Cambrian through Mississippian Age Limestones/Chert/Dolomites Deposits

The Alabama Valley and Ridge consists of a series of folded and faulted parallel ridges and valleys that trend northeast-southwest with elevations ranging from 175 m to 650 m. Ridges are made of sandstone and chert while valleys are generally developed on limestone and shale. In this province a ridge type karst is present. Sinkholes are sporadic, small in diameter and a few meters deep.

The Valley and Ridge karst aquifer system consists of several Paleozoic strata of Cambrian to Devonian (Mississippian) age including the Shady Dolomite (limestone, dolomite, chert, and silty clay), Conasauga Formation (limestone, dolomite, and shale of varying proportions), Brierfield Dolomite (dolomite with locally abundant chert), Ketona Dolomite (mostly chert free, remarkably pure dolomite), Bibb Dolomite (siliceous dolomite characterized by locally abundant chert), Knox Group (dolomite, siliceous dolomite, dolomitic limestone, cherty limestone, and chert-free, relatively pure micritic limestone), and the Little Oak Limestone- Lenoir Limestone (limestone, chert, bentonite) (GSA, 2017).

The Bangor and Monteagle Limestone formations serve as a major water source within the Alabama Valley and

Ridge predominantly used for public supply, although several domestic and agricultural wells are also known.

About 513 caves are known in the area, the longest one being 5.4 km long (Anderson Cave, Shelby County), and the deepest one being -94 m (Bat in the Pocket Cave, Etowah County). Numerous springs are present, and some are in use by municipalities (e.g., Warren Spring, Blount County).

Coastal Plain Province

The Coastal Plain Province in Alabama is characterized by gently rolling hills, sharp ridges, prairies, and broad alluvial flood plains. Calcareous rocks underlying the Coastal Plain are of sedimentary origin and consist of porous limestone, chalk, and marl. These strata dip underground to the southwest at approximately 6 to 7.5 m per km and strike generally in east-west belts.

The Selma Group is comprised of the Mooresville Chalk, Demopolis Chalk, and the Prairie Bluff Chalk in western Alabama, and the Blufftown Formation in eastern Alabama (Monroe, 1941).

The chalk is mainly calcareous marl with dark gray color, hosting very few to no karst surface and underground features even though they outcrop extensively in the southern half of the state. These units are aquicludes that reach a thickness of up to several tens of meters.

The Paleogene calcareous deposits of the Coastal Plain Province are represented by the Lisbon and Crystal River Formations. Toulmin and LaMoreaux (1963) reported that the Lisbon Formation outcrops in southeast Alabama consists primarily of sand but also contains significant amounts of limestone and sandy limestone. The Lisbon aquifer is a major public, domestic, agricultural, and industrial water source for central and southeastern Alabama.

The Crystal River Formation includes all calcareous deposits of late Eocene age lying stratigraphically above the Moody's Branch and below limestone beds of Oligocene age (Smith, 2001). The Crystal River Formation is characterized by white to cream medium-textured to coquinoïd limestone that is soft and chalky to compact and brittle (Puri, 1953, 1957).

The Chickasawhay Formation (Oligocene series), which overlies the Vicksburg Group, consists of bluish-gray,

glauconitic, soft, sandy calcareous clay, and layers of hard white limestone (Copeland, 1966).

The karst developed in the Coastal Plain Province is plateau type karst. Sinkholes were identified in the area, some large in diameter and only a few meters deep.

About 113 caves are known in the area; the longest one being only 417 m long (Lion's Den, Clarke County) and the deepest cave is –15 m (Chastain Cave, Clark County). A few small to medium size springs are present in the area. The numbers of surface and underground karst features is a result of the presence of porous limestones, where karst features are poorly preserved.

Piedmont Province

The Piedmont province is a section of the “older Appalachians” as described by Fenneman (1938). This undulating plain is the result of long-term degradation of the surface rocks while the underlying rocks are severely deformed and angled to the surface. The Piedmont province in Alabama is a wedge shaped feature bounded on the south by coastal plain sediments and to the northwest by the Alabama Valley and Ridge. Piedmont geology is complex consisting of high- and low-grade metamorphic and igneous rocks including quartzite, phyllite, slate, schist, amphibolite, and gneiss (GSA, 2017). There are some sinkholes in the Sylacauga Marble.

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PACKER TESTING AND BOREHOLE GEOPHYSICAL CHARACTERIZATION OF OBSERVATION WELLS IN A VERTICALLY INTEGRATED KARST AQUIFER IN AUGUSTA COUNTY, VIRGINIA

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Abstract

Geophysical borehole logging and zone-isolation packer testing at adjacent State Observation Wells (SOWs) in Augusta County, Virginia, indicate the presence of shallow and deep horizontal karst conduits that are hydraulically connected by a highly transmissive, vertical fracture network. Despite the presence of a downward open-hole hydraulic gradient, ambient- and pumping-induced water level responses were identical during zone isolation tests in two conduit zones measured in SOW 70 and one conduit zone measured in an adjacent observation well (SOW 70A). Identical hydraulic responses between all 3 monitoring points is interpreted to be the result of a solution-enlarged, vertically oriented fracture network that is capable of muting measurable head differences during zone isolation tests. Results from multiple open-hole flow logging tests within SOW 70 have also shown distinct variations in vertical flow that correspond with seasonal groundwater recharge. The occurrence of these vertically oriented, highly transmissive fracture sets is thought to be coincident with folding within the Staunton-Pulaski thrust sheet, and could be an important mechanism for the vertical integration of distinct hydrologic features in similar structural settings. The series of tests on SOW 70 and SOW 70A has resulted in a better practical and conceptual understanding of the monitored karst aquifer near Staunton and demonstrates the utility in collecting multiple types of borehole geophysical data during different times of the year on karst wells.

Introduction

Observation wells have been used for decades throughout the world to investigate aquifer characteristics and assess

the availability and quality of groundwater resources. Despite significant advances in remote sensing and computer modeling, water-level measurements from observation wells remain the principal source of information about how aquifers respond to the hydrologic stresses acting on any given region (Taylor, 2001).

The Virginia Department of Environmental Quality (VDEQ), in cooperation with the U.S. Geological Survey (USGS), currently operates a network of 325 active observation wells throughout the state, the majority of which are located in Virginia's Coastal Plain Groundwater Management Area (Figure 1). Construction details for most of the state observation wells in the Coastal Plain are relatively well known as they were

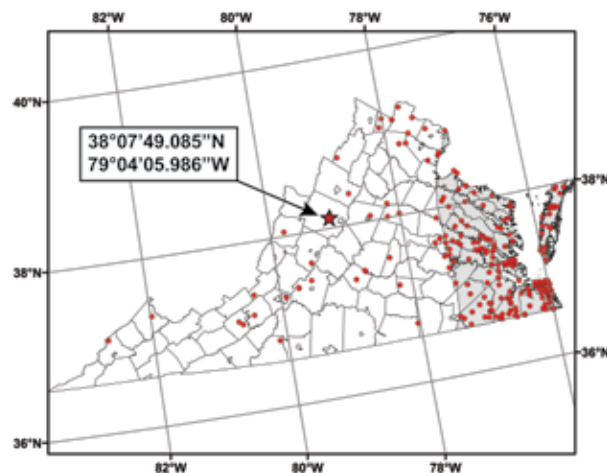


Figure 1. Observation wells operated by the VDEQ and USGS in Virginia. Red star denotes study location. Coastal Plain Groundwater Management Area shaded in gray. Site coordinates NAD83 horizontal datum.

purpose-built by DEQ or USGS geologists to monitor specific confined aquifers and were cased and screened in a manner preventing communication with overlying aquifers.

State observation wells in areas west of Virginia's Coastal Plain are typically former supply wells completed in deformed sedimentary or crystalline bedrock with construction details that are often highly generalized or unknown. Below surface casing, the open boreholes commonly intersect multiple water bearing fractures or conduits as they were originally constructed to maximize yield. Since 2006, VDEQ geologists have used borehole geophysical tools to characterize the construction of these observation wells in order to better understand their construction and the geology of the aquifers they monitor. This paper discusses the results of one of these studies on State Observation Well 70 (SOW 70) in Augusta County.

Geologic Setting and Background

The study area is in Virginia's Valley and Ridge Physiographic Province and borders the City of Staunton near the southern headwaters of the South Fork of the Shenandoah River. SOW 70 is located along the axial trace of an unnamed, north-east plunging anticline in the hanging wall of the Staunton-Pulaski fault (Figure 2). The well was drilled in limestone, dolomite, and sandy dolomite of the Conococheague Formation of Cambro-Ordovician Age (Rader, 1967).

SOW 70 was reportedly drilled to a terminal depth of 76 m (250 ft) in 1964 as a supply well for a nearby shopping center with a reported yield of 1075 L/min (284 GPM). The well was abandoned as a supply for unspecified reasons before eventually being obtained by the state for monitoring purposes. Periodic and later automated groundwater-level measurements have been collected from the well since 1974 and exhibit a relatively stable long-term trend and a seasonal range as high as 4.5 m (15 ft) (Figure 3). Well construction was first evaluated in 2006 using a black and white borehole camera. The fixed-view camera revealed what appeared to be a single horizontal conduit near the bottom of the well (70 m, 230 ft).

In 2010, a shallow observation well (SOW 70A) was installed adjacent to SOW 70 (4.5 m, 15 ft) in order to evaluate the possibility of monitoring both shallow and

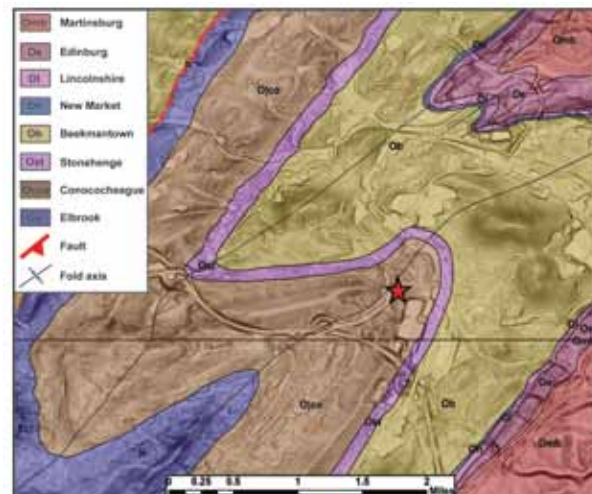


Figure 2. Geologic setting of the Augusta County state observation well site. Geology from Campbell et al., 2006.

deep portions of the karst aquifer at the site. SOW 70A was drilled to a depth of 19 m (62 ft), cased and grouted to 15 m (50 ft) and yielded an estimated 568 L/min (150 GPM). Air rotary installation of SOW 70A caused significant water level fluctuation in SOW 70 once drilling encountered limestone bedrock at 9 m (29 ft).

Methodology

VDEQ initiated geophysical borehole logging at the site in December 2015 following the installation of a roof hatch in the concrete well-house surrounding SOW 70.

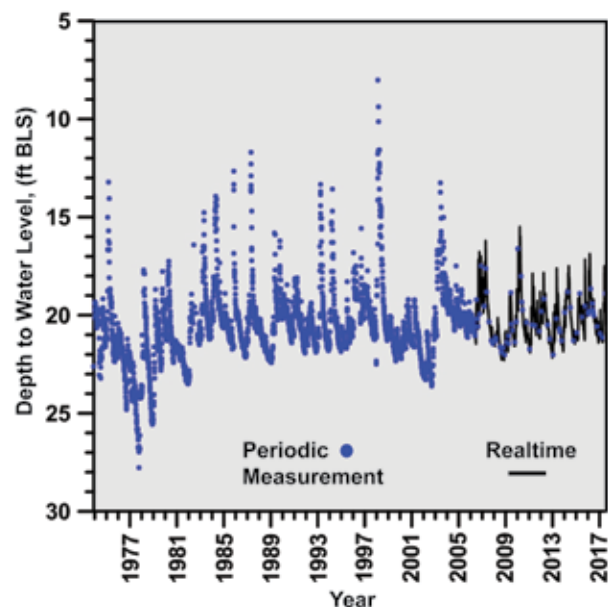


Figure 3. Long term water level hydrograph for SOW 70.

Logging of SOW 70 included both optical and acoustic borehole imaging, 3-arm caliper, multi-tool (natural gamma, lateral resistivity, 16- and 64-inch normal resistivity, spontaneous potential, fluid resistivity, temperature), and electro-magnetic flow measurements under ambient and pumping conditions. Both boreholes were surveyed with a pan/tilt color borehole camera.

An inflatable packer (Aardvark 4 inch) was installed in SOW 70 from March 24 to May 19, 2016 to measure differential head responses between upper and lower portions of the former supply well and the shallow observation well. The packer assembly was threaded to sections of 50 mm (2 inch) diameter PVC pipe and carefully lowered to a depth of 34 m (112.5 ft) below land surface (BLS) where geophysical logs indicated the borehole wall was smooth and competent. The exterior of each threaded PVC pipe joint was reinforced with layers of electrical- and pump-tape to prevent possible leakage of rubber gaskets. Vented pressure transducers (Winsitu Level Troll 700s) were installed to monitor water levels in both zones of SOW 70. A vented Aquatroll 200 was installed at the main water bearing conduit in SOW 70A to measure water level and fluid conductance response. On March 24, 2017, after all three probes had collected 15 minutes of data, the packer was inflated with nitrogen gas to a pressure of 1585 kPa (230 PSI). Following 2.5 hours of equilibration, a 3" Grunfos submersible pump was lowered to a depth of 15 m (50 ft) in SOW 70A and used to stress the well at 45 L/min (12 GPM) for 25 minutes. On April 14, 2016 the packer assembly was deflated and lowered to a depth of 64 m (211 ft) and SOW 70A was this time pumped at 51.4 L/min (13.6 GPM) for 103 minutes. In addition to testing for response to pumping induced stresses, the packer assembly was left in the borehole for several weeks to document ambient response to precipitation. Weekly checks were made to ensure proper packer inflation and tape-down measurements were made using an electronic tape to check the transducer data for instrument drift. The maximum difference between hand-taped and recorded measurements was 4.2 cm (0.14 ft), but most transducer data deviated less than 1.2 cm (0.04 ft) from tape-down measurements. Relative water depths were converted to water level elevations using an onsite permanent benchmark and a Sokkia SDL30 Digital Level and fiberglass survey rod.

On September 17, 2015, the borehole electromagnetic flowmeter was calibrated in a specially constructed clear plastic flow-cell that enabled comparison of the device's reported flow rates to volumetric and impeller-driven flow-meter rates. The instrument calibration was again checked on June 14, 2016 at 22 induced flow rates ranging from 21.4 L/min (5.65 GPM) of downward flow to 20.8 L/min (5.50 GPM) of upward flow. The tool's measured flow response was in close agreement with induced rates (Figure 4). Open borehole flow logging of SOW 70 was performed on three separate occasions during the 2016 water year and once near the beginning of the 2018 water year: December 9, 2015, May 19, 2016, June 15, 2016, and November 13, 2017.

Results

Camera logging of the shallow observation well SOW 70A revealed that the well had a good casing seal and intercepted two small (less than 15 cm/6 in thick) horizontal conduits developed along bedding between 15.5 m (51 ft) and 16.2 m (53 ft) below land surface (bls). The second camera log of SOW 70 was made with a pan/tilt color camera that allowed for a more thorough inspection of the well. The camera log of the former supply well showed an irregular casing contact with bedrock at 29 m (94 ft) that was obscured on the first camera log in 2006 due to an accumulation of bacteria and corrosion.

Ambient borehole flow measurements made in SOW 70 on December 9, 2015 detected 6.8 L/min (1.8 GPM) of groundwater flow from the compromised casing seal at 29 m (94 ft), down the borehole to the horizontal conduit

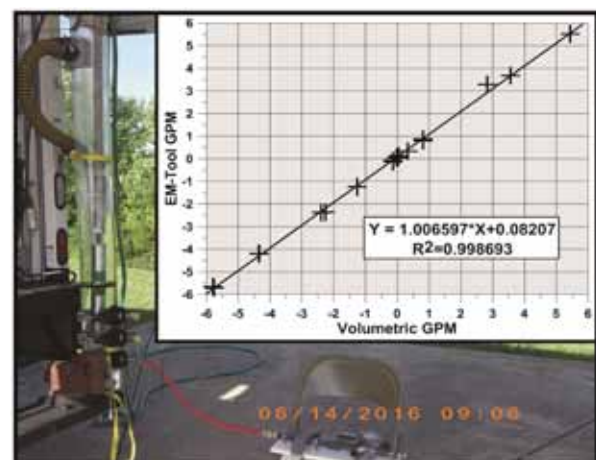


Figure 4. Results of electro-magnetic flowmeter calibration check performed June 14, 2016.

at 70 m (230 ft). The downhole flow between the two zones implied that the hydraulic head for the upper zone was higher than the hydraulic head for the conduit at 70 m (Johnson et al., 2005) (Figure 5).

Isolation of the compromised casing seal from the receiving conduit produced no significant head differences under ambient conditions. Pumping of SOW 70A produced identical drawdown responses in both zones of SOW 70 despite the limited amount of stress (8.53 cm / 0.28 ft drawdown) that could be applied to the aquifer with the available test pump (Figure 6). Pumping and ambient water level responses were identical at both packer depths in SOW 70. During both pump tests on SOW 70A, the pressure / conductivity probe stationed below the test pump in SOW 70A recorded a slight decrease in specific conductance of groundwater from the shallow conduit during both pump tests (~15 uS/cm). Data collected the month following pump testing showed water levels in each zone responded identically to recharge (Figure 7). On May 26, 2016, a small increase in groundwater specific conductance in response to precipitation was recorded at the conduit in SOW 70A, a change that preceded water level increases at the site by 2 days. Semi-diurnal earth tide signals, due to lunar dilation of water bearing fractures, were present in all zones monitored, although less prevalent in the shallow SOW 70A.

Two earthquake responses were recorded by the dataloggers due to a Richter M7.0 earthquake in Japan on May 15, 2016, and a M7.8 earthquake in Ecuador on May 16, 2016 (Figure 8). Although teleseismic water level oscillations were noted in both zones of SOW 70 and SOW 70A, the response from the lower conduit of SOW 70 exhibited the highest amplitude (7.62 cm / 0.25 ft). Water level oscillations began 48 minutes after the M 7.0 Japan earthquake and lasted for 44 minutes. The M 7.8 earthquake produced higher amplitude water level oscillations in all zones 14 minutes after it occurred in Ecuador and fluctuations lasted for almost an hour.

Borehole flow logging was conducted the day of final packer removal on May 19, 2016 and later on June 15, 2016 following a successful flow-cell calibration check, detecting significant downhole flow on both occasions (3.0 L/min / 0.8 GPM and 2.3 L/min / 0.6 GPM respectively). Borehole flow data was also collected on November 13, 2017 in a period of seasonally low

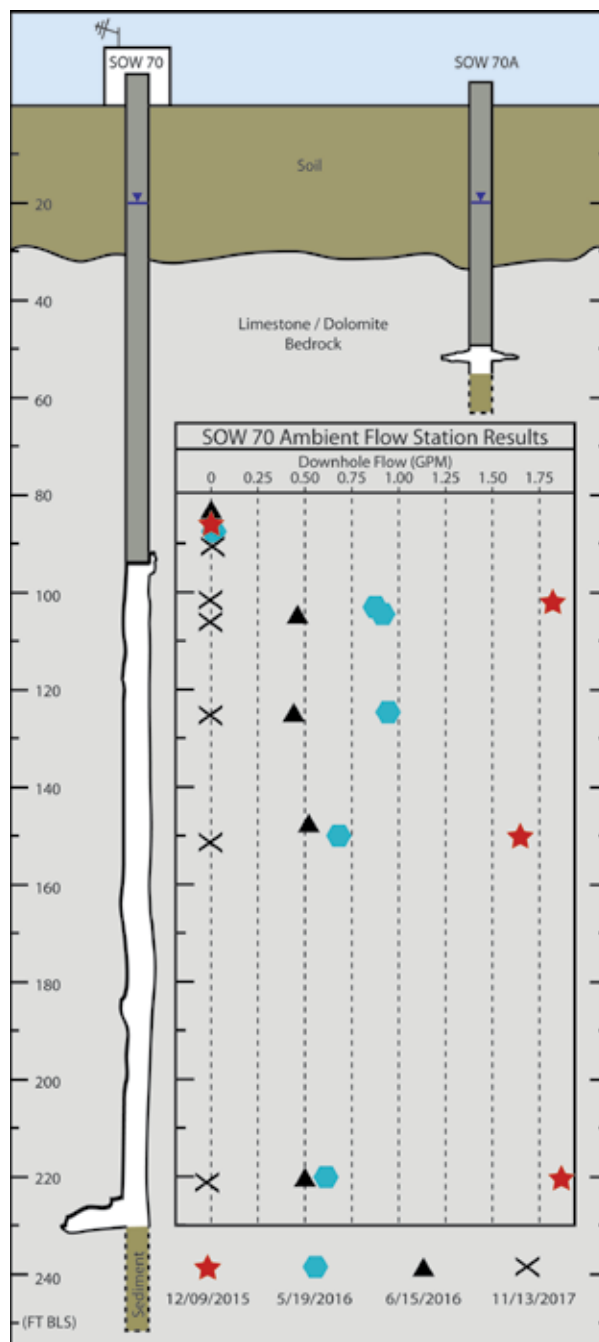


Figure 5. Schematic summarizing construction and ambient open borehole flow conditions observed during geophysical logging.

groundwater levels during which no significant vertical flow was detected (Figure 5).

Discussion

Four open-borehole flow logs conducted during the winter to early summer months have documented ambient downward flow between shallow and deeper

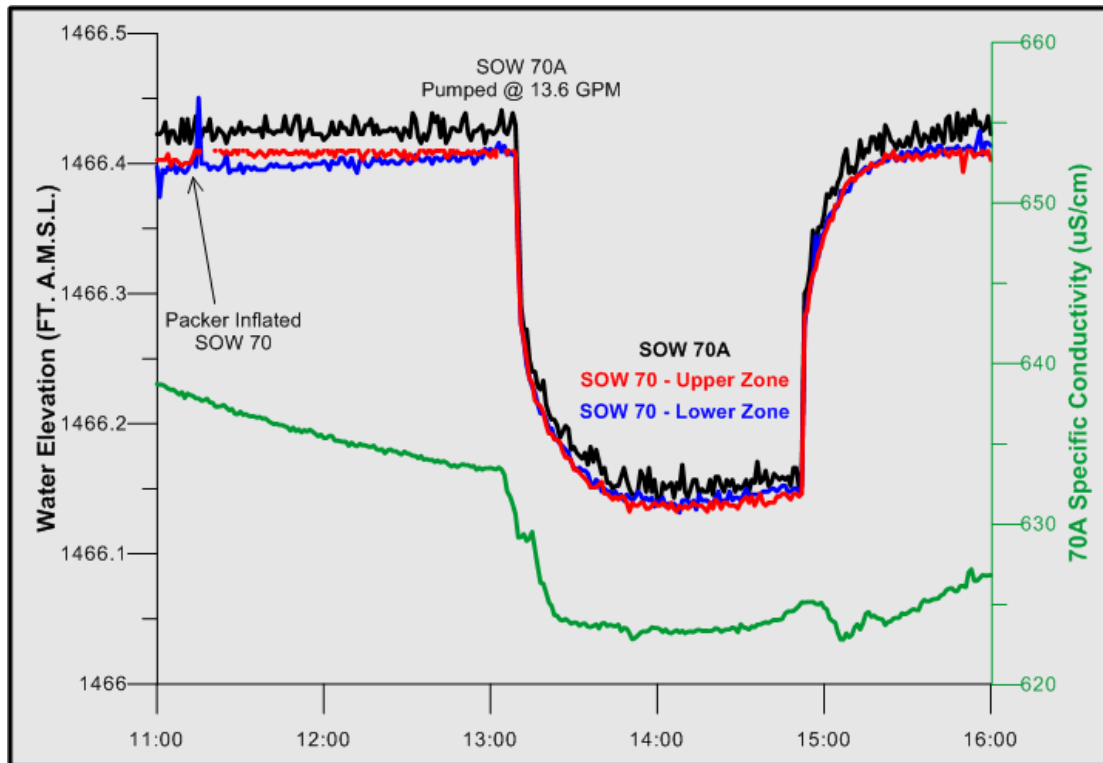


Figure 6. Groundwater level and specific conductivity responses to pumping of SOW 70A on April 14, 2016. Green line shows specific conductance of groundwater at the main water bearing conduit 15 m (52 ft) b/s in SOW 70A.

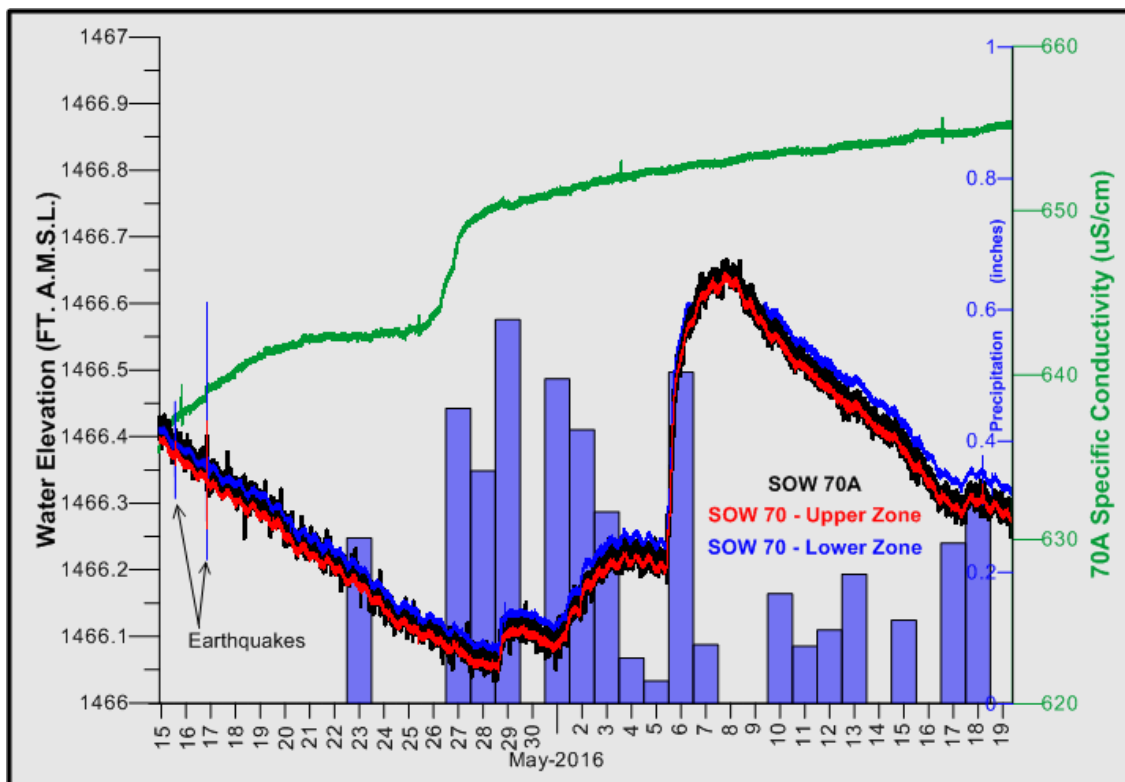


Figure 7. Ambient responses to precipitation, earthquakes, and semi-diurnal lunar fracture dilation from April 15 to May 19, 2016. Inflatable packer stationed at 64 m (211 ft) b/s.

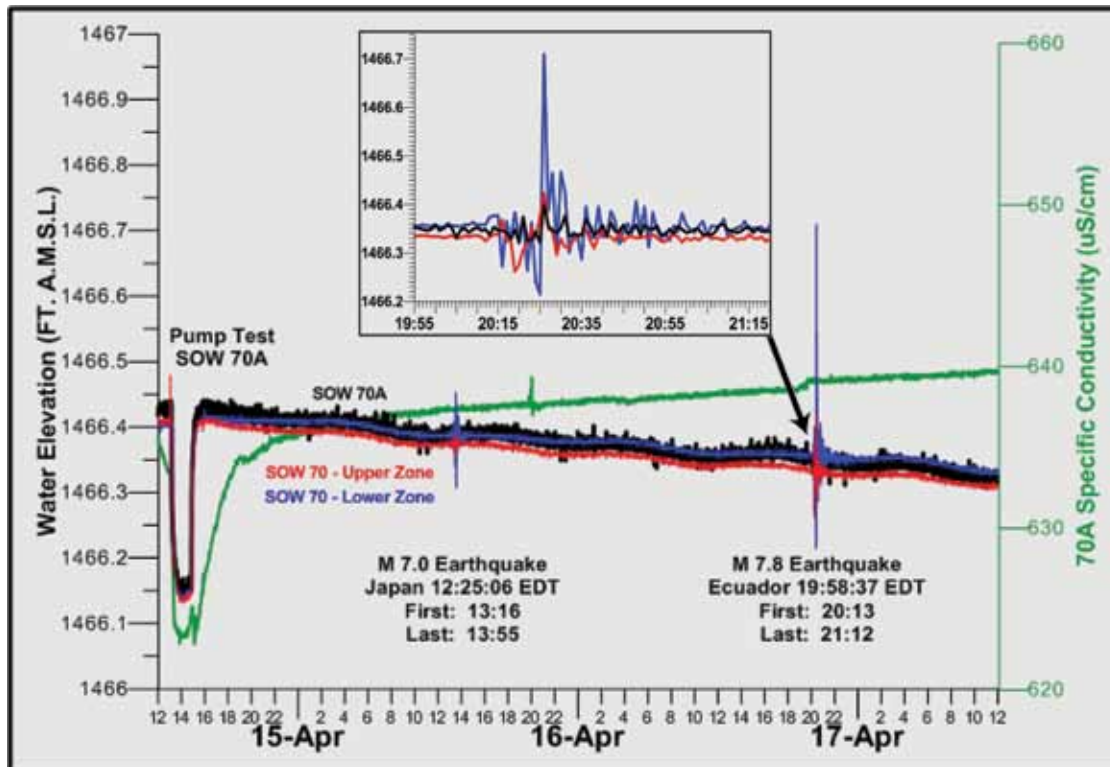


Figure 8. Teleseismic water level oscillations recorded in SOW 70 and 70A on April 15 and 16, 2016. Inflatable packer stationed at 64 m (211 ft) bls.

parts of the aquifer at the site. The downhole flow rate was higher during the winter, when most groundwater recharge occurs in the region, and lower in the late spring and summer months when recharge rates tend to slow in response to plant growth and increased evapotranspiration (Nelms and Moberg, 2010).

The fact that isolation of the two zones resulted in no significant difference in ambient and pumping water levels could be the result of equipment failure or natural aquifer conditions. Borehole flow logging and packer testing are prone to error for a variety of reasons, but most commonly due to improper setup, calibration, or a highly irregular borehole shape that does not allow for proper instrument seal. During all tests, caliper and video logs were used to position the flow instrument and packer seal at smooth unfractured intervals to reduce the chance for error due to flow bypass. Bracketing of the borehole flow tests with flow-cell calibration checks further increased confidence in ambient downward flow detected in SOW 70. The lack of significant ambient and pumping head differences between isolated zones, coupled with persistent ambient open-borehole flow is therefore thought to reflect the presence of high-transmissivity vertical features that locally integrate

the bedding plane conduits yielding water in both wells. In effect, the open borehole in SOW 70 acts as a high transmissivity artificial conduit in an already well integrated aquifer. The vertical fracture network within the aquifer is capable of muting measurable head differences during zone isolation tests as flow gradients within the wellbore shift instantaneously to other equally transmissive parts of the aquifer.

Although only horizontal water bearing features are noted in the exposed portions of both boreholes, vertical integration of the karst aquifer is supported by the presence of steeply dipping sealed fractures in geophysical logs, the presence of steeply dipping solution-enlarged fractures observed in nearby outcrop, and the site's location along the axis of a plunging anticline where axial-plane fracturing is usually more prevalent (White, 1988). It is possible that at a significantly higher pumping rate (~378 L/min, ~100 GPM) vertical transmissivity between the two zones may be exceeded, resulting in measurable differences between zone-isolated pumping heads.

Groundwater conductance changes were recorded at the water bearing conduit in SOW 70A during pumping and

in response to recharge, though the magnitude of response was minor (<15 uS/cm) and near the rated accuracy of the conductivity logger ($\pm 0.5\%$ of reading, 3 uS/cm). The fluid conductance declines recorded during pumping of SOW 70A, followed by a delayed rebound after water level recovery, probably relate to displacement of relatively stagnant borehole water with groundwater more representative of aquifer chemistry. In contrast, the slight fluid conductance increase on April 26 occurred during the onset of rains that soaked the area following an unusually dry late winter and preceded groundwater level increases in the aquifer by two days. The reason for this fluid conductance increase is poorly understood but may reflect infiltration or flushing of road salts or other contaminants from upland urban landscapes. Similar conductance increases that preceded minor or muted spring discharge responses were determined to be due to recharge carrying seasonally applied road salts in the northern Shenandoah Valley (Doctor et al., 2011).

Teleseismic water level responses have been recognized in SOW 70 since the well was equipped to record water levels at 5 minute intervals in 2006. The well commonly responds to large ($>M$ 7.0) earthquakes around the globe – yet failed to respond to the August 23, 2011 M 5.8 earthquake in Mineral, Virginia (Sheets, 2015). The higher frequency (1 minute) data collection rates used during the zone isolation tests allowed for a more detailed observation of teleseismic water level response at multiple depths in the karst aquifer. The higher amplitude and duration response of the deeper conduit during both earthquakes could be a reflection of differences in aquifer transmissivity and storage that manifest as greater amplification of seismic water level oscillations in the lower part of the aquifer (Bredehoeft et al., 1965). Slight changes (± 1 uS/cm) in specific conductance recorded around the time of both earthquakes in SOW 70A (Figure 8) are below the rated accuracy of the probe and occur either too long after or before each quake to be related to seismicity.

In conclusion, geophysical logging and packer testing have resulted in an improved understanding of aquifer conditions monitored by the Augusta State Observation Well and have demonstrated the utility in collecting flow data during different times of the water year to better understand the dynamics of groundwater flow in fractured rock aquifers.

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USING GEOPHYSICS TO MAP BEDROCK FAULTS, DIKES, AND SURFICIAL GEOLOGY IN RELATION TO KARST FEATURES IN THE BRIERY BRANCH QUADRANGLE, ROCKINGHAM COUNTY, VIRGINIA

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Abstract

Several faults have been identified in the Cambrian and Ordovician carbonate strata in western Rockingham County, Virginia. These faults were recognized by mapping offsets between stratigraphic units in the hanging wall of the North Mountain fault system. Portions of these faults are associated with karst features, but are covered by alluvium and thick soil development in the floodplains of Dry River and Briery Branch; therefore, the position of the faults could not be located with accuracy through surface mapping alone. In an earlier study, ground penetrating radar (GPR) and audio-magnetotellurics (AMT) geophysical methods were used to locate the expression of these faults at depths greater than ~5 m. Here, we employ electrical resistivity imaging (ERI), and borehole video to examine the influence the faulting may have on near-surface karst expression. These geophysical datasets also help in the identification of igneous dikes and karst features present in the subsurface, and shed light on how these structures may affect the local groundwater flow regime and karst development.

The ERI surveys were useful in identifying the precise position of inferred bedrock faults, as well as karst features in the shallow subsurface. On the ERI profiles, the faults inferred through geologic mapping appear as sub-vertical low resistivity zones, indicating increased fracture porosity and weathering along the fault surface. Enhanced fracturing in these zones was also observed in adjacent borehole video logs. Diabase dikes appear as sub-vertical high resistivity features, and were verified

at the surface through outcrop observation. Sinkholes and other karst features were also identified in the ERI profiles, generally expressed as low-resistivity anomalies. A pseudo-3D ERI survey was completed over a closed depression in highly weathered alluvium overlying limestone bedrock that clearly images the outline of the depression in the subsurface, as well as a possible water or mud-filled solutional conduit. The surface expression of the depression was approximately 165 ft (50 m) in diameter, while the low-resistivity anomaly was 15 to 50 ft (5 to 15 m) wide and appeared at depth of 15 to 80 ft (5 to 25 m).

Introduction

In support of detailed geologic mapping, several geophysical surveys were completed west of Harrisonburg in Rockingham County, Virginia to confirm the presence and more accurately delineate the subsurface location of faults in the northeast corner of the Briery Branch 7.5-minute (1:24,000 scale) quadrangle. These faults were recognized by mapping offsets between stratigraphic units in Cambrian and Ordovician carbonate strata in the hanging wall of the North Mountain fault system. Portions of these faults are associated with karst features, but are covered by alluvium and thick soil development in the floodplains of Dry River and Briery Branch. Due to the alluvial cover, the position of the faults could not be located with accuracy. Several geophysical techniques were used to map bedrock geologic structures including faults, fracture zones, and diabase dikes, to estimate the thickness of alluvium and deeply weathered bedrock,

and to shed light on how these structures may affect the local groundwater flow regime and karst development.

Earlier geophysical investigations employed ground penetrating radar (GPR) and audio-magnetotellurics (AMT) as a means of investigating the depth of the alluvial cover atop the bedrock and for potentially illustrating the location of major faults at depth (Pierce and Doctor, 2011; Doctor et al., 2014). GPR that was collected with a 25 MHz antenna was useful in mapping the thickness of the alluvial deposits to a depth of approximately 80 ft (25 m), and could identify areas of possible subsidence of layered alluvium into underlying voids (Pierce and Doctor, 2011; Doctor et al., 2014). The AMT method was capable of imaging broad resistivity contrasts along thrust faults at depths of up to 1650 ft (500 m) (Pierce and Doctor, 2011; Doctor et al., 2014).

In the present study, electrical resistivity imaging (ERI) was used in order to provide additional detail in the near-

surface. The high resolution ERI surveys successfully revealed evidence of subsurface geologic features due to the high electrical resistivity contrast between unfractured carbonate bedrock and the low resistivity of clay-infilled bedrock fracture zones and solutinal features. The very high resistivity of basalt allowed for the additional imaging of an igneous dike.

Methods

Four ERI lines were completed on two farm properties along State Route 33 near the western limits of the Shenandoah Valley and north of Dry River (Figure 1). The geophysical lines ranged from 790 to 1800 ft (240 to 550 m) in length and had an estimated depth of investigation of 160 to 360 ft (50 to 100 m). The geology of the study area is shown in Figure 1. The ERI surveys were conducted above faulted and folded Cambrian and Ordovician carbonate rocks east of Cooper Mountain. A pseudo 3-dimensional ERI survey composed of 6 parallel profiles was also completed over a covered

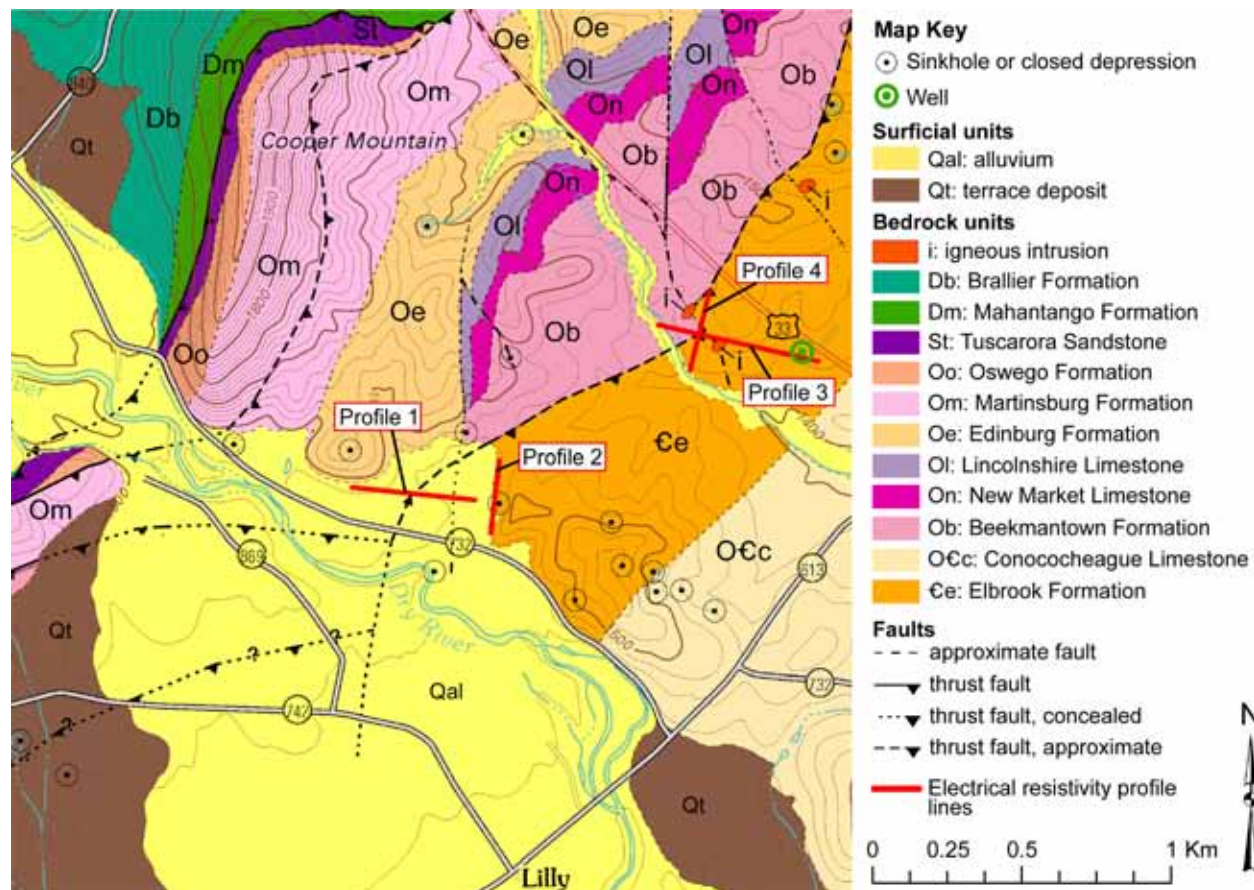


Figure 1. Draft geologic map of the study area located near Lilly, Virginia within the Briery Branch 7.5 minute quadrangle (unpublished mapping by D.H. Doctor). Electrical resistivity profile lines are shown in red.

sinkhole located in the alluvial deposits of Briery Branch (not shown on Figure 1).

Electrical Resistivity Imaging Results

The interpretative results of the 2-D ERI profiles 1–4 are illustrated in Figures 2 and 3. All figures have the same electrical resistivity scale for ease of comparison.

ERI Profile 1 (Figure 2) was completed with 70 electrodes at a 20 ft (6 m) spacing for a total length of 1360 ft (414 m) and a theoretical depth of investigation of 270 ft (83 m). Three resistivity layers are illustrated in the ERI profile. The first layer is approximately 10 to 25 ft thick (2 to 7.5 m) and has moderately high resistivity values that range from 240 to 1500 ohm-meters (yellow to orange). This layer is interpreted as more resistive sandy alluvial deposits which are mapped beneath the entire length of ERI Line 1 terminating and possibly thinning to the west towards the beginning of the line. The second layer has a lower resistivity (<240 ohm-meters) and shows up as blue on the ERI profiles. This layer extends to a depth of approximately 50 to 70 ft (15 to 21 m) below ground surface and is interpreted to represent a combination of clayey soil and

highly weathered limestone bedrock. The increased clay content, water-saturation, and fracture porosity results in the lower modeled resistivity values. The third and deepest layer is high resistivity ranging from 240 to over 4000 ohm-meters. Higher resistivity values represent competent, unweathered bedrock with a low saturated fracture porosity. Low resistivity zones detected below the suspected bedrock interface likely represent zones of increased fracture concentrations (e.g., saturated bedrock fracture zones), or soil-clay-water infilled solution voids within the carbonate bedrock. Such zones would have higher saturated fracture porosity and possibly clay content and are therefore more electrically conductive and would have a lower resistivity than the surrounding less fractured, drier bedrock. Air-filled voids would also be highly resistive and may have little contrast from the unfractured bedrock.

Two sub-vertical low resistivity zones can be observed in ERI Profile 1; both appear to be steeply dipping to the southeast and appear to project to the surface in the vicinity of electrodes #35 and #53. These features may represent underlying zones of increased brittle fracturing and karst weathering in the underlying bedrock. These

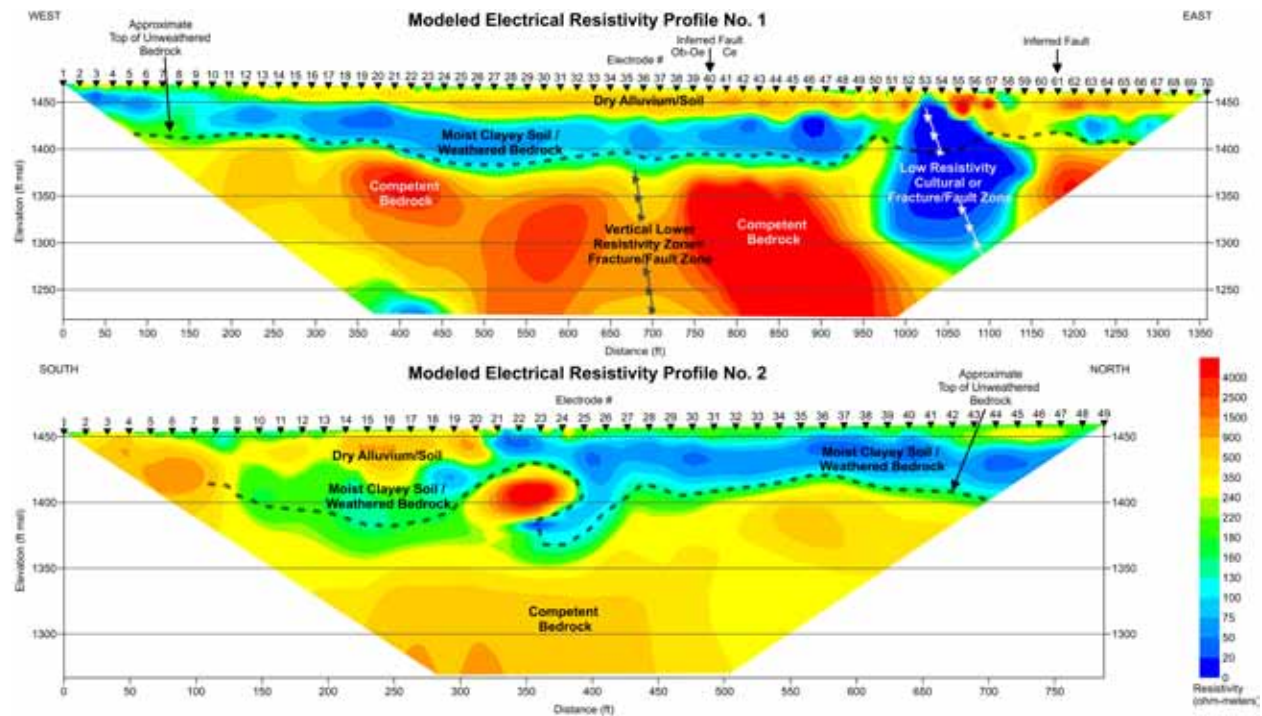


Figure 2. ERI Profile 1 (upper panel) and Profile 2 (lower panel). Note the presence of lower resistivity fracture/fault zones in the Profile 1, which correspond to inferred fault locations beneath the alluvium of the floodplain of Dry River (Figure 1). In Profile 2, a sinkhole is located at the surface near electrode 21 (1 ft=0.3048 m).

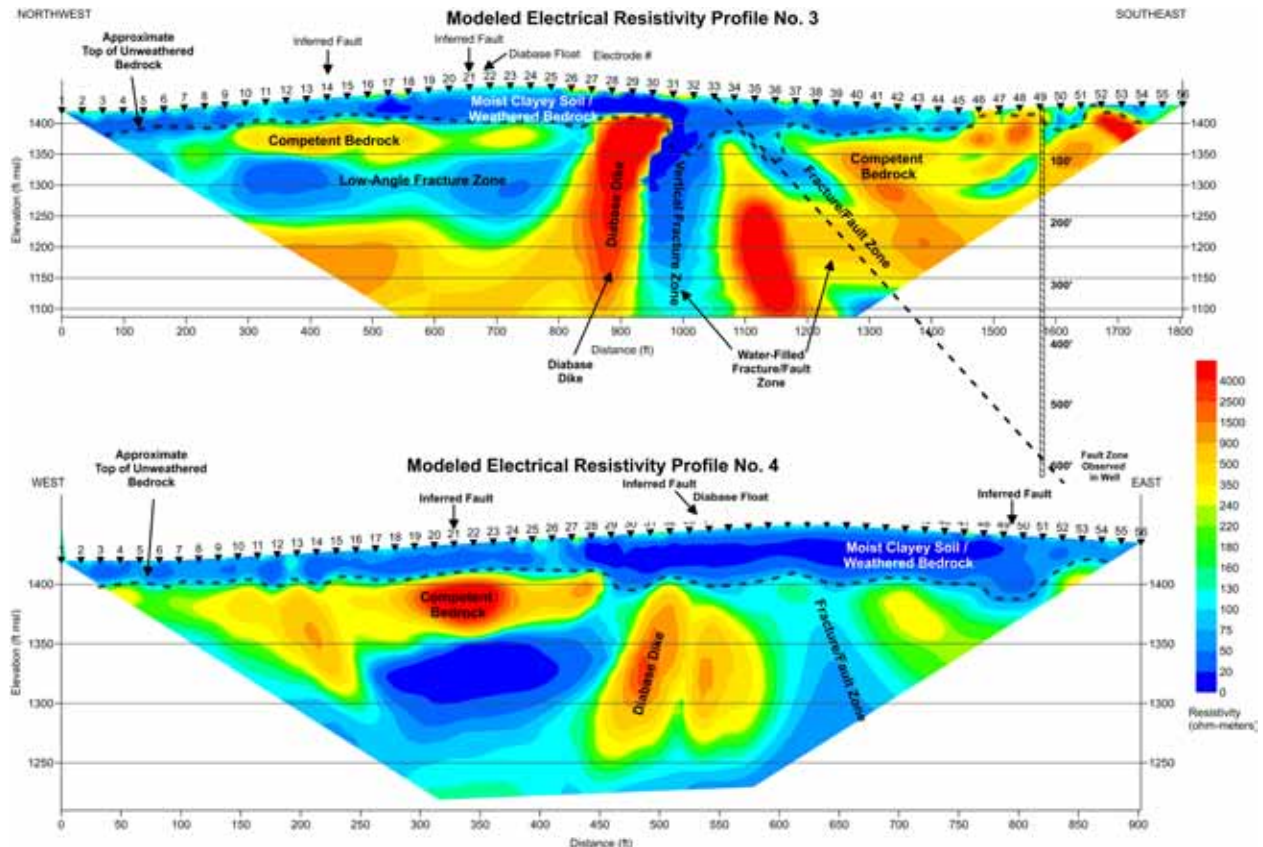


Figure 3. Electrical resistivity Profile 3 (upper panel) and Profile 4 (lower panel). Low resistivity zones are interpreted as water-filled fracture zones possibly associated with faulting, and contact metamorphism. Vertical high resistivity zones coincide with mapped diabase dikes. A fault zone observed in Simmons Well shown in Figure 1 appears to correspond with a southeast-dipping low resistivity fracture zone in Profile 3. 1 ft=0.3048 m.

features are near and possibly coincidental with the two mapped faults shown in Figure 2.

While in the field, we were informed by the landowner that an old metallic shed and other trash partially fill a sinkhole that had formed in the zone of extreme low resistivity near the east end of Profile 1. Therefore, this is a zone of potential cultural interference that explains the unusually large zone of low resistivity.

ERI Profile 2 (Figure 2) was completed with 49 electrodes at a 16 ft (5 m) spacing for a total length of 790 feet (240 m) and a theoretical depth of investigation of 160 feet (50 m). A similar three resistivity layer model is observed in this profile. The shallow high resistivity (alluvium) layer occurs beneath the southern half of the line and thins or is absent to the north away from Dry River. The second layer (clayey soil and highly weathered limestone bedrock) extends to a depth of approximately 40 to 70 ft (12 to 21 m). The underlying

bedrock appears competent with no identifiable low resistivity zones. An open-throat sinkhole was observed at the surface adjacent to electrode #22, and a possible bedrock pinnacle may occur just beneath it in the vicinity of electrodes 20–24, with a sediment-filled conduit extending below the pinnacle to a depth of nearly 100 ft (30 m).

ERI Profile 3 (Figure 3) was completed with 56 electrodes at a 33 ft (10 m) spacing for a total length of 1800 ft (550 m) and a theoretical depth of investigation of 360 ft (110 m). ERI Profile 4 (Figure 3) was completed with 56 electrodes at 16 ft (5 m) spacing for a total length of 900 ft (275 m) and a theoretical depth of investigation of 180 ft (55 m). ERI Profiles 3 and 4 can be described using a 2 layer resistivity model since the resistive surficial alluvium layer is missing. The profiles therefore have a surficial low resistivity layer (shown in blue) representing clayey soil and highly weathered limestone bedrock overlying a higher resistivity layer representing

competent bedrock. Low resistivity zones detected below the suspected bedrock interface likely represent fracture zones or karst voids possibly related to inferred fault locations. Sub-horizontal low resistivity zones may be stratigraphically controlled or may represent low-angle thrust zones. Sub-vertical low resistivity zones may represent steeply-dipping fracture or fault zones, such as high angle transverse faults, or may be related to increased fracture permeability found in the contact zone around a vertical diabase dike (Figure 3). Steeply-dipping high resistivity zones observed in the profiles are interpreted to represent an igneous dike, as float of basalt was observed at the surface (Doctor et al., 2014).

Pseudo 3-D ERI Profiles of a Sinkhole

A pseudo 3-Dimensional electrical resistivity imaging survey was completed over a closed circular depression with internal drainage believed to represent a cover-subsidence sinkhole. The underlying karst feature or sinkhole is covered by unconsolidated alluvial deposits that are mapped surrounding the Briery Branch alluvial fan. The alluvium is between 50 and 80 ft (15 to 24 m) thick and composed of weathered sand and gravel deposits. The resultant subsidence sinkhole forms a broad, shallow circular depression. Six ERI profiles were completed across the sinkhole in a northwest to

southeast orientation as shown in Figure 4. Each ERI line was deployed with 28 electrodes with an electrode spacing of 16 ft (5 m) and a line spacing of 33 ft (10 m). The depth of investigation for the survey was approximately 100 ft (30 m). The ERI data was analyzed as 2-D profiles and merged into a pseudo 3-D matrix and analyzed as a 3-D ERI survey. The interpretative results of the pseudo 3-D survey is shown in Figure 4.

The sand and gravel alluvium and underlying bedrock are imaged as moderately high resistivity layers. A thin circular deposit of low resistivity material occupies the center of the depression, likely reflecting the accumulation of fine silt, organic-rich soil and high soil moisture in the central part of the sinkhole. This low resistivity layer thickens to the northeast side of the circular depression where a deep, vertical low resistivity zone is imaged. This feature is believed to be the outlet pipe for the sinkhole representing a solution-widened, sediment and clay-infilled cavity if it is in the bedrock, or possibly a soil pipe if it is in unconsolidated alluvium. Piping and raveling of alluvial sediment into the underlying karst voids likely formed this soil-covered sinkhole. Note that the outlet pipe of the sinkhole is not situated in the center of the depression.

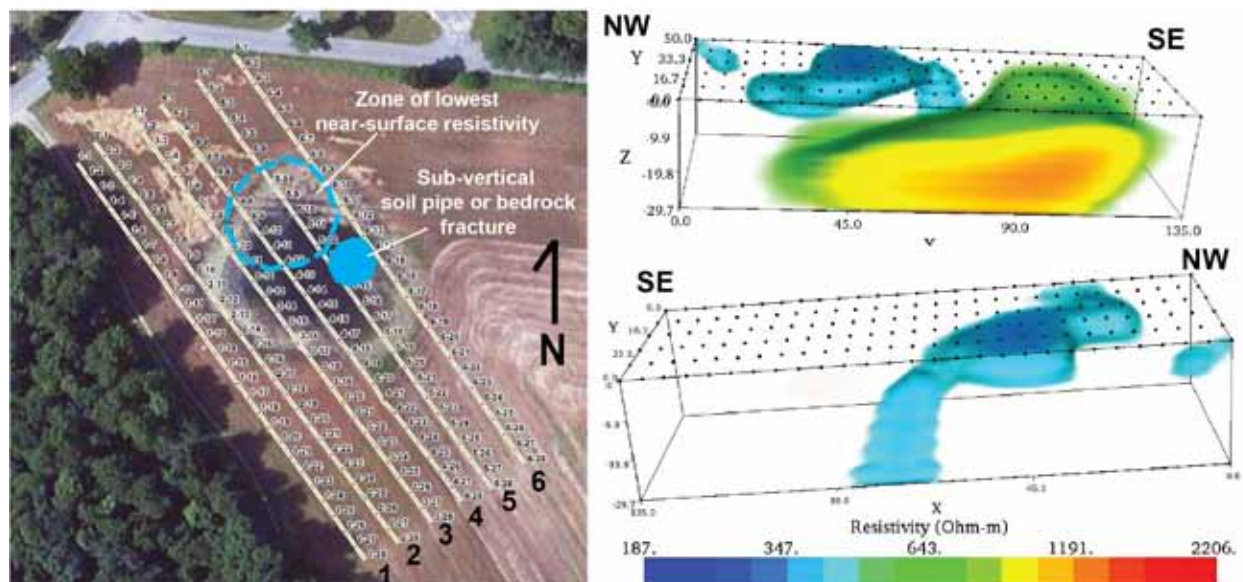


Figure 4. Location map and pseudo 3-D ERI results of a geophysical survey completed over an ephemerally ponded circular depression interpreted as a cover-subsidence sinkhole. The sinkhole is situated within alluvial fan deposits in the floodplain of Briery Branch, and is located at the intersection of State Route 731 and 750, approximately 5 miles southwest of Dry River where the ERI survey locations shown in Figure 1 were completed. Moderate and high resistivity values are not shown in the pseudo-3D ERI profiles.

Conclusions

This study demonstrated that the use of high resolution electrical resistivity imaging can be useful for confirming the presence and refining the location of geologic features and structures where overburden deposits may obscure such details. In this instance, ERI was used to help map faults, diabase dikes, alluvial deposits, and karst features in folded and faulted carbonate bedrock in the western Shenandoah region of Virginia. ERI successfully revealed evidence of subsurface geologic features due to the high contrast between the high electrical resistivity of unfractured carbonate bedrock and the low resistivity of clay-infilled bedrock fracture zones and solutional features. The very high resistivity of basalt allowed for the additional imaging of an igneous dike. ERI surveys were equally successful in detecting areas of carbonate bedrock covered with an alluvium, and where only weathered residuum covered the bedrock. Solutional karst development along the faults is evidenced by low resistivity values extending to depths greater than 100 feet in the fault zones. This study also demonstrates the utility of using ERI surveys for detecting karst development along zones of deformation in folded and faulted carbonate bedrock.

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INVESTIGATING SUBSURFACE VOID SPACES AND GROUNDWATER IN CAVE HILL KARST USING RESISTIVITY

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Abstract

For this study, we selected two sites on Cave Hill at the Grand Caverns Natural National Landmark near Grottoes, Virginia, on the basis of existing surficial features, with the idea of exploring the connection between these features and the karstic subsurface using electrical resistivity (ER). The first of these, in the southern section of the hill, is a large swale. The second, a sinkhole located further north, was chosen in part because it is also the site of a U.S. Geological Survey (USGS) study investigating soil moisture content.

At the swale, the resistivity sections suggest that groundwater flows along bedding planes along the trend of an synform fold axis which is situated approximately parallel to and beneath the swale feature. For the resistivity lines crossing through the sinkhole, the inversion profile images show several potential perched aquifers, situated between the caverns and the sinkholes at the surface. The caverns were also imaged along with the water table approximately 70 meters below the surface.

The results indicate that bedding geometry and rock type are the dominant factors that define groundwater distribution and karstic features within Cave Hill. Specifically, a calcareous quartz arenite ridge defines a lithologic boundary with the limestone at which many of the sinkholes form and concentrated groundwater recharge appears to originate.

Introduction

Grand Caverns Natural National Landmark lies in the southeastern Shenandoah Valley of Virginia and is home to the oldest show cave in the United States. The park and adjacent private lands include a complex of at least five known caves: Grand Caverns, Madison Cave, Steger's Fissure, Jefferson Cave, and Fountain Cave, all within the northern section of Cave Hill karst. The cave complex lies below a series of sinkholes that run in two approximately north to south parallel lines.

The location of void spaces and water pathways in the subsurface can give insight into the structure of a specific karst environment, including the relationship between these and the epikarst. Electrical resistivity is particularly useful in locating these features because void spaces are more resistive and groundwater is more conductive than surrounding bedrock of low permeability (Palacky, 1987).

Figure 1 shows the two selected sites on Cave Hill and cross-section locations. At the swale at location 1, we collected seven 14 electrode (81 m) ER lines (Figure 2a), four running approximately perpendicular to the swale

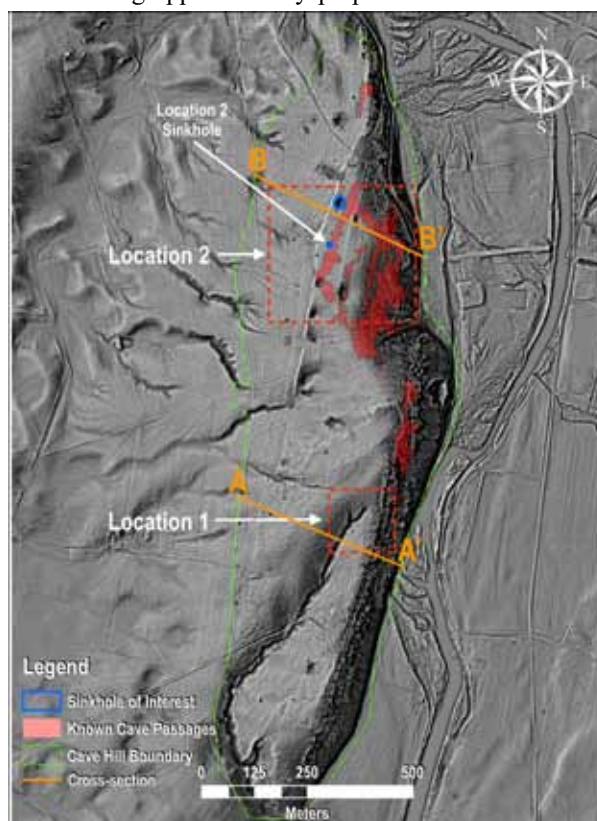


Figure 1. Locations of two surface features of interest on Cave Hill showing the combined hillshade + Topographic Position Index (TPI) image, and known cave passage overlay. (Maps courtesy of D.H. Doctor, USGS.)

(SW01-04) and three roughly parallel, one through the center (SW05) and one on each side (SW06 and SW07). For the sinkhole at location 2 (Figure 2b), we collected one 56 electrode (344 m) ER line roughly parallel to a line defined by the westernmost series of sinkholes (GCDD09), and a 28 electrode (169 m) ER line perpendicular to the first and centered on the sinkhole (GCDD10). Centered on the selected sinkhole, the 56 electrode line also ran across a larger sinkhole to the north and adjacent to another sinkhole to the south. The

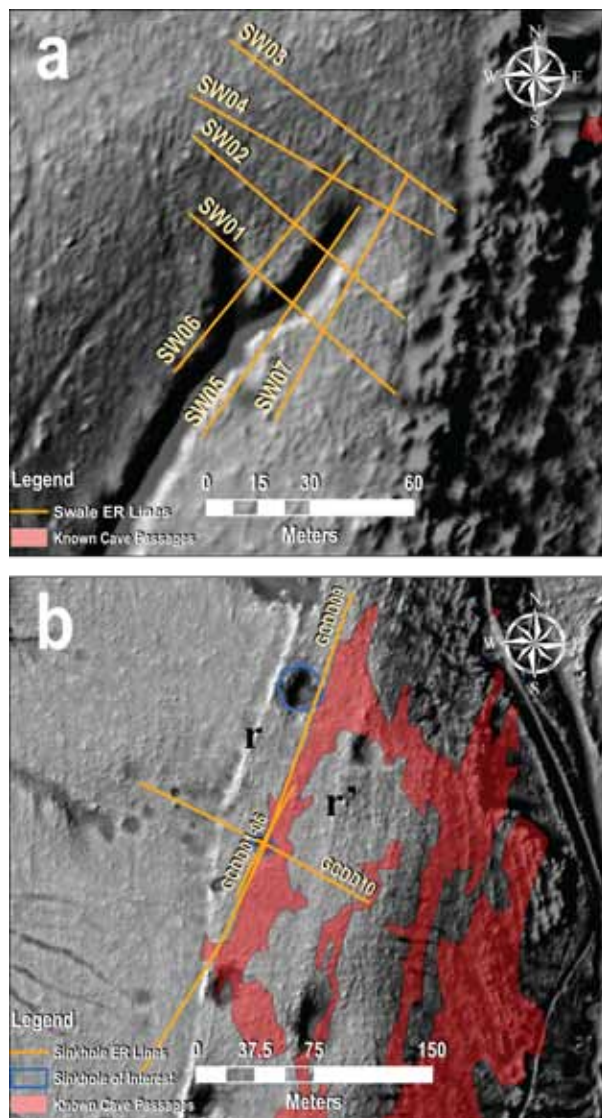


Figure 2. (A) ER lines deployed at location 1. (B) ER lines deployed at location 2. *r* and *r'* represents calcareous arenite and dolostone ridges respectively. Background is a LiDAR-derived hillshade + TPI image and overlain with known cave passages (courtesy of D.H. Doctor, USGS).

resulting ER images were interpreted within the context of geologic cross-sections, a high resolution airborne-derived LiDAR digital elevation model (DEM), and known surface features and known cave passage locations at depth.

Geological Setting

The Shenandoah Valley is part of the Valley and Ridge province of Virginia, and is nestled between the Blue Ridge fault to the east and the Little North Mountain fault to the west. These faults are part of a western verging foreland fold and thrust belt formed during the Alleghenian Orogeny when Gondwana collided with Laurentia (Faill, 1998; Rader and Gathright, 2001). The valley is underlain by both siliciclastic and carbonate bedrock primarily deposited in marine environments during the Paleozoic (Rader and Gathright, 2001).

Within the valley bedrock are Cambrian and Ordovician carbonate units deposited as divergent continental margin (DCM) sediments between the rifting of the Rodinia supercontinent and Taconic Orogeny (Rader and Gathright, 2001). These DCM units consist of the Shady, Rome, Elbrook, Conococheague, Stonehenge, Beekmantown, New Market, and Lower Lincolnshire formations (Rader and Gathright, 2001).

Cave Hill is situated within the Cambrian age Conococheague Formation, which generally consists of laminated light- to dark-grey dolomitic limestone, thinly-bedded flat pebble conglomerate layers, coarse-grained calcareous quartz arenite, algal-laminated dolostone and limestone that frequently contains mudcracks, ribbon rock, and chert (Gathright et al., 1978). These sedimentary structures suggest deposition of the Conococheague was primarily influenced by cyclic eustatic sea-level changes within an environment that was dry and arid at times (Weber et al., 1995; Read and Repetski, 2012).

The South River flows alongside the eastern flank of Cave Hill. Much of the cavern passages within Cave Hill are located above river level; however, parts of Madison Cave and Steger's Fissure extend downward as deep as 30 meters below river level (Kastning, 1995). Doctor et al. (2014) suggest that both Grand Caverns and Madison Cave were phreatically formed due to the presence of subaqueous calcite coatings as well as local clay and silt sized sediments with an absence of foreign sand,

gravel, and cobble sediments. The evolutionary biology of the phreatobitic crustacean *Antrolana lira*, commonly known as the Madison Cave isopod, found in Madison Cave and unique to the Shenandoah Valley, suggests the initiation of the formation of Cave Hill karst occurred a minimum of 20 million years ago (Hutchins et al., 2010; Doctor et al., 2014).

Data & Methods

Electrical Resistivity

All ER measurements were collected with the AGI SuperSting R-1 geoelectrical imager. For most lines, xyz-coordinates were collected at each electrode using a Leica Zeno 20 GPS unit. The Zeno 20 can obtain horizontal accuracy to 1cm and vertical accuracy to three times the achieved horizontal accuracy. For most locations, we were able to collect good data; occasionally complicated by heavy cloud cover or overhead foliage. The suspect electrode locations and all elevation values were interpolated by using a 1 meter high resolution airborne LiDAR-derived digital elevation model (DEM) obtained from the USGS National Map website (<https://viewer.nationalmap.gov/basic/>).

Measured ER data were processed using AGI's EarthImager® 2D Resistivity and IP Inversion Software. We achieved the best results for each line using merged Schlumberger and Dipole-Dipole data sets for the inversions.

Structural Geology and Geospatial Investigation

We obtained strike and dip measurements from 17 outcrops on Cave Hill, and recorded observations of rock type and other notable characteristics such as sedimentary structure, fold patterns, and proximity to cave entrances. Trend and plunge of two fold axes were approximated using stereonet generated by Stereonet 9.9 (Allmendinger, Cardozo, and Fisher, 2013; Cardozo and Allmendinger, 2013).

We exported two elevation profiles across Cave Hill and perpendicular to the two fold axes from the Global Multi-Resolution Topography (GMRT) Grid Version 3.3 (Ryan et al., 2009) in GeoMapApp (Marine Geoscience Data System, 2013), which were used with the structural data to draw two cross-sections (Figure 3).

We imported the 1 m DEM into ArcGIS® to create a polyline shapefile representing the paths in which

surficial water would flow on Cave Hill (i.e., artificial streams), using the hydrology tools for flow direction and flow accumulation from the Spatial Analyst toolbox. This result was combined with an elevation image of hillshade overlain by the topographic position index (TPI) and the cross-sections to correlate the inverted ER profiles with the surface features.

Results

Structural Geology and Geospatial Investigation

Bedrock near location 1 primarily consists of algal laminated dolostone and micrite. We determined the structure of the southern portion of Cave Hill consists of three higher-order folds within an overall anticline (Figure 3a), and we observed parasitic folding in algal laminated dolostone on the southeastern flank. The swale feature cuts through a syncline at the study location. Further South (~80 m), the swale feature deviates

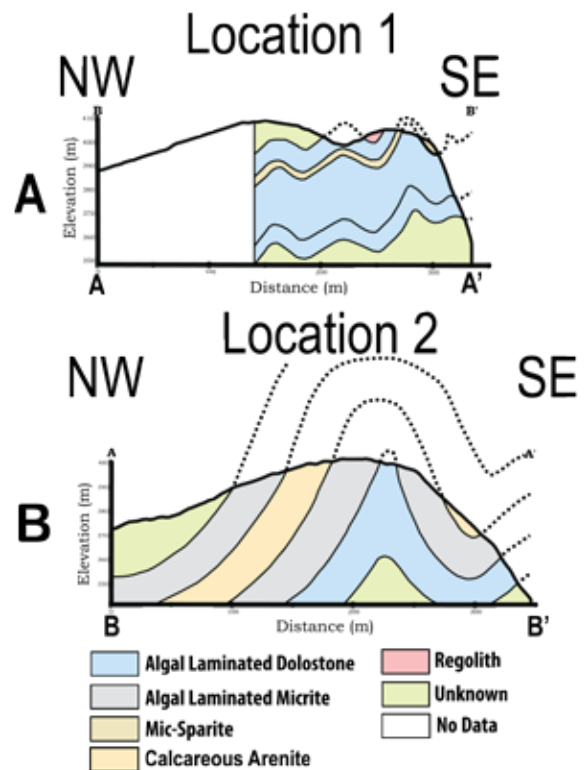


Figure 3. (A) Location 1 cross-section shows high-order folding within an overall syncline. (B) Location 2 cross-section shows sub-vertical bedding and an overall anticline. Refer to Figure 1 for cross-section location. A and B, after profiles exported from the GMRT Grid Version 3.3 (Ryan et al., 2009) in GeoMapApp (Marine Geoscience Data System 2013).

westward from strike (~30 m) and begins to cut through the antiform axial fold.

Bedrock near location 2 consists of algal laminated micrite, algal laminated dolostone, and calcareous arenite. The rock units here are incorporated into an anticline-syncline pair (Figure 3b). A thick bed of micrite located between calcareous arenite to the west and algal laminated dolostone to the east lies under the ER deployment area. Survey GCDD09 crossed diagonally (~20°) over the arenite bed.

The artificial streams generated from the DEM indicate that surface water flows into the swale feature (location 1) primarily from the northwest (Figure 4). This is consistent with the stereonet we generated from the geologic data, showing that the fold axis on the southeastern flank of Cave Hill, near location 1, trends ~206° SSW and plunges ~15°, while the fold axis on the western flank, near location 2, trends ~214° SSW and plunges ~20°. The swale deviates the surface water along strike to the SSW where it is able to flow freely into a local stream. Surface water at location 2 flows to the northwest; however, a calcareous arenite ridge, identified both in the field and with the aid of a hillshade + TPI map, appears to block most surface water from flowing directly into local streams. Instead, surface water is forced into the subsurface through sinkholes located along the eastern side of the ridge. There is also a second parallel ridge located to the East (~50 m) that appears to be acting in a similar manner.

Electrical Resistivity Near the Swale

The 14 electrode lines we deployed at this site resolved the resistivity structure to a depth of slightly less than 20 meters. The background resistivity for all sections ranged from semi-conductive (333–1,000 Ωm) (Figure 5, [a]) to moderate values (~1,000–3,333 Ωm) (Figure 5, [b]).

Horizontal to sub-horizontal oblong conductive features (<333 Ωm) are present within the upper subsurface (<10 m) (Figure 5, [c]); section SW06M has a single conductive layer extending across the entire section (Figure 5b, [SW06], [c]). Deeper in the subsurface (≥ 10 m), sections SW01M, SW03M, SW04M, SW05M, and SW06M show resistive features (>3,333 Ωm) towards the edge of our depth resolution (Figure 5, [d]). Sections SW02M, SW03M, and SW06M each contain one resistive (>3,333 Ωm) small ovoid feature in the upper subsurface (Figure 5, [d']).

Electrical Resistivity Near the Sinkhole

We were able to resolve the resistivity structure to approximately 82 meters for GCDD09M and 40 meters for GCDD10M. The sections all consisted of moderate background resistivity values (1,000–6,250 Ωm) (Figure 6, [b]). The upper-subsurface (<10 m depth) contains a band (~5 m thick) of horizontally to sub-horizontally oriented semi-conductive (250–1,000 Ωm) to conductive oblong features (<250 Ωm) (Figure 6, [c]). The angle of orientation of the conductive bands become steeper (~15°–60°) and thickness generally increases from topographic high areas towards sinkhole features at which they plunge to deeper depths (~25 m depth) (Figure 6, [c']). Jagged semi-conductive layering (625–1,000 Ωm) is present in the deepest portions of GCDD09M (~65–82 m depth) (Figure 6a, [c'']).

Resistive ovoid shaped features (~6,250–10,000 Ωm) are oriented under the conductive bands (~10–16 m depth) such that their major axes (~6–20 m length) are parallel to the sides of the sinkhole (Figure 6a, [d']). At depth

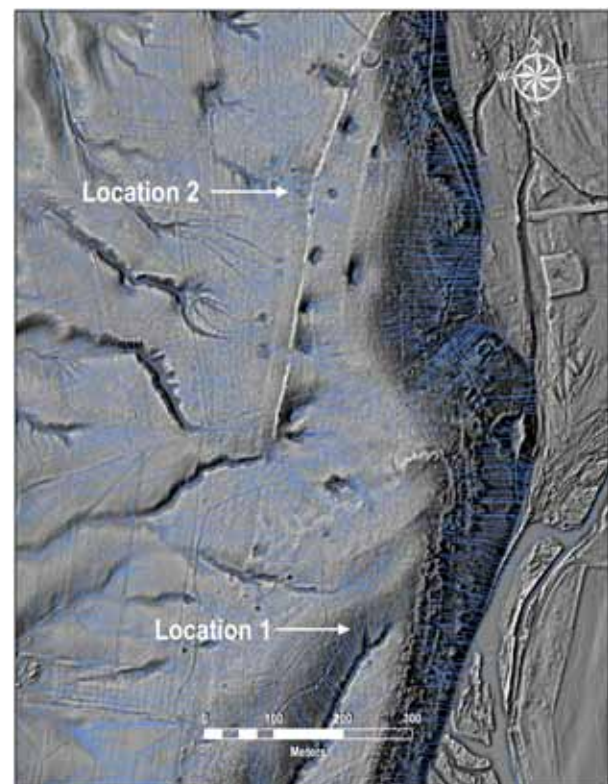


Figure 4. Artificial streams representing the paths in which surficial water would flow on Cave Hill. Background is a LiDAR-derived hillshade + TPI image (courtesy of D.H. Doctor, USGS).

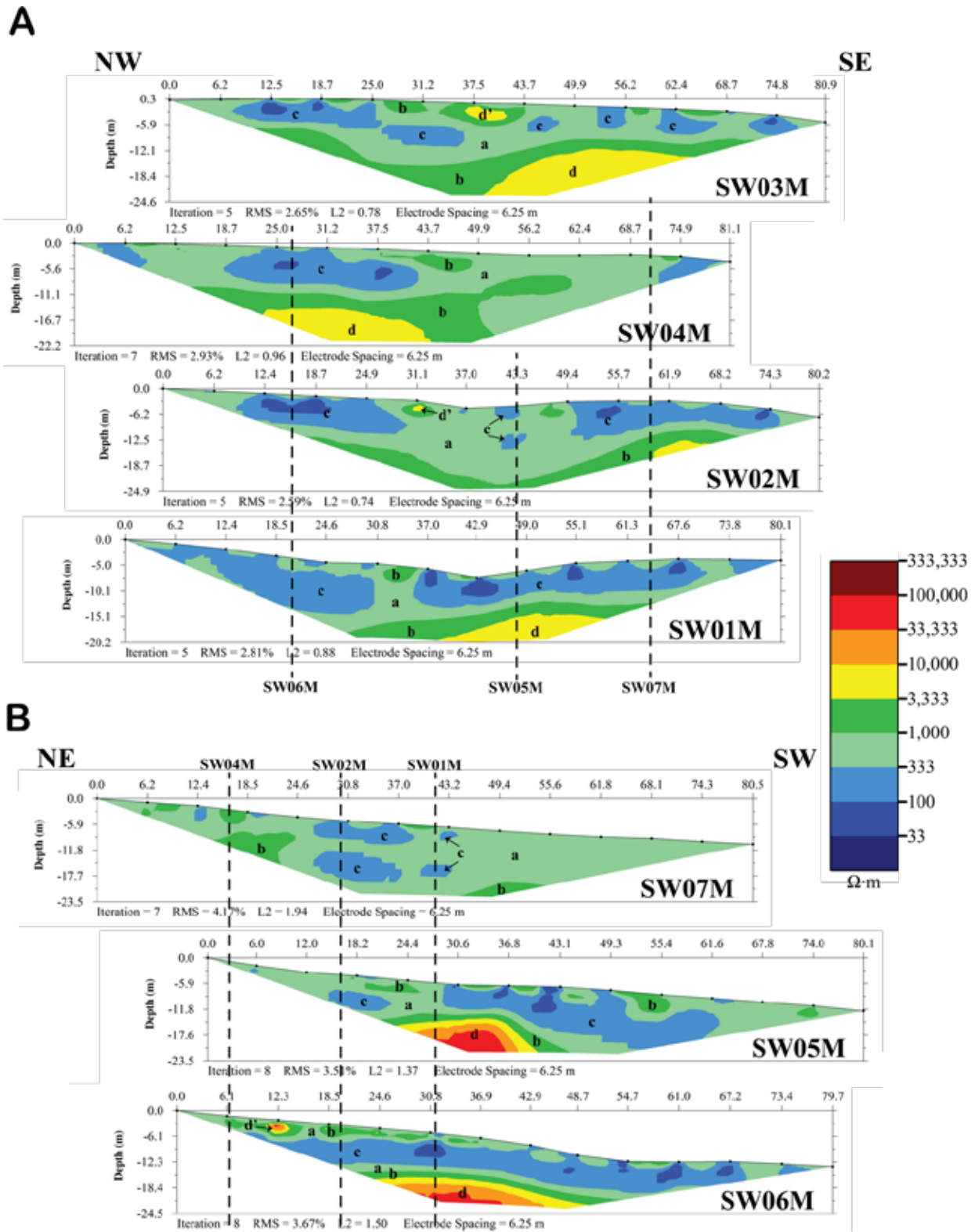


Figure 5. Location 1 ER sections. (A) southeast to northwest sections situated approximately perpendicular to the swale feature. (B) northeast to southwest sections situated approximately parallel to and within the swale feature.

(~16–45 m), are larger resistive (~6,250–25,000 Ωm) ovoid features (~30–50 m length) (Figure 6a, [v]). There is an area on the southwestern side of GCDD09M that contains an extremely-resistive ovoid feature (>100,000 Ωm) oriented between two conductive bands (Figure 6a, [d'']).

Discussion

Soil survey data suggests the soil profile consists of eroded loam to silty loam and is approximately 1.83 meters thick through the B horizon (USDA, 2016). Since the soil profile is thin, its presence can generally be excluded from the ER sections; although it is a component in regolith, which is made up of soil and weathered bedrock. Loam has resistivity values between 20 and 160 Ωm (Angenheister 1982), and limestone and dolomite are generally 1,000 Ωm (Palacky, 1987; Stepišnik, 2008; Ishmail and Anderson, 2012), but can range as high as 100,000 Ωm (Palacky, 1987). Stepišnik (2008) reported limestone rubble and soil containing weathered bedrock to range between 200 and 1,000 Ωm . Ishmail (2012) stated the transition zone between soil and bedrock can range between 105 and 900 Ωm .

The resistivity value of all subsurface material is dependent on how water saturated the material is (Palacky, 1987), and decreases almost uniformly with increasing water saturation (Suau and Spurlin, 1982). Therefore, we interpret highly-saturated, saturated, and little- to non-saturated regolith to be <1,000 Ωm . Zhu

et al. (2011) showed, with borehole conformation, that ER was successful in finding water saturated areas, but could not distinguish between water filled conduits and saturated ground with ER alone, which will not be attempted by this study.

Knowing that limestone resistivity can be as high as 100,000 Ωm , we can deduce that values greater than this are likely open air voids. Open air void spaces and caves are generally considered to have higher resistivity than the surrounding bedrock due to the near-infinite resistivity of air (Gibson et al., 2004; Mitrofan et al., 2007; Chalikakis et al., 2011; Ismail and Anderson, 2012; Martínez-Moreno, 2014). Models compared to ER sections with known caves by Martínez-Moreno (2014) suggested that caves should be irregular to ovoid shaped and increase in resistivity from the edges to the center.

Location 1, Karstic Swale

We interpret the near surface conductive features in these sections to represent regolith or weathered bedrock (with increased clay mineral content), through which water would be able to infiltrate. This is evident from the correspondence of conductive anomalies between SW06M and SW05M with SW01M, SW02M, and SW04M (Figure 5), and is similar to the results produced by Roningen and Burbey (2012) and Carriere (2013). This flow direction is consistent with what we would expect given the antiform fold axis plunge. The isolated conductive area of SW07M (Figure 5b [SW07M], [c])

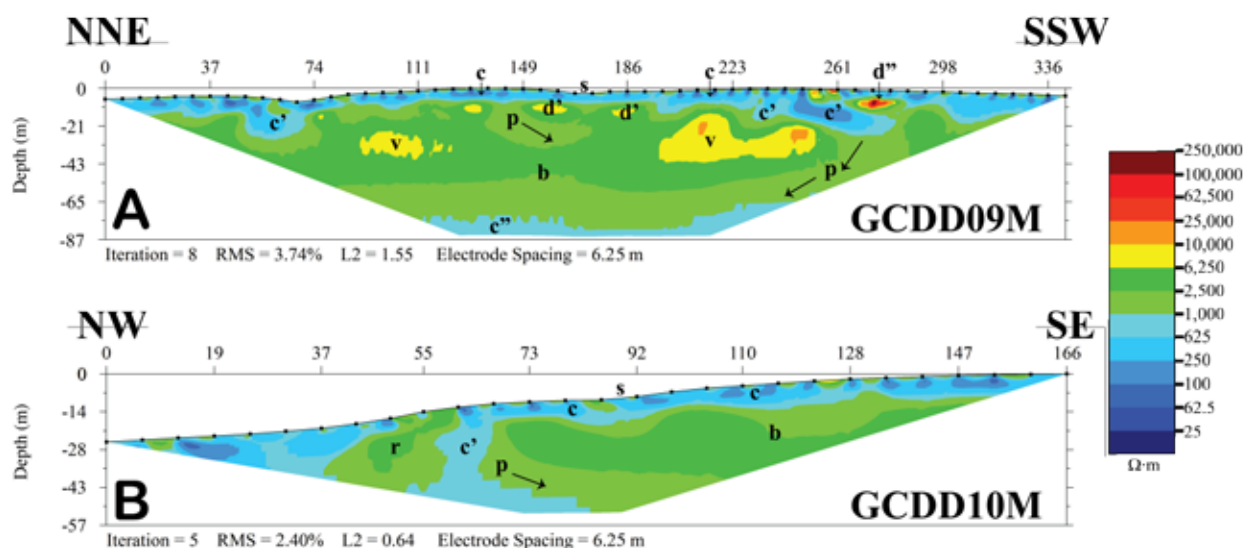


Figure 6. Location 2 ER sections centered over sinkhole. (A) north-northeast to south-southwest 56 electrode section (B) southeast to northwest 28 electrode section. *s* marks the location of the USGS soil moisture survey.

along with the near absence of bedrock seems to indicate that water infiltrates downward through unconsolidated material until it reaches and flows along bedrock. Resistive to highly-resistive anomalies (Figure 5, [d] d) are possibly permeable bedrock beneath the areas of weathered bedrock near the surface. It is possible that the more resistive of these features are sampling open air void spaces or caves either too deep to resolve or slightly off line, but this cannot be shown conclusively.

Location 2, Caverns

We interpret the conductive regions near the surface (Figure 6, [c]) to be semi-saturated to saturated soil and regolith, with the bottom of the conductive regions marking the transition into bedrock. In some places (Figure 6, [c']), the conductive regions penetrate the bedrock to depths of as much as ten meters, forming a network of preferred groundwater pathways or perched aquifers (the 2d nature of the survey make it impossible to distinguish between these two possibilities). Three of these features are situated under sinkholes that have formed along the eastern side of a calcareous arenite ridge (Figure 2b, [r]; Figure 6b, [r]), which dips ~69° NW. A second dolostone ridge exists approximately 50 meters to the east (Figure 2b, [r']), with a second row of sinkholes to the east of that ridge; it seems likely that similar aquifers exist here as well, especially given the presence of caverns below (Figure 2b), but our lines did not extend this far southeast. The calcareous arenite ridge that is included in our survey appears to interrupt the flow of surface and shallow groundwater flow to the west/northwest, causing the water to infiltrate into the ground at its eastern boundary as shown by the aquifer (Figure 6b, [c']), the largest and deepest saturated area between the two ridges. Furthermore, the specific placement of the sinkholes along the ridge seems to be associated with the portions of the ridge that are more strongly detectable at the surface; the DEM artificial stream models show that sinkholes have not formed where the surface water is able to penetrate the ridge.

The infiltrating water images in Figure 6b reaches depths at the limits of resolution (nearly 50 m), and likely continues past the capillary fringe and into the water table approximately 70 m below the surface (Figure 6a, [c']), equivalent to the depth of the river that runs at the base of the hill. Between the aquifers and the water table, we note several resistive features (Figure 6a, [d', v]) that partially capture portions of the known cavern complex below (at

least in the case of [v]; the features in [d'] are likely smaller, shallower, and previously undetected void/ partially void spaces. These anomalies have higher resistivity than the surrounding bedrock, but they are not as high as what is expected for an open air cave. This is likely due to the lines being on the edge and/or slightly offset from the known cave passages. An additional small highly resistive feature (Figure 6a, [d'']) is likely a void space, either being more genuinely resistive than the [v] features, or more directly sampled. The bedrock seems to exist at a range of resistivity (Figure 6, [b]), from approximately 1,000 Ωm to 6,250 Ωm . The more conductive regions may directly correspond to the more saturated areas, and while to some extent this could be an artifact of the smoothing process inherent in the inversion, it could also identify groundwater pathways through the carbonate bedrock from the aquifers to the caves and/or water table below (Figure 6, [p]).

Conclusions

This study provides significant insight to the factors governing surface and groundwater transport, sinkhole formation, and cave formation at Cave Hill. We found these features to be largely determined by rock type and bedding orientation, which differs from location to location, leading to the formation of different surface features and different water pathways and void geometries in the subsurface.

At the swale, we were able to show a clear image of the surface water and shallow subsurface groundwater flow, with water in the saturated regolith appearing to flow along bedding planes in the approximate direction of an antiform plunge. Our data did not sample to depths required to image the full karst system at this location, and therefore we are not able to confirm the presence of any void spaces, despite the higher resistivities towards the bottom of the sections that might suggest their existence. We were also not able to show the water pathways all of the way from the surface to the water table.

At the sinkhole, ridges, formed from rock less prone to dissolution, block the surface runoff of rain and meltwater, and force groundwater infiltration on the western flank of the ridges along the steeply dipped bedding planes. Over time, dissolution increases the porosity the carbonate bedrock, ultimately causing the formation of voids and sinkholes. This process, along with a fluctuating water table, helped to carve out the large cavern complex we see today.

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ROLE OF FLOODS ON SINKHOLE OCCURRENCE IN COVERED KARST TERRAINS: CASE STUDY OF THE ORLÉANS AREA (FRANCE) DURING THE 2016 METEOROLOGICAL EVENT AND PERSPECTIVES FOR OTHER KARST ENVIRONMENTS.

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Abstract

The Loire River basin is regularly impacted by sinkholes because of its specific geological context, karstic limestone overlain by soft cover deposits. The intense rainfall event and the associated floods that occurred in this area in May and June 2016 triggered tens of sinkholes in a few square kilometers. At least 20 houses, one flood protection dyke of the Loire River and two highways were damaged by collapses. These events highlight not only the vulnerability of the area, especially in the case of a disastrous flood of the Loire River, but also the unexpected kinetics of the collapse process.

Two different types of sinkholes occurred in the impacted areas: north of Orléans, collapses of the filling of vertical caves are suspected; in the Loire valley, the flood accelerated the internal erosion of alluvium in the karstic active network, triggering cover collapses (spatial and temporal sinkhole frequency increased by an estimated factor of 16,000 to 24,000).

In parallel, an innovative internal erosion numerical modeling approach, based on Discrete Element – DEM and Lattice Boltzmann methods – LBM, has been developed through a partnership between the French Geological Survey (BRGM) and the Environment and Agriculture National Research Institute (IRSTEA). The upward propagation of cavities within the cover were successfully simulated. The role of different parameters (soft cover cohesion, hydraulic head, system geometry, etc.) in the sinkhole occurrence were tested by a parametric analysis.

Introduction

A large amount of water is usually considered to be an aggravating factor for the occurrence of sinkholes (Hyatt et al., 1996; Gordon et al., 2012). In France, the meteorological event of spring 2016 constitutes a new example of that assertion. Beyond the simple statement, lessons learned from this event enabled the French Geological Survey (BRGM) and the Environment and Agriculture National Research Institute (IRSTEA) to improve the understanding of internal erosion processes.

General & Geological Context

The Beauce Karstified Limestone

The city of Orléans is located 130 km south of Paris, in the Loire Valley. The Beauce limestone, a 50 to 90 m thick Tertiary lacustrine limestone, constitutes the geological bedrock (Lorain, 1973). On both sides of the Loire Valley, the Beauce limestone is overlain by other Tertiary sediments (a few meters thick) and the groundwater level is between 10 to 20 m deep. In the Loire floodplain, the limestone is mantled by Quaternary alluvium (5 to 15 m thick) (Figure 1). In these areas, the groundwater level is near the ground surface.

An extensive karstic cave network is assumed to underlie the area but, except for a few sites, our knowledge of network configuration is relatively poor. Speleological investigations are limited by the very few cave entrances and the water-filled nature of the karst system. The exceptions are the Loiret springs where about 4.3 km of passages have been explored by scuba divers

(Boismoreau, 2008) and some caves in the Orléans Forest (Moreau, 2002). Sinking stream, springs and the sinkhole activity in the 170 km² of the Loire floodplain around Orléans attest also to the current activity in the Beauce limestone karst terrain (Figure 1). Total water losses from the Loire to the karst aquifer are between 7 and 20 m³.s⁻¹ (Gutierrez and Binet, 2010). Water returns to the Loire River by springs and rivers (Lepiller, 2006), such as the Loiret River.

Sinkhole History in the Orléans Area

Studies undertaken since 1903 counted approximately 640 sinkholes in the Loire floodplain around Orléans (Gombert et al., 2015; Perrin et al., 2015; Figure 1). The latest reported sinkholes occur at a rate of 3 to 4 per year. A lot of them are probably backfilled without official reporting. Thus, the minimal sinkhole frequency is approximately 0.02 to 0.03 occurrences per square kilometer per year. The mean diameter of the holes is 1 to 2 m but can

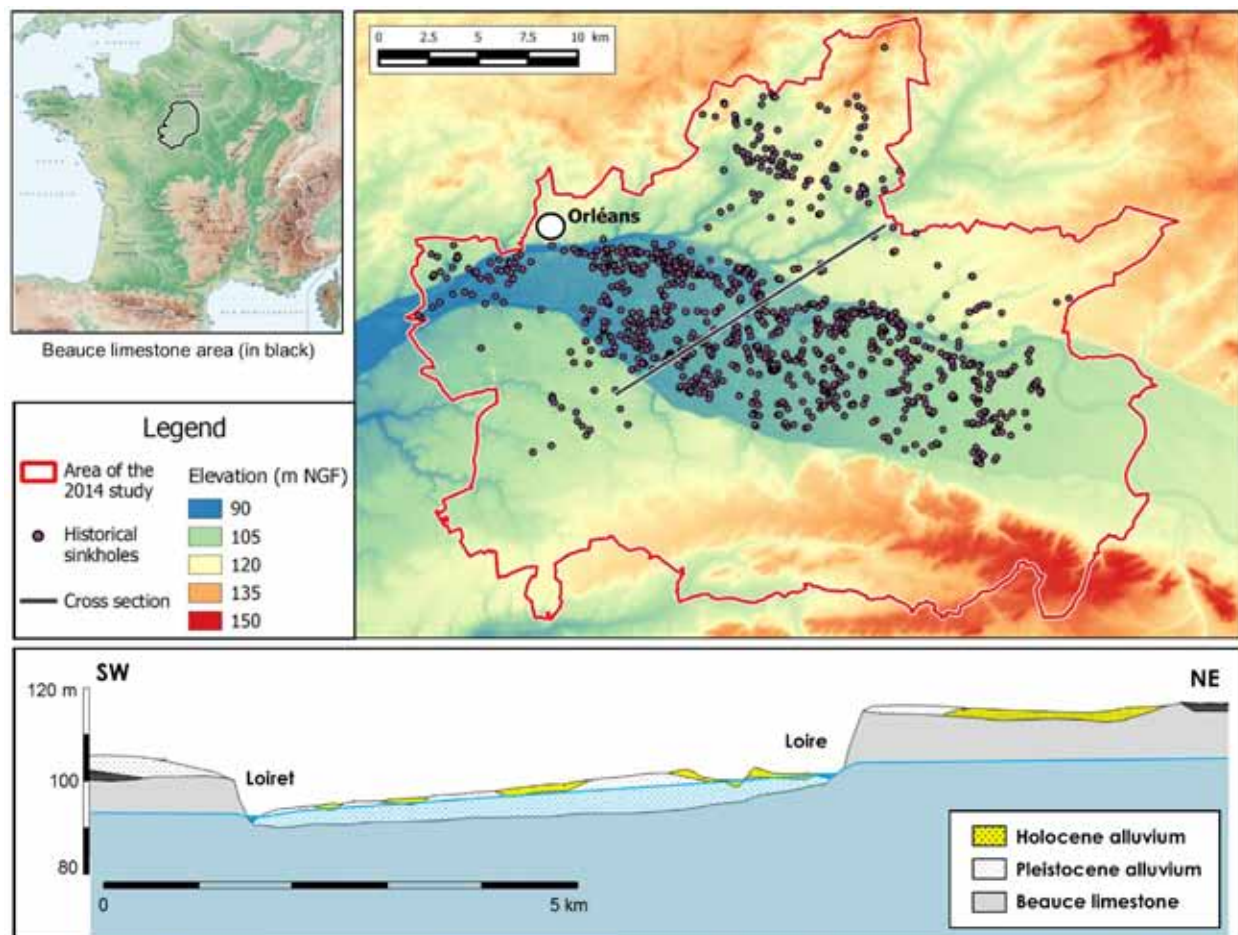


Figure 1. Map of geological context and sinkholes in the Orléans area, and geological cross section through the Loire floodplain.

be much larger; the biggest recent sinkhole was 16 m in diameter and 7.5 m in depth. It occurred in 2010 at Saint-Pryvé-Saint-Mesmin and destroyed a house, fortunately without casualties (Gutierrez et al., 2010). The collapse mechanism is interpreted to be mainly soil piping (or suffosion: downwashing of alluvium by water towards cavernous bedrock with relatively small and poorly connected voids – not necessarily well-developed and -integrated cave networks), followed by the collapse of the thin residual soil layer. This phenomenon is likely not sufficient to explain the biggest sinkholes, unless there is a concentration of voids in a small area. For that kind of event, the collapse of the limestone is also probable (bedrock collapse). An unusually high dissolution rate in the limestone was recently postulated and could be an additional destabilizing factor (estimated dissolution of 1 cm per year for a 1 m² cave in which calcium concentrations were measured and compared to those obtained in Loire River (Perrin et al., 2017).

Outside the Loire floodplain, the other parts of the Orléans area seem much less sensitive to the sinkhole collapses, except for the Orléans Forest where hundreds of sinkholes are known (not shown on Figure 1). Speleologists have excavated some of them. All seem to be old cave entrances, naturally filled by sediments and apparently stable (Moreau, 2002). Without infrastructure and other cultural influences, the area is less surveyed than the Loire floodplain, that is until the 2016 meteorological event occurred.

Spring 2016 Meteorological Event and Its Consequences

Massive Rainfall and Triggered Floods

Between May 28 and June 1, 2016, northern France was affected by massive rainfall. In the Orléans area, around 140 mm were recorded during these five days, the equivalent of three normal rainy months. River floods occurred. For example, Paris saw the highest level of the Seine River since 1982 (Boizard et al., 2016).

In northern Orléans, most part of the rainwater ran off the saturated soil surface towards the Retrève dry valley. Thirty km were flooded for the first time since 1982 (Figure 2 – Gidy area). The area was severely impacted for two weeks, including the main highway between Orléans and Paris, four small towns and an industrial park. The public and industrial financial losses were estimated at €20 million (private losses are unknown).

Near the Loire River, a 1-km² area located on the Loire floodplain was flooded by the overflow of an artificial canal (Figure 2 – Chécy area). One to 2 m of water covered a recently built neighborhood, the water-treatment plant and several fields for 10 days.

Karst Sinkholes Triggered by Rainfall and Floods: Two Postulated Processes

A cascading effect of rainfall and floods produced around a hundred sinkholes that formed immediately or a few days after the meteorological event (Figure 3). BRGM and two other public institutions were called to help local authorities to ensure public safety. Sixty percent



Figure 2. Flooded areas during the spring 2016 meteorological event. (a) Gidy area: flood of the Retrève dry valley. (b) Chécy area: flood by the overflow of an artificial canal.

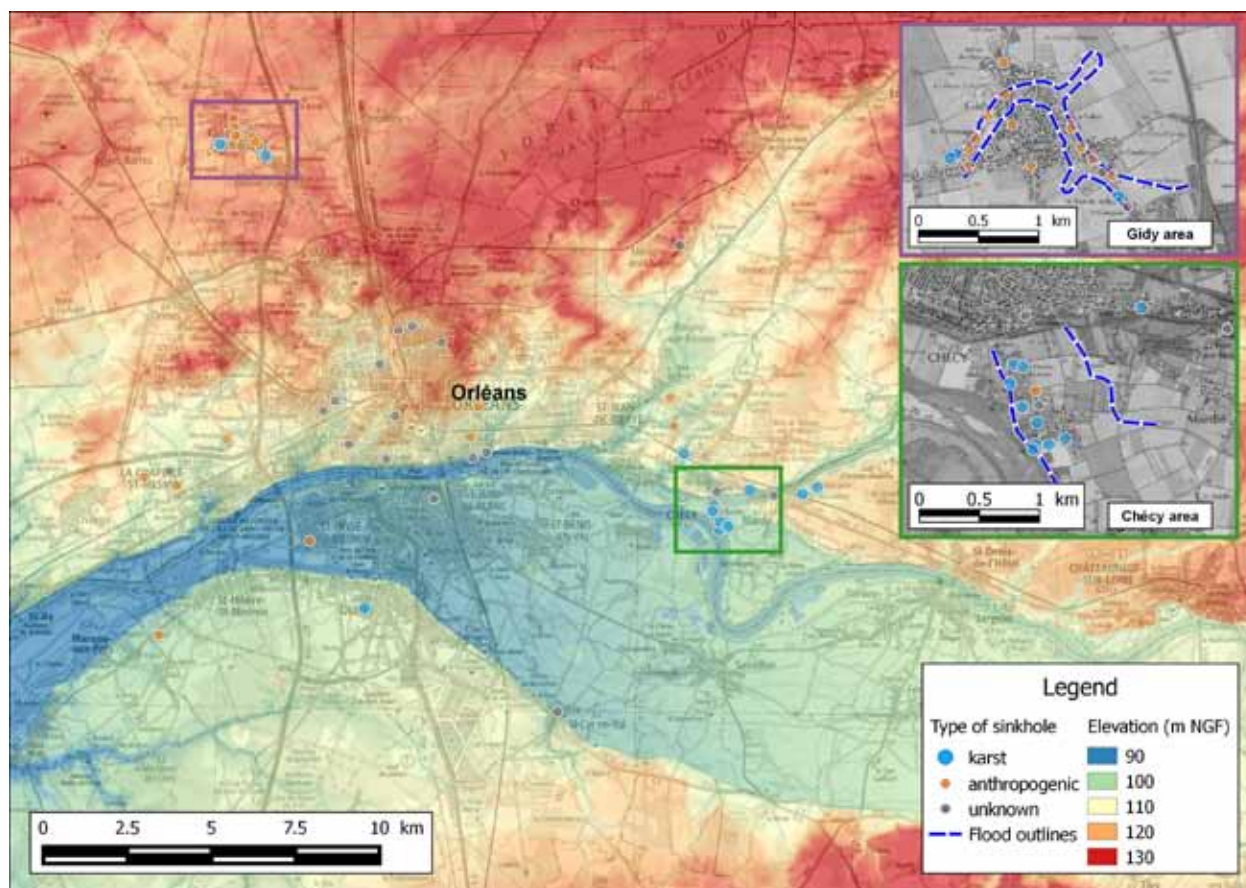


Figure 3. Map of sinkholes triggered by the spring 2016 meteorological event.

of the sinkholes were concentrated in the two-flooded areas of Gidy and Chécy, the others were distributed in the rest of the Orléans urban area and in the countryside. Twenty-five percent of the sinkholes seriously affected buildings or roads (restricted areas).

Based on local expertise and scientific investigations, half of the sinkholes were caused by anthropogenic cavities (failures of abandoned quarries and cellars, soil suffosion in small underground constructions). A quarter of the sinkholes, including some of the largest, were associated with karst collapses. The origins of the remaining quarter remain unknown.

Five karst sinkholes were around 10 m in diameter and 2 to 3 m in depth (Figure 4). Most of the other karst sinkholes are around 1 to 2 m in diameter and less than 1 m in depth.

In the Gidy area, the occurrence of karst sinkholes was unexpected: not a single similar event has been recently recorded in northern Orléans.

The Chécy area, located in the Loire floodplain, is, in contrast, more prone to sinkhole occurrence (see above), but the frequency (spatial and temporal) was unusually high. The sinkhole occurrence rate evaluated in “normal” conditions (0.02 to 0.03 per square kilometer per year), was accelerated by a factor of 16,000 to 24,000 because of the flood (13 sinkholes in one km² during the 10 days flood => sinkhole occurrence rate=470 sinkholes per square kilometer per year).

Considering the two geological terrains affected by floods and the contrasting karst activity in these two areas, two different processes are assumed:

- In the Chécy area, the flood-induced vertical flow in the soil increased the suffosion of alluvium into pre-existing and active karst caves. We hypothesized that the water load may also have triggered the final collapse of the thin residual layer.
- In the Gidy area, the thickness of the altered cohesive limestone layer overlying the caves (≈15 m) would not permit that kind of internal erosion observed in the Chécy area. Our



Figure 4. Two major sinkholes triggered by floods.

hypothesis is that the collapse of a formerly vertical cave filled by sediments or backfills caused sinkholes to develop (Figure 5a).

Perspectives for a Better Karst Sinkhole Risk Management

Although there were no fatalities, the consequences of these karst sinkholes were not negligible. The direct financial losses are estimated around €1 million (three uninhabitable houses, underpinning of five other houses and industrial buildings, road rebuilding, backfilling of sinkholes).

Moreover, these events reveal the extreme sensitivity of the Loire floodplain to the sinkhole phenomenon. The high flood induced sinkhole occurrence rate (470 per square kilometer per year – see above) might trigger thousands of collapses in the 170-km² area in case of an exceptional flood of the Loire (200-year return period) that could destroy old protection dykes. Such dramatic floods occurred 3 times in 20 years in the 19th century (not in the last 150 years). Furthermore, breaches in the old protection dykes formed during these historic events may have been triggered by karst sinkhole collapses.

BRGM is working on different studies to improve numerical modeling of internal processes resulting in ground collapses.

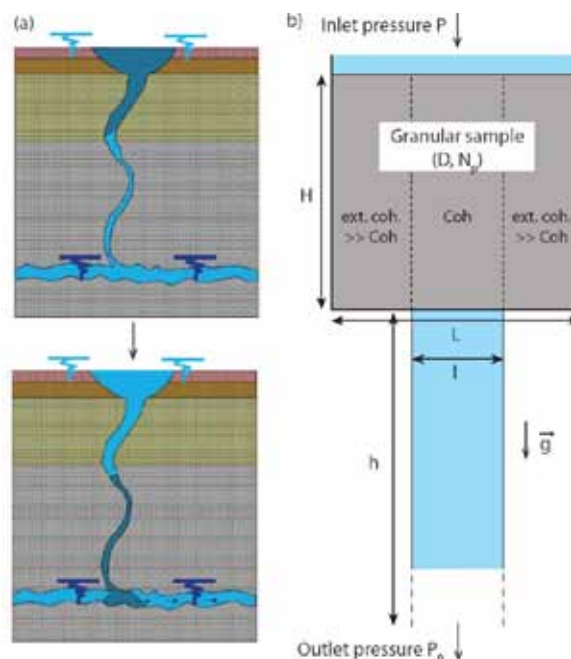


Figure 5. (a) Field situation of soil collapse within a flooded underground conduit. (b) Scenario for the numerical modeling. See Figure 6 for description of the parameters.

Numerical Modeling of the Internal Process

The BRGM-IRSTEA Partnership

As part of the nation-wide studies on dyke stability, the IRSTEA is used to perform numerical modeling and laboratory experimentation of the horizontal internal erosion, resulting in weakening or failure of these sensitive earthworks. In 2016, the BRGM and the IRSTEA began a scientific partnership to adjust the horizontal modeling in order to address the vertical internal erosion in the covered karst terrains (Luu et al., 2017).

Numerical Model

The model combines the Lattice Boltzmann Method (LBM) and the Discrete Element Method (DEM) to describe efficiently the flow of the fluid phase (LBM) and the movement of the solid phase (DEM).

The LBM is an explicit 2D finite difference scheme over a discrete lattice mesh (Boltzmann equation) that involves the collision and propagation of fluid particles. The soil is considered as cemented granular materials and modeled using a 2D Discrete Element Method, which includes cohesion via solid bonds between particles (Jiang et al.,

2013). When a contact force reaches the yield strength, the bond is broken and the contact becomes purely frictional via a Kelvin-Voigt relationship, which models the normal force and a viscous-regularized Coulomb law for the shear force.

To deal with the solid-fluid coupling, a relationship based on a momentum-exchange method is used (Feng, 2007). The simulation setup consists of a conduit initially clogged by an immersion (Figure 5a). In order to impose a preferential path for the flow within the granular sample, two soil cohesions are used. In the external layers, the bond strength is fixed at $C=1000$ N, whereas in the central layer, cohesion varies between 5 to 20 N. The erosion of the soil layer is triggered by a pressure gradient.

Two scenarios are simulated (same diameter grains, same height, two different lengths L , corresponding to particle numbers $N_p=11816$ and 3042 – see Figure 6).

Thereafter, the soil cohesion is characterized by a dimensionless cohesion number defined as the ratio between bond strength to the particle's buoyant weight: $C_{oh}=C/(\rho_s-\rho_f)gV$, where $\rho_s-\rho_f$ is the submerged apparent density, g is the gravitational acceleration and V is the particle's volume. The initiation of motion in sediments is classically analyzed by defining the Shields number (ratio of fluid force on the particle to the weight of the particle). For the cemented soil modeled here, this criterion should be extended by introducing the cohesion number C_{oh} . Work is under way to further define this issue.

Erosion Regimes

The behavior of the granular layer subjected to a pressure gradient is parametrically studied. Figure 6

reports the implemented parameters. By varying the conduit size Δ ($\Delta=l/D$), the granular cohesion (C_{oh}) and the inlet fluid pressure (P), two situations are observed: a “blocking” stable case (no erosion) or an intermittent evacuation of the granular sample through the predefined internal conduit.

This phenomenon is separated into three different erosion regimes (Figure 7). At the lowest magnitude of erosion, a stable cavity is marginally formed. If erosion parameters increase, an upward internal erosion mechanism arises, where the destabilization front direction is opposite to the flow direction. Finally, plug collapse occurs where the whole granular column falls all at once, but not under its own weight. A bond breakage along the conduit, due to erosion triggered by the hydraulic gradient, precedes this collapse.

Three phase diagrams related to the conduit size (Δ), the cohesion number (C_{oh}) and the inlet pressure (P) for the two samples are illustrated in Figure 8. We indicate the erosion threshold by the lines. Globally, a high enough conduit size, a high enough inlet pressure and a small enough cohesion can trigger the erosion process. The first diagram shows that the higher C_{oh} , the higher Δ is required to erode soil. As regards the eroding effect of increasing P , the two other diagrams display very sharp thresholds. This observation needs additional studies.

The simulations also point out the influence of the granular sample length L on the erosion threshold. The latter is slightly “delayed” for the smaller sample, in the sense that for a higher critical Δ , a smaller critical C_{oh} and a higher critical P are involved in the erosion process. To capture the physics underlying this result, work is under way, focusing on the inter-particle cohesion, in order to monitor how microscale behavior leads to bond rupture.

Solid phase		Fluid phase	
Particle mean diameter, D	$6 \cdot 10^{-3}$ m	Conduit length, l	$[3-27] \cdot D$
Polydispersity, D_{max}/D_{min}	1.5	Conduit height, h	$100 \cdot D$
Granular sample length, L	$33 \cdot D$, $67 \cdot D$	Inlet pressure, P	$[0-2000]$ Pa
Granular sample height, H	$70 \cdot D$	Outlet pressure, P_0	0 Pa
Particle density, ρ_s	$2.2 \cdot 10^3$ kg/m ³	Fluid kinematic viscosity, ν	$4 \cdot 10^{-5}$ m ² /s
Normal, shear and rolling stiffnesses $k_n = k_s = 10 \cdot k_w$	$1.1 \cdot 10^5$ N/m	Fluid density, ρ_f	$8.5 \cdot 10^2$ kg/m ³
Friction coefficients, $\mu = 3 \cdot \mu_w$	0.3	Lattice grid size, Δx	$6.3 \cdot 10^{-4}$ m
Damping coefficient, η	68.3 kg/s	Lattice speed, c_s	10 m/s
Bond stiffnesses, $k_{n,b} = 0.4 \cdot k_{s,b}$	$0.5 \cdot k_n$	Hydraulic radius factor, R_h	0.8
Bond strength, $C=C_n = 2C_s$	$[5-20]$ N		

Figure 6. Geometrical, solid and fluid model parameters implemented in the simulations.

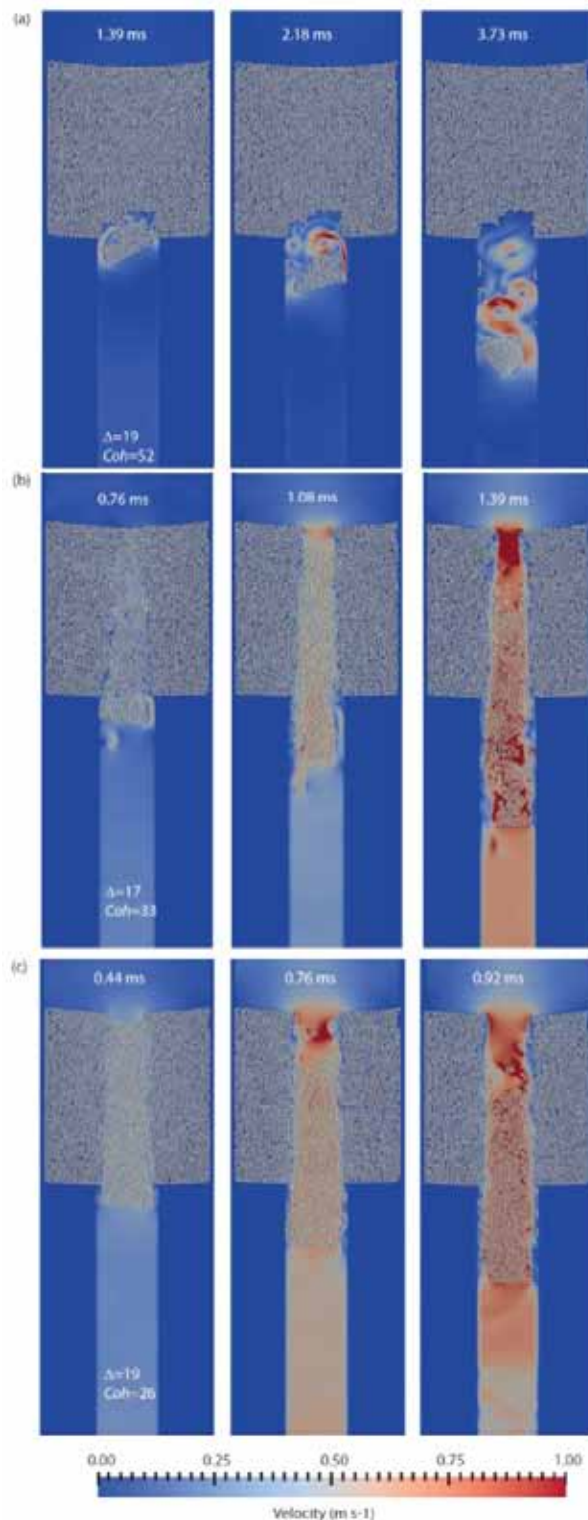


Figure 7. Erosion regimes: (a) stable cavity, (b) progressive collapse, (c) plug collapse.

Conclusion

The sinkholes triggered by the spring 2016 meteorological event prove the vulnerability of the Orléans area to cavity collapses. The last two years of research on development of karst sinkholes, led by the BRGM, addresses understanding of the soil particle behavior (thanks to the IRSTEA) to the on-site responses in an emergency. This multi-scale study is promising for the future. Improving the prediction of where, why and when a sinkhole will occur is a work in progress. Linking the numerical modeling illustrated here to “geotechnical” reality will be a significant step in characterizing sinkhole hazards and risks. It will be done through improving the parametric studies and developing experimental tests. The model is already providing an excellent visual medium (video) to explain the sinkhole phenomenon to the general population. Informing and educating the public is an important task in improving risk management (outreach). New scientific studies on the Loire floodplain began on the basis of these perspectives.

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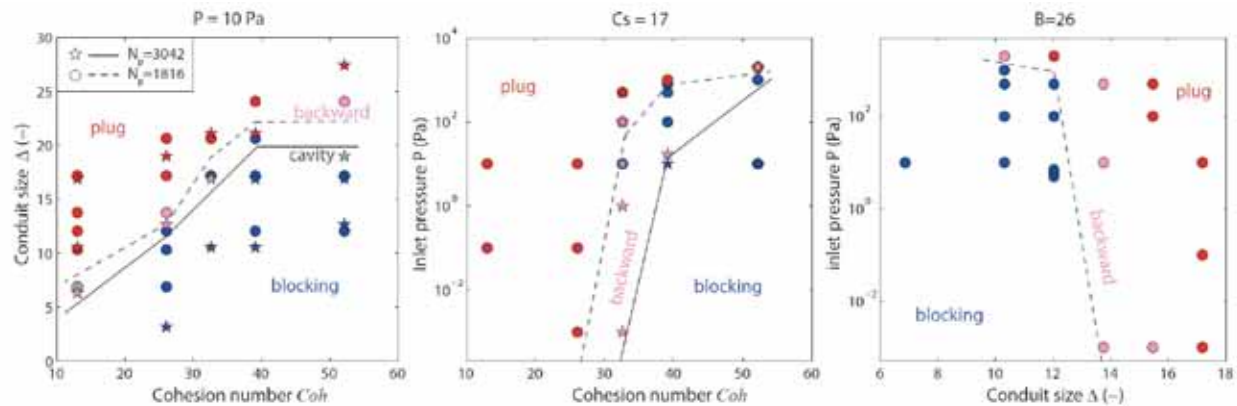


Figure 8. Phase diagrams: influence of the conduit size Δ ($\Delta = l/D$, see above), the cohesion number C_{oh} and the inlet pressure (P) on the different features, namely the blocking (blue), the cavity (grey), the backward extrusion (pink) and the plug extrusion (red).

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QUANTITATIVE COMPARISON OF SINKHOLE GEOMORPHOLOGY OF FOUR KARST REGIONS IN OHIO

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Abstract

The Ohio Geological Survey has mapped karst in Ohio since 2009. Field mapping of sinkholes has suggested that geomorphological parameters vary between the Bellevue, Delaware, Hillsboro, and Springfield karst regions. Statistical tests confirm that these parameters distinguish the four regions. An understanding of how they differ and what causes those differences can be used to better manage these karst features.

Differences between sinkholes within each region were quantified using nine parameters derived from digital elevation model (DEM) analysis. These parameters included: depth, perimeter, area, volume, length of major and minor axes, eccentricity, circularity index, and orientation of karst features. Of these parameters, orientation was displayed on rose diagrams and the others were graphed on boxplots. The Conover-Iman (CI) test was used to determine if parameters were statistically distinct ($\alpha=0.05$) between karst regions.

Bellevue has the largest sinkholes in the state and differs statistically from other regions by perimeter, area, volume, major axis, and minor axis. Delaware has the deepest sinkholes, and depth is statistically distinct from all other regions except Springfield. Springfield has the smallest number of sinkholes, and no parameter distinguishes Springfield from all other regions. Hillsboro has the smallest mean sinkhole size, but the most sinkholes. Sinkholes in Hillsboro are also statistically more circular than other regions as shown by eccentricity, and circularity index. Three of the four karst regions show alignment with structural lineaments. The exception is the Hillsboro region, where sinkholes are very circular and exhibit no preferred orientation.

Variations in sinkhole size, shape, and distribution are influenced by multiple factors. For example, dissolution in the four regions is influenced by bedrock type, with increasing solubility from dolomite to limestone to evaporites. Sinkholes in Bellevue may be highly

developed because Bellevue is underlain by evaporites. Bellevue also experienced multiple events that likely lead to increased bedrock fracturing and water availability from melting ice. Conversely, most of Hillsboro was glaciated only once and has less-developed sinkholes. Unlike other regions, Bellevue was affected by ancient lakes as well. Large sinks in Bellevue indicate higher dissolution activity and sinkholes that have merged, while small circular sinkholes in Hillsboro are less active and not developed enough to merge and become irregular. Improved knowledge of the differences between these regions will assist in mitigating and avoiding these geologic hazards.

Introduction

Karst has been studied in Ohio for many years. White's 1926 publication, *The Limestone Caves and Caverns of Ohio*, laid the groundwork for karst mapping in Ohio and established that the fracture caves of northern Ohio are preglacial. Dissolution of these features likely began soon after bedrock deposition (Forsyth, 1988). Some early karst mapping was completed in Bellevue by Tintera (1980), and from 1981 to present, many caves have been mapped and studied by the Wittenberg University Speleological Society. As early as the 1980s, cursory karst mapping was conducted for potential site selection of the Superconducting Super Collider and storage of low-level nuclear byproducts (Pavey et al., 1999). Cataloging karst features is essential for multiple health and safety reasons. Sinkholes channel surface water directly into groundwater, spreading pollution from the surface and causing flooding during heavy storms. In 2008, severe karst-related flooding in Bellevue, Ohio, brought attention to karst as a geologic hazard and provided impetus for detailed karst mapping (Raab et al., 2009; Pavey et al., 2012).

Since 2009, the Ohio Geological Survey has been field mapping karst features and sinkholes in Ohio with funding from the United States Geological Survey Great Lakes Geologic Mapping Coalition. The focus

has been on detailed field mapping and identifying karst features in Delaware (Aden et al., 2011), Springfield (Aden, 2012), Bellevue (Aden, 2013; Aden, 2014), and Hillsboro (Aden, 2015; Aden, 2016) (Figure 1).

Sinkholes have been analyzed geomorphologically by size and shape (Brinkmann et al., 2008; Weishampel et al., 2011; Basso et al., 2013; Doctor and Young, 2013; Aguilar et al., 2016), by examining alignment and the relationship to bedrock structure (Florea, 2005), and by clustering (Gao et al., 2005).

Empirical field observations by the Ohio Geological Survey indicate that the geometries of sinkhole features in four karst regions in Ohio are distinct from one another. The most noticeable observed distinctions are in sinkhole density, shape, and volume among the regions. To better understand how local geology, glacial history, and hydrologic conditions affect karst development, this study quantitatively compares sinkhole geomorphology and distribution within these four karst regions using the Conover-Iman statistical test and nearest neighbor analysis.

Study Area

The four Ohio karst regions included in this study are Bellevue, Delaware, Springfield, and Hillsboro, which are named based on their largest city (Figure 1). The regions overlie Devonian, Silurian, and Ordovician-age dolomites, limestones, and evaporites (Hobbs, 2009), which are susceptible to increasing degrees of dissolution. Within the regions, sinkholes are present where glacial drift is thin.

The Bellevue region is 776 km². Empirical field observations indicate that the Bellevue region has large, irregularly shaped complex sinkholes. Regional drainage is controlled by karst to the extent that there are almost no natural surface streams and most runoff drains into sinkholes. Thin drift, averaging 4.4 m thick over sinkholes, overlies the Devonian-age Columbus and Delaware Limestones. The limestones are underlain by the Silurian-age Bass Islands Dolomite and the dissolution-prone anhydrites and gypsum of the Salina Group. The Quaternary-age deposits are Wisconsinan lacustrine sand, lake-plane moraine, lacustrine and beach sand, and ground moraine (Pavey et al., 1999). Maximum relief in the region is 117 m.

The Delaware region is the largest study area at 1,020 km². Drift that overlies sinkholes averages 4.5 m thick. Sinkholes tend to be linear and are developed in the Silurian-

age Salina group and the Devonian-age Columbus and Delaware Limestones. The most notable dissolution cave in the Delaware Limestone is Olentangy Indian Caverns. Quaternary-age deposits are primarily Wisconsinan end moraine and ground moraine (Pavey et al., 1999). Maximum relief in the region is 86 m.

The Springfield region is the smallest study area, has the least amount of sinkholes, and encompasses only 384 km². The majority of karst is in the Silurian-age Cedarville, Springfield, and Euphemia Dolomites. Fewer features are found within the Silurian-age Massie Shale, Laurel Dolomite, Osgood Shale, Dayton Limestone, Brassfield Limestone, and Ordovician-age limestones and shales. The Quaternary-age deposits are primarily Wisconsinan ground moraine (Pavey et al., 1999). Thin drift is typically less than 6.5 m thick where sinkholes are located. Maximum relief in the region is 94 m.

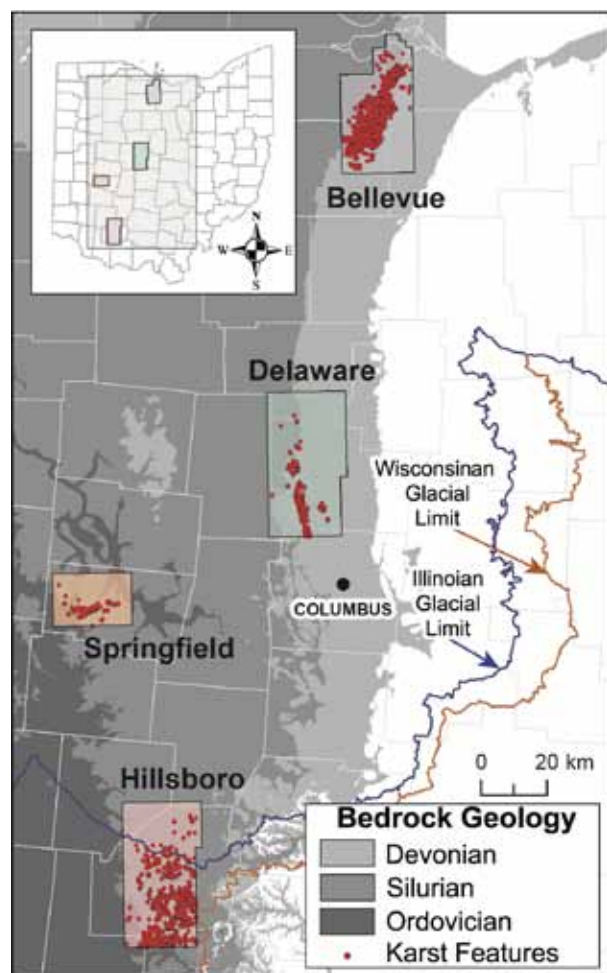


Figure 1. Locations of the four karst regions in Ohio where mapping is complete.

The Hillsboro region is the second largest study area at 996 km². Field observations reveal that the sinkholes are relatively small and circular, usually not complex, and typically are located in clusters in the uplands bluffs above stream valleys. Most sinkholes are found in the Silurian-age Tymochtee, Greenfield, and Peebles Dolomites, Lilley Formation, and Bisher Formation. Some karst is present also in the lower Silurian- and Ordovician-age carbonates. The Quaternary-age deposits are primarily Wisconsinan end and ground moraine and dissected Illinoian ground moraine (Pavey et al., 1999). This region was first glaciated by Illinoian ice and then partly by Wisconsinan ice (Figure 1). The majority of the karst features are found in the area that was only glaciated during the Illinoian. Drift thickness typically is less than 3.8 m where sinkholes are found. Maximum relief in the region is 211 m.

Methodology

Potential sinkholes were identified in GIS and field verified. Then the geomorphological parameters were measured in GIS to provide data for statistical analysis and differentiation of karst regions.

The DEM used for analysis was created from 2006 light detection and ranging (LiDAR) data and has 0.76 m horizontal and 0.15 m vertical accuracies. The DEM was processed to identify potential karst by filling lows and then subtracting the filled DEM from the original unfilled DEM. This new DEM was converted to polygons and adjacent polygons were dissolved. Polygons unrelated to sinkholes were removed using aerial photography and field checking, and the remaining polygons represent the area of each sinkhole. Sinkholes are defined as internally draining, enclosed depressions, which develop through bedrock dissolution. Sinkholes artificially split by roads or ditches on the DEM were considered to be a single sinkhole and were processed as such.

Field verification was important to confirm the existence of sinkholes identified using GIS and to locate additional sinkholes that were too small or too recent to appear on the DEM. Sinkholes discovered in the field were added to the dataset as point locations but could not be used for geomorphological analysis. In total, 91% of the sinkholes used for analysis were field checked and of those, 72% were confirmed as karst and 28% were suspected to be karst.

Geomorphological parameters for the sinkholes in each of the four regions were calculated in GIS and plotted on boxplots. These measurements include depth, perimeter, area, volume, length of major and minor axes, eccentricity, circularity index, and orientation (Table 1). Sinkhole point locations were analyzed for clustering by determining the average nearest neighbor distance and then comparing the expected distance to the actual distance (Gao et al., 2005). Finally, a kernel density raster was generated to assess how sinkhole point locations cluster in the different regions, but these data did not have a substantial role in the comparative analysis of the regions.

The distribution of the data for the parameters in each of the sinkholes was analyzed in the statistical programming language R (R Core Team, 2017) using built-in statistical tests and plotted using the libraries *ggplot2*, *scales* (Wickham, 2009), *circular*, and *rose.diag* (Agostinelli and Lund, 2013). The Shapiro–Wilk test (Shapiro and Wilk, 1965; Razali and Wah, 2011) and quantile-quantile plots were used on each of the nine parameters for each of the four regions to determine the type of data distribution. These tests indicated that the data are not normally distributed and therefore nonparametric tests were applied. Note that the Shapiro–Wilk and other similar tests do not work well for sample sizes ≤ 30 (Razali and Wah, 2011), and Springfield has 30 sinkholes.

Parameter	Definition	Calculation Method
Depth (m)	Difference between bottom elevation and spill over elevation within the sink	Zonal Statistics as a Table (range) in ArcGIS
Perimeter (m)	Length of the sinkhole boundary at the spill over elevation	Zonal Geometry as a Table in ArcGIS
Area (m ²)	Each sink with the boundary defined by the elevation of the spill over point	Zonal Geometry as a Table in ArcGIS
Volume (m ³)	How much a sink would hold if it were hypothetically flooded to the spill over elevation	Zonal Statistics as a Table using sum based on difference DEM in ArcGIS
Major Axis (m)	Longest length of an idealized ellipse fit to the sink	Zonal Geometry as a Table in ArcGIS
Minor Axis (m)	Width of an idealized ellipse fit to the sink	Zonal Geometry as a Table in ArcGIS
Elliptical Eccentricity	Ranges between 0 (a circle) and 1 (a completely elongated ellipse; a line) (Doctor and Young, 2013)	$\sqrt{1 - \frac{(\text{minor axis}/2)^2}{(\text{major axis}/2)^2}}$
Circularity Index	Given the sinks known area, what would the perimeter be if it were a perfect circle, then compare that to its actual perimeter (Doctor and Young, 2013)	$\frac{\text{expected perimeter} = 2\pi\sqrt{\text{area}/\pi}}{\text{perimeter}} - 1$
Orientation in degrees	The main direction each sink trends along	Calculate Polygon Main Angle in ArcGIS

Table 1. Definitions of the geomorphological parameters and how they were calculated.

Kruskal–Wallis tests (Kruskal and Wallis, 1952) were performed to determine if a geomorphological parameter for at least one of the four regions is statistically distinct from another. In all cases, the test was significant at $\alpha=0.05$, indicating that at least one region is distinct from the others for each of the nine parameters. To determine which parameters are distinct for each region, a series of *post hoc* Conover-Iman (CI) tests ($\alpha=0.05$) (Conover and Iman; 1979; Dinno, 2017) were performed using the Benjamini-Yekutieli (2001) adjustment to control the false discovery rate. Note that the CI test is a one-sided test, so p -values had to be less than $\alpha/2$ to show median difference.

Of the eight parameters analyzed (CI test) and plotted on boxplots, three were selected as representative and are shown below. On the boxplots, the center line of the box represents the median (McGill et al., 1978) and the mean (white diamond) is included to show the significance of the outliers.

Results

Sinkholes cover 27.90 km² of the total 3,176 km² included in the four regions. Almost 97% of the sinkholes are in the Bellevue region by area. The four regions include 2,635 sinkholes that are measurable on the DEM, and 5,091 total karst points that include caves springs and sinkholes not on the DEM.

	Bellevue	Delaware	Springfield
Hillsboro	depth, perimeter, area, volume, major axis, minor axis, orientation, eccentricity, circularity index	depth, perimeter, area, volume, major axis, orientation, eccentricity, circularity index	eccentricity, circularity index
Springfield	perimeter, area, volume, major axis, minor axis	N/A	
Delaware	depth, perimeter, area, volume, major axis, minor axis, eccentricity		

Table 2. Results of the Conover-Iman test showing which parameters are statistically distinct when comparing regions.

Several analyses demonstrate how each region is distinct (Tables 2, 3). Conover-Iman results, selected boxplots, and rose diagrams depict the differences between geomorphological parameters for each region (Figures 2–6).

Some parameters statistically distinguish one region from all others. For example, Bellevue had the largest sinkholes in the state and is statistically distinct (CI test) from the other regions by perimeter, area (Figure 2), volume, major axis, and minor axis. Bellevue also has

		Delaware	Springfield	Bellevue	Hillsboro
depth m	min	0.01	0.35	0.00	0.04
	max	6.55	5.50	8.58	6.48
	mean	1.72	1.33	1.10	1.23
	median	1.41	0.87	0.77	0.91
perimeter m	min	6.99	20.97	5.22	5.44
	max	2,155.77	2,322.98	26,857.40	1,209.08
	mean	168.39	277.22	883.87	99.12
	median	96.70	92.75	306.34	73.29
area m ²	sum	298,406.28	44,381.88	26,908,754.84	648,400.38
	min	1.34	16.33	0.73	0.79
	max	31,171.76	14,574.11	1,342,262.54	23,109.99
	mean	956.43	1,479.40	26,855.04	502.25
	median	269.89	224.84	2,216.88	196.70
volume m ³	sum	238,305.98	31,791.82	28,877,405.32	400,077.16
	min	0.02	4.11	0.02	0.02
	max	25,831.37	14,144.52	3,666,017.52	28,694.72
	mean	763.80	1,059.73	28,819.77	309.90
	median	108.16	98.66	716.19	65.38
major axis m	min	0.76	3.48	0.64	0.67
	max	152.62	119.03	952.03	104.44
	mean	20.47	21.65	72.82	12.55
	median	13.15	11.50	36.41	9.37
minor axis m	min	0.52	1.49	0.36	0.29
	max	68.37	39.78	521.08	70.43
	mean	8.89	10.11	37.21	8.11
	median	6.73	6.17	19.76	6.53
eccentricity	min	0.20	0.34	0.12	0.00
	max	0.99	0.95	1.00	0.97
	mean	0.81	0.79	0.77	0.69
	median	0.85	0.84	0.81	0.71
circularity index	min	2.32	2.35	2.25	2.12
	max	6.59	9.62	14.01	5.69
	mean	3.21	3.75	3.51	2.71
	median	2.99	3.06	3.09	2.60
Nearest neighbor distance m		120.98	274.44	137.23	83.24
number of karst points/sinks		505/312	112/30	1974/1002	2500/1291
sum of sinks area within region km ²		0.30	0.04	26.91	0.65
% of region covered by sinks		0.03	0.01	3.47	0.07

Table 3. Results of the geomorphological, clustering, and area analyses.

the largest maximum values for all eight parameters, as well as the largest mean and median values for all parameters except for depth, eccentricity, and circularity index (Table 3). Note that although orientation was used for statistical comparisons, it is excluded from Table 3 because it is a different data type.

Sinkholes in Hillsboro are more circular than the other regions, and eccentricity (Figure 3) and circularity index were statistically distinct (CI test) from the other regions. Hillsboro has the smallest mean and median values for all parameters on Table 3 except for depth. These results quantitatively confirmed field observations that sinkholes here are small and circular.

Other parameters distinguish one or two regions but not all three (Table 2). For example, nine parameters distinguish Hillsboro from Bellevue, and eight distinguish Delaware from Hillsboro. Springfield can be distinguished from Hillsboro and Bellevue by perimeter and major axis length. Delaware had the deepest mean sinkholes (Figure 4), and depth was statistically distinct (CI test) from Bellevue and Hillsboro but not Springfield. The sinkholes in Delaware are 1 m deeper than Springfield and Hillsboro and 2 m deeper than Bellevue. However, since Springfield had the least data, no parameter statistically distinguished (CI test) Springfield from Delaware.

Orientation also varies by region (Figure 5). In Bellevue and Delaware, the dominant sink orientation is ENE to

WSW, while Springfield is NWN to SES. On the other hand, the sinks in Hillsboro (Figure 5) are very circular, strongly reflected by the lack of preferred orientation in the rose diagram.

Nearest neighbor analysis confirms ($\alpha=0.05$) that karst features in all four regions cluster to differing degrees as measured by the nearest neighbor distances (Table 3). Kernel density shows that in Bellevue, few sinkholes cluster based on distance, but many cluster within the same large depression. Hillsboro is the opposite; many sinkholes cluster based on distance, but very few are within the same depression because the sinks are so small. Hobbs (2009) reports that Bellevue contains the highest sinkhole density in Ohio. While this is certainly true based on sinkhole area, the Hillsboro region contains many more individual sinkholes.

Discussion

The Bellevue region is statistically distinct (CI test) from other karst regions in Ohio. Bellevue sinkholes are an order of magnitude larger in mean area, perimeter, and volume than those found in other regions. Previous studies have suggested that depressions in Bellevue are so large because the region is underlain by very soluble gypsum (Sasowsky et al., 2003; Dinsmore, 2011). Parts of the Salina Group were deposited as anhydrite and chemically altered to gypsum, resulting in expansion (White, 1926; Kihn, 1988; Pavay et al., 1999). This expansion likely fractured the surrounding Columbus

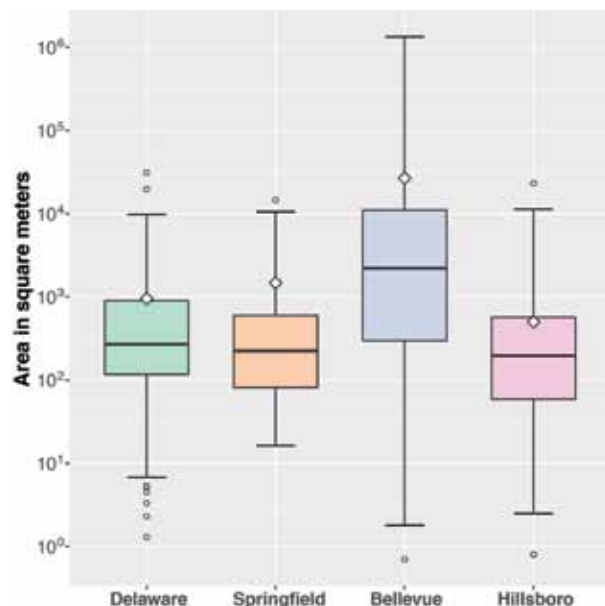


Figure 2. Boxplots comparing area (log10 scale).

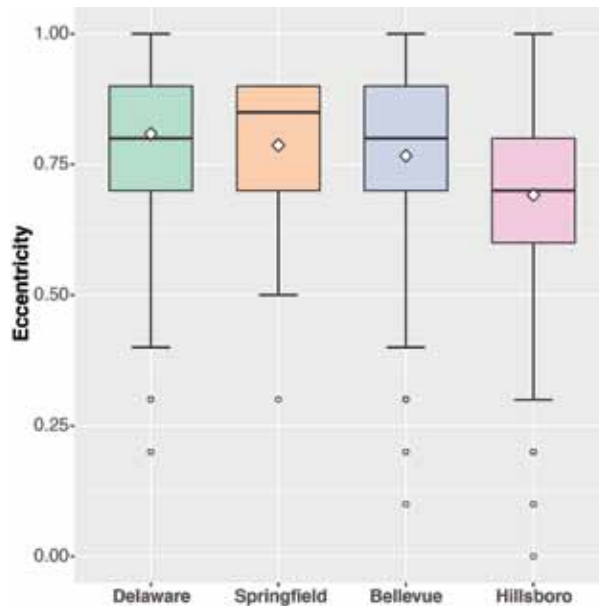


Figure 3. Boxplots comparing eccentricity.

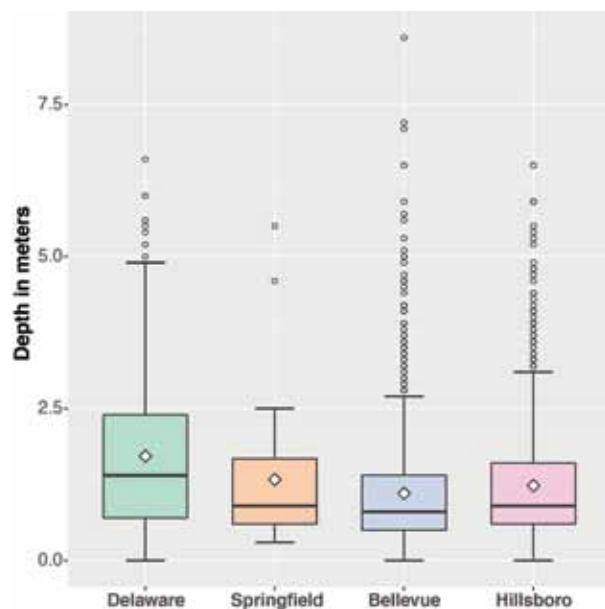


Figure 4. Boxplots comparing depth.

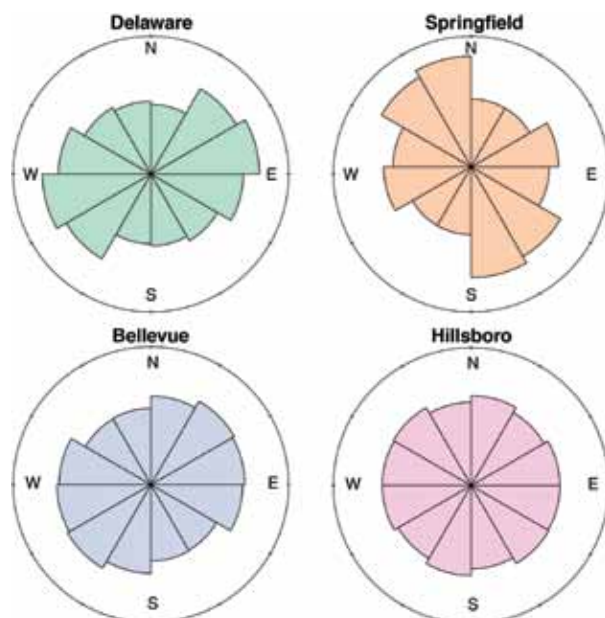


Figure 5. Rose diagrams showing orientation.

Limestone, facilitating collapse after subsequent gypsum dissolution (Dinsmore, 2011). This region also includes many caves, such as Seneca Caverns, that are thought to have formed by dissolution and collapse of evaporites (White, 1926; Kihn, 1988; Dinsmore, 2011). Gypsum is approximately 100 times more soluble than carbonate rocks, so karst in gypsum develops more rapidly (Gutiérrez et al., 2014). This same underlying-evaporite influence is not present in the other regions and appears to be the primary cause of the large features in Bellevue. Bellevue is also characterized by large,

upwelling springs in the north known as *blue holes*, the water chemistry of which has been linked to dissolution of anhydrite and gypsum (Sasowsky et al., 2003).

Bellevue also experienced more cycles of glaciation than other regions, especially compared to Hillsboro. Anderson and Hinds (1997) provide an example of glacial loading and unloading, leading to increased dissolution in an evaporite environment, with rebound potentially increasing fracture size and connectivity. Increases in glacial melt water volume can also increase dissolution (Anderson and Hinds, 1997; Gutiérrez et al., 2014), which could be compounded by fractures created over multiple glaciation events.

Furthermore, Bellevue was flooded during the Wisconsinian by Lake Maumee, an ancient lake that was located where Lake Erie is now (Forsyth, 1959; Calkin and Feenstra, 1985). During this time, 86% of present Bellevue sinkholes would have been under water. As Lake Maumee and later ancient lakes receded, a series of sandy beach ridges were deposited (Forsyth, 1959). This beach-ridge sand is poorly consolidated relative to typical clay-rich tills and can subside quickly when dewatered by groundwater fluctuations (Ford and Williams, 2007). This sand also has a higher hydraulic conductivity, perhaps allowing for increased infiltration. The presence of this sand, along with the occurrence of evaporites and history of glaciation, may be why the largest sinkholes are found in the Bellevue region (Dinsmore, 2011).

Sinkholes in the Hillsboro region are statistically distinct (CI test) from the other regions by their circularity and from Bellevue and Delaware by their small size. Sinkholes are usually circular when they first form (Brinkmann et al., 2008). Therefore, karst regions with circular sinkholes are relatively less developed. The majority of Hillsboro was influenced only by the Illinoian glaciation, reducing exposure to melt water, loading cycles, and the resulting fracturing. Over time, sinkholes merge together (Brinkmann et al., 2008; Aguilar et al., 2016) and preferentially erode, forming large irregular depressions. Unlike in Delaware and Bellevue, sinkholes in Hillsboro are highly circular and formed in dolomites. Dolomite has a much lower dissolution rate than limestone (Liu et al., 2005) or evaporites. The high degree of circularity, small size, low rate of dolomite bedrock dissolution, and reduced glacial influence all suggest the sinkholes in Hillsboro are less developed than others in the state.

The Delaware region has the most linear sinkholes of the four regions as measured by mean eccentricity, and is statistically distinct (CI test) from all but Springfield. A sinkhole eccentricity of greater than 0.98 has been suggested to distinguish between linear artificial features, such as ditches, and natural sinkholes (Doctor and Young, 2013). Only 0.7% of sinkholes are above this value, but some of these are definitive sinkholes, one of which is directly over Olentangy Indian Caverns in the Delaware region. However, eliminating thousands of non-sinkhole linear depressions may outweigh the exclusion of a few valid sinkholes. A similar method of assessing sinkhole shape is circularity index. Doctor and Young (2013) propose a maximum value of 1.7 to eliminate linear, anthropogenic features; this would remove 23% of the sinkholes. Note that the sinkholes with a circularity index above 5 are bisected by roads or drainages, which artificially increase their irregularity. Urbanization increases runoff (Ford and Williams, 2007) and sinkholes in the Delaware region are statistically distinct (CI test) from Bellevue and Hillsboro as the deepest and most linear, perhaps exacerbated by their presence in a rapidly developing suburban area. Reevaluating these features in the future could help assess their rate of change.

The low density of sinkholes in the Springfield region could be a result partly of the dissolution-resistant dolomite bedrock, but also owing to thick glacial till in parts of the region. Even though Springfield has only 30 sinkholes, it can still be distinguished from Hillsboro and Bellevue.

Some observations apply to all four regions. For example, sinkhole orientation typically is controlled by the direction of fractures in the bedrock (Florea, 2005; Gao et al., 2005) because they focus dissolution along planes of weakness. Some lineaments, indicative of bedrock structure, have been mapped in Ohio (Struble and Hodges, 1980; Wickstrom et al., 1992). In Bellevue, Delaware, and Springfield, lineaments generally align with the trends shown on the rose diagram (Figure 5). Hillsboro is a slight exception because the sinkholes are circular and have not yet developed enough to indicate an orientation on the DEM.

Data analyses that involve statewide remote sensing and large aggregated datasets always present challenges and limitations. One limitation of DEM-based geomorphological analysis is that only the features that are represented on the DEM can be analyzed by size

and shape. This excludes 2456 karst features located by field work that were too small or recent to appear on the DEM. Collecting new LiDAR data will allow these and other features to be detected, thus improving the precision of these statistics and further illuminate differences between the regions. Additional data would also improve the statistical significance of the Springfield region, allowing for a more thorough analysis. Until then, sinkholes discovered in the field were only used for clustering analysis.

Some sinkholes have not changed significantly since the data was collected, while others have grown or been filled by landowners. In many cases, the DEM does not measure complete sinkhole depth because the deepest part of a sinkhole is often a small, open fracture below the DEM resolution. Excluding those that were filled, nearly every sinkhole visited was deeper than shown on the DEM. Depth, area, perimeter, and volume should be considered minimums, because erosion only makes sinkholes larger over time.

Conclusions

Statistical tests confirm empirical field observations and show that geomorphological parameters distinguish the karst regions of Ohio. The large and irregular sinkholes in Bellevue are potentially linked to increased bedrock fracturing and melt water associated with Ice Age glaciers and to the influence of underlying gypsum. By contrast, sinkholes in Hillsboro are small, circular, and clustered likely because of their immaturity, limited glaciation, and less soluble dolomite bedrock. The sinkholes in the Delaware and Springfield regions exhibit characteristics between the extremes of the other two regions. In the Delaware region, ever-increasing urbanization may control depth and linearity of sinkholes. Low sinkhole density in Springfield presents challenges when quantitatively compared to other regions. Better understanding of how these sinkholes developed and are distributed among the regions will aid in public recognition and mitigation of these geologic hazards.

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ASSESSMENT OF KARSTIFICATION DEGREE IN THE COPACABANA GROUP FOR A TAILINGS DAM FOUNDATION, SOUTH ANDES, PERU

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Abstract

The worldwide occurrence of carbonate rocks is extensive, and Peru is no exception. Many mining facilities are located in or on carbonate rocks. Under specific conditions, carbonate rocks show varying degrees of karstification, which represent a potential high risk of damage or failure to mine facilities, especially tailings and water impoundments due to subsidence or internal erosion problems. Adequate engineering measures, including proper characterization of the foundation materials, should be taken to characterize foundation materials and mitigate the risk.

This paper presents the assessment of the potential of karst dissolution in the Copacabana Group underlying about 50% the foundation of a proposed tailings dam and storage facility, located in the South Andes of Peru. A thorough geotechnical site investigation program was carried out in the area, which included regional and local geological mapping, geotechnical drilling, test pits, permeability tests, effervescence test in cores, petrographic analyses, and X-Ray diffraction tests. Hydrogeological studies, such as pumping and tracer tests, were also performed by other consultants to verify the observations, conclusions, and opinions developed from the geotechnical investigation program.

The results of the geotechnical investigation allowed proper characterization of the dam foundation and the tailings storage facility and estimation of the degree of karstification in the carbonate rocks of the Copacabana Group. The completed geological site characterization was then used to locate the tailings dam and impoundment

area to avoid areas of pervasive karst and to implement defensive engineering measures, including grout curtains and slush grouting of smaller cavities and joints, among others.

Introduction

The tailings storage facility (TSF) is located in the South Andes of Peru, at -14.27 latitude, -70.31 longitude and an altitude between 4200 and 4500 m.a.s.l (Figure 1). Approximately, 50% of the foundation is underlain by the Copacabana Group, which is predominantly limestone. The remainder of the TSF foundation is underlain by the Ambo Group which is a clastic sequence (sandstone, siltstone, and shale).

This paper presents the assessment of the karstification degree of the Copacabana Group, based on information from geologic and geotechnical investigations, laboratory test results, and bibliographic research. This information allowed us to define the best location of the tailings dam (total height of 80 m), the axis of which is oriented in a N-S direction, and to determine the engineering measures necessary to mitigate the risks to the TSF.

Conditional Factors for the Development of Karstification

Limestones and dolostones constitute the rocks prone to dissolution activity at the project site. In order for a sequence of rocks to develop karstification, it is necessary for certain factors to act together. The most important factors are given below (Waltham, Bell & Culshaw, 2010).

Mineral Composition

Calcite (CaCO_3) is the principal component of limestones and is soluble in carbonic acid (H_2CO_3), present in natural waters. Another important component of carbonate rocks is dolomite ($(\text{Ca}, \text{Mg})(\text{CO}_3)_2$), which is the principal component of dolostones, and presents a slower dissolution rate in comparison to the calcite.

Organic Material Content and Water pH

The dissolution potential of water with respect to calcite (CaCO_3) is related to the CO_2 content of the soil, which originates mostly due to the decomposition of organic material and dissolution in rain water as it infiltrates through the soil. Also, the humic acids in the soil can produce underground waters with pH values ranging between 4.5 and 5 and in some extreme cases, values lower than 4, which intensify the karstification process.

Hydraulic Conductivity

The hydraulic conductivity of the limestones depends on its lithology and structural orientation. These geologic controls also affect the karstification degree because they facilitate or interrupt the penetration of the surface waters. The hydraulic conductivity depends, to a large degree, on the joints and discontinuities created during diagenesis and the subsequent deformation of the bedding.

Physiographic Location and Weather

The development of karstification also depends on the location of the study area, as well as the weather of the area. Karst is common in tropical regions (terrains at lower altitudes) with high humidity and temperature, which produces more CO_2 in the soil (more biologic activity) and higher precipitations.

Human Activity

The dissolution can be accelerated due to the changes in underground waters induced by human activity, or because of changes in the quantity, geochemistry, distribution, and flow of the surface waters that drain through the limestones.

Geological-Geotechnical Investigation

The geological-geotechnical investigations were executed in order to evaluate the foundation of the future TSF, the characteristics of the geological structures (faults and folds) and the degree of karst dissolution present in the study area, through the execution of in situ and laboratory tests.

The investigations consisted of: geological mapping (local and regional), execution of geotechnical boreholes (vertical and oriented), permeability tests, test pits and trenches, and the installation of piezometers (Figure 1). Also, hydrogeological studies and tests by other consultants were performed, in order to support



Figure 1. Map of Peru with geographic location of the project (right) and geological map with location of geotechnical investigations (left).

and verify the results of the geological-geotechnical investigations.

In earlier stages of the project, geophysical tests (geoelectric tomography, seismic refraction, and MASW) were conducted with the purpose of determining the stratigraphic characteristics and competence of the bedrock at the TSF site and to detect cavities and fault zones. The results provided a preliminary idea of foundation conditions in the area.

Geological Mapping

With the objectives of defining lithological units, important geological structures, and evidence of karst dissolution in the study area, geological mapping was conducted by examining outcrops register, road access cuts, and borehole platforms.

Geological Units

Based on the regional geology (Lopez et al., 1996) and local geological mapping, the TSF site is underlain, in ascending stratigraphic order, by the Ambo Group siltstones and sandstones (Lower Carboniferous), the Copacabana Group limestones (Lower Permian), and the Mitu Group sandstones and conglomerate (Upper Permian). The Paleozoic bedrock is mostly covered by Quaternary deposits (glacial, glacial-fluvial, and alluvial). All these geological units are presented in Figure 2, which shows the stratigraphic column of the project.

The calcareous rocks of the Copacabana Group are exposed on the north valley slope; the Ambo Group, which underlies the Mitu Group by angular discontinuity, is exposed on the south valley slope. Figures 3 and 4 present cross sections along the dam axis and along the river axis, respectively.

Because of the importance of the Copacabana Group to the project, a more detailed description of its stratigraphic characteristics is presented in a following section of this paper.

Structural Geology

Unconsolidated surficial deposits mantle the bedrock and mask structure through much of the project area, especially along the valley floor; however, we consider that the most important structural features present in the area correspond to block faulting, related folding, and angular discordance between bedrock units (Figure 1).

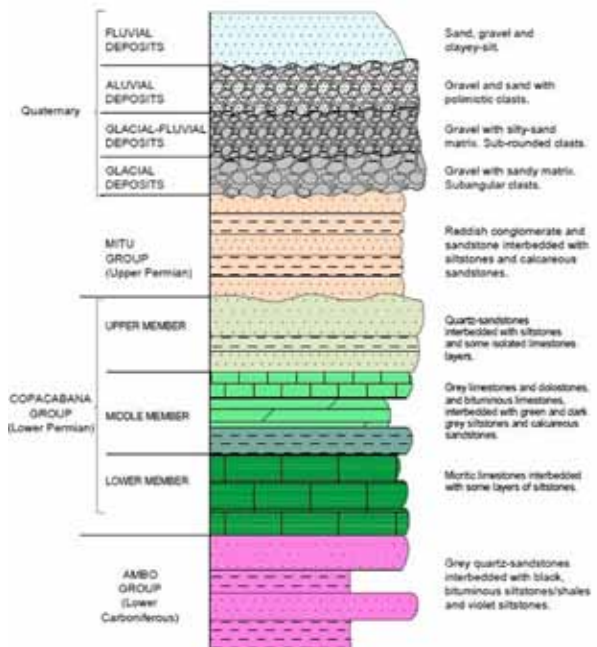


Figure 2. Stratigraphic column of the project.

The arrangement of these structures has direct influence over the quality of the rock mass and the flow direction and confinement of the underground water.

A major east–west-striking fault system, comprising two separate fault strands, is inferred to underlie the dam site and the impoundment area in the east–west section of the valley. The fault system juxtaposes Ambo Group sandstones on the south side of the valley against lower and middle units of the Copacabana Group along the north side of the valley. This fault likely accounts for the abrupt, rectilinear change in the valley from north–northeast to east–west.

A second group of faults strikes northwesterly to almost due north generally on the north side of the valley. These faults displace Copacabana units and may displace the east–west fault system controlling the drainage through the dam site area. Other minor faults and folds are present in the Ambo Group on the south side of the valley and elsewhere in the general project area.

The fault system underlying the valley floor and the northwest to north-striking faults cutting the Copacabana Group on the north valley slope faults likely provide some control of karstification near the dam site and may separate an area of relatively severe karstification downstream of the dam site from less severe solution activity in the impoundment area.



Figure 3. Geological cross section A-A' along the dam axis (looking downstream).

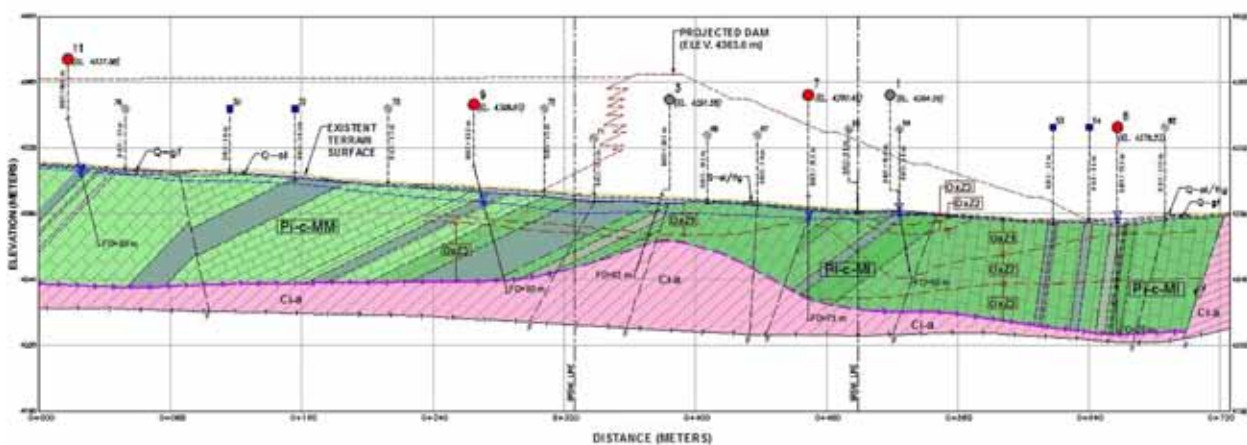


Figure 4. Geological cross section B-B' along the river axis (looking the north valley slope).

Also, anticlines and synclines are present in the area, affecting the Copacabana and Ambo Groups, as shown in Figures 1 and 3; their axes have generally N-S and E-W orientations. Bedding orientation of the geological units will be detailed in a following section of this paper.

Geotechnical Boreholes

Eighteen geotechnical boreholes (4 with directionally oriented core, 4 inclined, and 10 vertical) were drilled along the dam axis and in the TSF impoundment area. Assessment of karstification in the Copacabana Group is based on information from 13 boreholes in which Copacabana limestones were identified. The depth of these boreholes ranges between 40 m and 140 m.

Permeability tests (Lefranc and Lugeon) were executed in each of the boreholes in order to estimate the hydraulic conductivity of the geologic formations. Additionally, ground water levels in the area were measured in single and double piezometers (Casagrande type) installed in each borehole.

Test Pits and Trenches

A total of 80 test pits and 3 trenches, with depths varying between 0.8 and 5 m, were excavated to characterize foundation materials and to locate possible sinkholes and cavities. No sinkholes, cavities, or other dissolution features were found in any of the exploratory excavations.

Hydrogeological Studies and Tests

The hydrogeological studies done in the TSF area were performed by other consultants and their principal objectives were to verify the extent of the Copacabana Group and the degree of karstification. Also, they were intended to determine if there were any significant changes in the flow of the principal stream through the project area and in nearby drainages that could evidence preferential paths of infiltration or discharge of ground waters.

The studies and tests executed in the area consisted of: hydrological and hydrogeological mapping, flow

measurements of surface waters, pumping tests, slug tests, water levels measured in piezometers, hydrochemical sampling of surface and underground waters, and tracer tests (Fluorescein, Eosin, and Rhodamine) from two injection points in the Copacabana Group, one in the impoundment area, and the other at the north extreme of the dam axis (Figure 1). The tracers were monitored by 30 control points downstream of the injection points; that included some of the installed piezometers, springs, and surface water flows inside and outside the project area.

From the pumping and tracer tests, we found hydraulic connectivity between both banks of the principal stream valley along principal geological structures (faults) present in the area. These faults act as preferential paths for water circulation.

Laboratory Tests

In order to determine the purity of the carbonate rocks of the Copacabana Group from petrographic and mineralogical viewpoints, we performed 45 petrographic analyses and XRD tests in samples taken from boreholes and outcrops. The results of these analyses provide additional information necessary to assess the karstification degree in the Copacabana Group. Of the 45 total tests, 13 presented calcite as the predominant mineral, 18 presented dolomite, and 14 presented quartz and others minerals associated with siltstones and sandstones. A summary of the results are shown in Table 1.

From these results, we conclude that the Copacabana Group has a varied composition; the lower member presents predominantly calcite and dolomite, while the middle member presents predominantly dolomite, calcite, and quartz.

The high dolomite content reduces the dissolution potential, therefore, the probability of developing significant karstification is generally low (Ford & Williams, 2007) in the middle member, where the dam will be founded; however, there are some horizons with high content of calcite, which are related to superficial dissolution, that must be treated with appropriate engineering measures. Limestones from the lower member that might be present in part of the dam foundation must be treated as well.

Copacabana Member	Total sample tested	Mineral composition		
		Calcite (%)	Dolomite (%)	Quartz (%)
Lower	11	9–65	9–97	1–39
Middle	34	0–64 83–97*	0–97	1–78

1. Own elaboration
2. *Presence of some horizons with high content of calcite.
3. The null content of calcite represents siltstones, and sandstones samples.

Table 1. Summary of mineral composition of Copacabana Lower and Middle members.

Assessment of the Factors in Karstification of the Copacabana Group Physiographic Location, Weather, Organic Material Content, and Water pH

At the beginning of the paper, we noted that the area of the proposed TSF is located on the South Andes of Peru, between 4200 and 4500 m.a.s.l. The weather in the area is cold, with precipitation varying between a dry season (April to November) and a rainy season (December to March). The development of vegetation is limited to ichu (a type of grass typical from the highlands) of low height. The organic soil thickness varies between 0.1 and 0.5 m.

The cold climate of the area, limits the influence of biologic activity and the production of carbonic acid, which is a critical factor in limestone dissolution. The hydrochemical characterization carried out in the area verified that the surface and ground waters present a neutral pH, slightly alkaline, which does not favor karst development.

Stratigraphy of the Copacabana Group

The Copacabana Group, based on geological mapping, boreholes information and laboratory test results, is predominantly a sequence of limestones, dolostones, and dolomitic limestones with interbedded calcareous sandstones and pelitic rocks (siltstone and shales), in varying proportions. For this reason, this Group has been divided into 3 units (lower, middle, and upper member).

Lower Member

This unit outcrops mostly at the bottom of the dam area. It consists of limestones and dolomitic limestones

alternating with horizons of siltstones and dolostones. In two boreholes we identified two cavity zones (lengths between 0.6 and 1.45 m). The outcrop area is characterized by the presence of karst towers, defined as isolated, steep-sided limestone outcrops separated by topographically low areas, produced by the differential erosion, tectonism and dissolution of the limestones (Maslyn, 1977).

The karst towers are present downstream of the dam footprint, oriented along an E–W alignment, associated with steeply-dipping limestones (Figure 5). They are the result of the structurally controlled solution activity along discontinuities in the rock mass (bedding planes and joints provide access to water). Outside of the dam area, small caves and cavities (0.6 to 2.4 m in diameter) have been identified on the slopes above the area of well-developed karst towers. Collectively the karst towers and larger cave and cavities are representative of endokarst.



Figure 5. Photo looking NW. Karst towers in the lower member of the Copacabana Group, downstream of the dam footprint.

Middle Member

This unit outcrops in the north side of the impoundment area and proposed dam footprint. It consists of limestones and dolostones alternating with siltstones and calcareous sandstones.

On the left abutment of the dam (looking downstream), an anticline is present with an E–W orientation that is transverse to the dam axis (Figure 6). This zone contains steeply-dipping and jointed rock, which is moderately to highly permeable and requires appropriate engineering treatment before the construction of the dam.

Three isolated dissolution cavities (lengths between 0.3 and 2.25 m), partly controlled by the regional fracture system, were identified in three boreholes. These cavities are considered to be isolated epikarst.



Figure 6. Photo looking NNW. Anticline in middle member at the dam area.

Upper Member

This unit is present on the north side of the impoundment area and 100 m above the north side of the axis dam. It extends to the east outside the study area (Figure 7), and consists mostly of quartz sandstones alternating with bituminous siltstone and isolated horizons of limestone. No evidence of karst dissolution is present in the upper member.

Structural Arrangement

The most important structures identified in the area correspond to geologic faults across the projected impoundment area and dam foundation. These faults strike NW and are filled with mostly clayey sand and gravel-sized material with an average hydraulic conductivity of 6.1×10^{-04} cm/s, with higher values occurring in the first 30 m of depth.

Bedrock in the Copacabana's middle and lower members is folded into a relatively tight anticline with steeply-dipping limbs, especially on the north slope above the valley floor.



Figure 7. Bedding of the middle member at the impoundment area and quartz sandstone outcrop of the upper member at the top.

The sub-vertical dips in limestone, coupled with flexural slippage along bedding planes and jointing due to folding, create a favorable environment for solution activity in the limestones (karst towers area).

The bedding of the Copacabana Group on the left abutment of the dam, strikes NW and dips between 20° to 80° to NE or SW, depending of its location regarding the anticline. At the bottom of the projected dam, the Copacabana Group exhibits an E–W to NW strike, with sub-vertical dip to the south. On the right abutment of the dam, the bedding of the Ambo Group strikes almost E–W to NW and dip between 5° to 65° to the SW.

The bedding on the impoundment area strikes N–S and dips to the west (Figure 7). This condition is favorable for the watertightness of the TSF, considering that the flow direction of the valley is west to east, and permeability across bedding is lower than along bedding.

Hydraulic Conductivity

D. Evans establishes a limit for developing karst morphology based on the hydraulic conductivity of limestones from Peru (Evans, 2015) using a depth vs hydraulic conductivity graphic. This limit was applied to the Copacabana's lower and middle member results of 275 permeability tests (Lugeon and Lefranc) executed in the geotechnical boreholes.

The results showed that the middle member would behave as a poor aquifer with hydraulic conductivities between 1×10^{-4} cm/s and 1×10^{-6} cm/s. On the other hand, the lower member, due to its higher alteration degree,

it would behave as a free aquifer semi-confined with a hydraulic conductivity average of 1×10^{-4} cm/s.

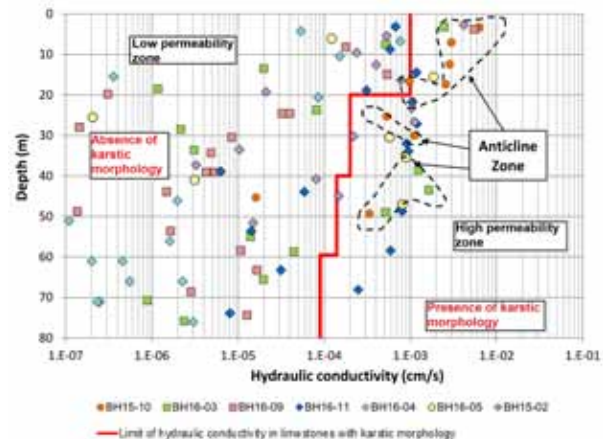
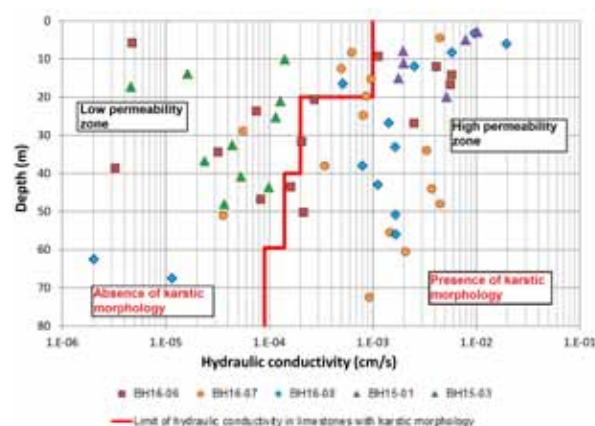
Figure 8 shows that the lower member mostly presents high permeability values, and this analysis indicates that is related to the development of karstic features.

Figure 9 shows the results of the middle member, which presents lower permeability values and therefore a less probability for developing karstic features, except for the results near the anticline zone, which presents high permeability due to the structural alteration of the zone and is related to the cavities found in some boreholes.

Water Levels and Water Circulation

In the TSF area there are two water levels. The first corresponds to a free aquifer located approximately subparallel to the existing natural terrain, which converges on both sides to the riverbed in the stream valley. The second corresponds to a deep confined aquifer located sub-horizontal at approximately 22 m in depth. However, downstream of the dam, both levels join at the same elevation indicating that the aquifers are connected and discharge over the rocks of the lower member of the Copacabana Group.

Initially we considered that preferential paths of water circulation could exist, favoring karstic cavities observed in some of the boreholes of the north side of the TSF; however, the results of the tracer tests show shorter paths of local water circulation, limited to the superficial zone of the limestones downstream of the projected dam. In any case, there are not likely to be longer preferential



Figures 8 and 9. Hydraulic conductivity values from permeability tests in boreholes (BH 16-XX/BH 15-XX), lower member of the Copacabana Group (left) and the middle member (right). Limit of karstic morphology (red line) from D. Evans, 2015.

paths because there is no observed remote discharge of water, and the extension of the Copacabana Group is limited. The circulation of water in this area is related mostly to structural features that act as preferential flow paths.

Dissolution and Oxidation Degree

In the lower member of the Copacabana Group, the degree of dissolution and oxidation observed on the cores is variable. Some sectors exhibit dissolution with high to moderate oxidation up to a depth of 40 m.

The dissolution degree and oxidation observed in the middle member is variable. Some sectors exhibit dissolution with moderate to high oxidation and others are low to null. At depths between 25 to 60 m, evidence of oxidation and dissolution disappears. The shallower depth that shows evidence of dissolution is related to the anticline located on the left side of the dam axis (looking downstream).

In two boreholes drilled in the lower member, we found two cavity zones, with a total length of voids of 2.05 m, representing 0.84% of the total length (245 m) drilled in this member. In the middle member, we identified three cavity zones, with a total length of voids of 3.55 m, representing 0.61% of the total length (579 m) drilled in the middle member. The finding of voids in five of the boreholes at the site is significant; however, the number of borings in which karst was found is less important than the size of the voids found and the length of voids as percentage with respect to the total number of meters drilled.

We concluded that karst voids are more prevalent in the Copacabana's lower member than in the middle member, which is similar to interpretations from surface geomorphology and geologic mapping.

Human Activity

Because water pH is one of the factors that causes dissolution of limestones, we recommend constant monitoring of pH in the proposed TSF, to prevent any decrease of the pH below 5. Decreasing pH will generate acidic water, and could increase the risk of developing dissolution in the carbonate rocks.

Engineering Measures to Mitigate Risk Due to the Karstification Degree of the Copacabana Group

According to the recommended treatments described by Schaefer (2009) and Fell (2008), on the projected area of the dam and the TSF, the engineering measures that

should be taken includes excavation of weathered, weak rock and/or rock showing evidence of solution activity in the dam foundation, followed by the treatment of joints or cavities with slush grouting or dental concrete depending on the size of the cavities, cracks, or joints discovered.

Also, it will be necessary to construct a grout curtain below the dam core, to fill possible cavities and improve the hydraulic containment of the geologic units. This curtain must reach its greatest depth on the left side of the dam (up to 40 m), where the Copacabana Group is present. Cross section A-A' (Figure 4) shows the estimated depth of the grout curtain.

Conclusions

The karstification degree on the Copacabana Group is variable and depends on the stratigraphy, lithology, mineralogy and geologic structure predominant in the project area. The Copacabana Group is not homogeneous, including solution-prone limestones, and significant quantities of dolostones, siltstones, and sandstones, which are not susceptible to dissolution. With respect to dolostones, dissolution can be very slow and as a consequence, the possibility of developing karst features is low to moderate.

The Copacabana's lower member is characterized by the presence of karst towers and small caves, indicating that this area should be classified as endokarst. The middle member exhibits karst features limited in extent and depth, represented by the isolated cavities found in some boreholes and are considered to be epikarst. Finally, the upper member does not exhibit any evidence of karstic dissolution.

Because of the higher degree of karstification in the lower member, it represents the largest risk to the project. The location of the dam has been designed, as much as possible, to avoid the lower member of the Copacabana Group (karst towers area is outside the footprint of the dam).

After the assessment of the factors relating to the development of karst conditions at the proposed dam and impoundment site, we conclude that the Copacabana Group represents a moderate to low risk to the project. It will be necessary, however, to apply engineering treatments to the foundation before construction of the dam.

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LITHOLOGY AS AN EROSIONAL CONTROL ON THE CAVE BRANCH AND HORN HOLLOW FLUVIOKARST WATERSHEDS IN CARTER COUNTY, KENTUCKY

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Abstract

Variation in rock erodibility controls the rate of surface development providing information on the landscape evolution. In fluvio karst systems, the contrast between carbonate and non-carbonate rocks may alter the topographic evolution of the system. In Carter County, Kentucky, the Cave Branch and Horn Hollow fluvio karst systems comprise limestone overlain and capped by sandstone. Streams in the watersheds illustrate erosional differences associated with lithology. Developing as a function of the rock erodibility, uplift rates, and stream power, longitudinal stream profiles provide a means to evaluate variability in denudation rates. Using the integral method of channel profile analysis, we examine if variation in lithology has created a state of disequilibrium in the Cave Branch and Horn Hollow watersheds and if the overall development of the system is a function of erosional resistance and of differential weathering between sandstone and limestone. By scaling erosion with drainage area, the integral method allows for the comparison of streams of varying watershed areas. Streams within the sandstone portions of the watersheds displayed a greater degree of equilibrium than the limestone watersheds. Limestone stream segments generated a greater steepness index, mean value of 0.03, than sandstone segments, mean 0.01. The greater degree of disequilibrium and greater steepness index of the limestone are related to the soluble nature of limestone and the glacial-fluvial development of this area. The erosion signature recorded in the sandstone appears to represent the conditions prior to the Ohio River incision. The rapid development of the karst system is in response

to the Ohio River incision disproportionately eroding the limestone. The erosional differences between the limestone and sandstone segments represent the response of the fluvial system during glacial and interglacial periods.

Introduction

Weathering and erosion of a landscape will leave a record of the factors involved in the topographic development. One way to interpret past environmental conditions and to understand landscape evolution is to examine longitudinal stream profiles (Bishop, 2007; Duvall et al., 2004; Goldrick and Bishop, 2007; Larue, 2011). A longitudinal stream profile plots the bed elevation against the length of the stream. Stream profiles are useful in the evaluation of a landscape as they set the boundary for hillslope processes, which is responsible for the denudation of a landscape (Whipple and Tucker, 1999). As landscape denudation occurs, a stream works to reach equilibrium conditions, where the amounts of erosion and deposition area equal. Equilibrium conditions result in a smooth concave-up profile (Goldrick and Bishop, 2007; Mackin, 1948; Phillips and Lutz, 2008). Factors, including tectonics, climate, change in base level, and variation in erodibility and lithology, influence the rates of erosion and deposition causing a stream to deviate from equilibrium and lose its equilibrium profile. In bedrock streams, dominant erosional forces are closely related to lithology and structure of the underlying bedrock (Miller, 1991; Wohl, 2013; Wohl and Ikeda, 1998).

Stream profiles are quantified using stream power equations (Bishop, 2007; Carlston, 1969; Duvall et al., 2004; Goldrick and Bishop, 2007; Hack, 1973). Stream power is a measure of the sediment-transport capacity for a stream as it is related to discharge and slope (Anthony and Granger, 2007; Hack, 1973; Knighton, 1998; Phillips and Lutz, 2008). Stream power equations can predict the amount of erosion occurring along a profile of a stream; any significant deviation from this prediction represents a state of disequilibrium (Phillips and Lutz, 2008). A common stream power equation used to evaluate a stream profile is expressed in terms of drainage area, which serves as a proxy for discharge, and slope (Phillips and Lutz, 2008):

$$\frac{dz}{dt} = U - KA(x)^m \left(\frac{dz}{dx}\right)^n \quad \text{Eq. 1}$$

Where z is elevation, t is time, x is horizontal distance, U is rock uplift rate, K is an erodibility constant, A is drainage area, and m and n are positive constants related to hydrologic conditions. Exponents m and n are a function of standard flow resistance and stream power relations (Phillips and Lutz, 2008; Sklar and Dietrich, 2013). Generally, topographic steady-state is assumed, $\frac{dz}{dt} = 0$, simplifying Eq. 1 to

$$\frac{dz}{dx} = \left(\frac{U}{K}\right)^{\frac{1}{n}} A(x)^{-\frac{m}{n}} \quad \text{Eq. 2}$$

The ratio of m/n represents the concavity index of a stream profile (Phillips and Lutz, 2008; Whipple and Tucker, 1999). Eq. 2 reveals a negative power-law relationship between drainage area and slope. When transient conditions prevail, stream profiles deviate from the power-law relationship because of variation in rock uplift rate or erodibility (Royden and Perron, 2013; Whipple and Tucker, 1999).

Fluviokarst

Fluviokarst is a landscape with surface and subsurface drainage, consisting of both fluvial and karst features (White and White, 1983). These systems typically occur at the contact of carbonate and non-carbonate rocks (Bočić, 2003; Jakucs, 1977). Lithology is a key component in the development of fluviokarst, with the difference in erosional resistance between lithologies

influencing the landscape as a whole. Non-carbonate rocks, specifically siliciclastic rocks, weather primarily by physical processes due to their low solubility as compared to limestone (Nesbitt et al., 1997). Limestone is susceptible to both physical and chemical weathering, with physical weathering being more common than had been previously reported (Dogwiler and Wicks, 2004). With respect to chemical weathering, streams in limestone bedrock can have unique features. Diversion of flow to the subsurface and its subsequent reemergence downstream, develop unique stream profile signatures (George, 1989; White and White, 1983; Woodside et al., 2015). Woodside et al. (2015) identified surface anomalies along a limestone bedrock stream. The anomalies, which occur downstream of swallets, are an increase in stream elevation, suggesting that they are a result of erosional process continuing upstream of the subterranean diversion and downstream of the water reemergence but with limited erosion of the surface channel between these points. Schroeder et al. (2015) reported the absence of surface anomalies in a fluviokarst system of southeastern Minnesota. A prevailing question as to why one fluviokarst system exhibits an atypical profile while another system exhibits a typical profile exists. Both systems are composed of non-carbonate rocks overlying carbonate rocks.

To understand this dichotomy, evaluating differences in erodibility based on lithology would be useful. Thus, we posit that lithology is a controlling factor in the development of a fluviokarst system. Specifically, we examine the Cave Branch and Horn Hollow fluviokarst systems in the Carter Caves area of northeastern Kentucky. The objectives of this study are to (1) determine if a state of disequilibrium exists because of a variation in lithology; (2) determine whether the limestone or sandstone is more resistant to erosion based on stream power; and (3) assess how erosional resistance is related to the overall development of the Cave Branch and Horn Hollow systems.

Study Area

This study will focus on the Cave Branch and Horn Hollow Basins (Figure 1), each with sections inside and beyond the boundaries of Carter Caves State Resort Park (CCSRP) in northeastern Kentucky. The fluviokarst watersheds, which have been extensively studied (Angel and Peterson, 2015; Dogwiler and Wicks, 2004; Engel and Engel, 2009; Jacoby et al., 2011a; Jacoby et al., 2011b;

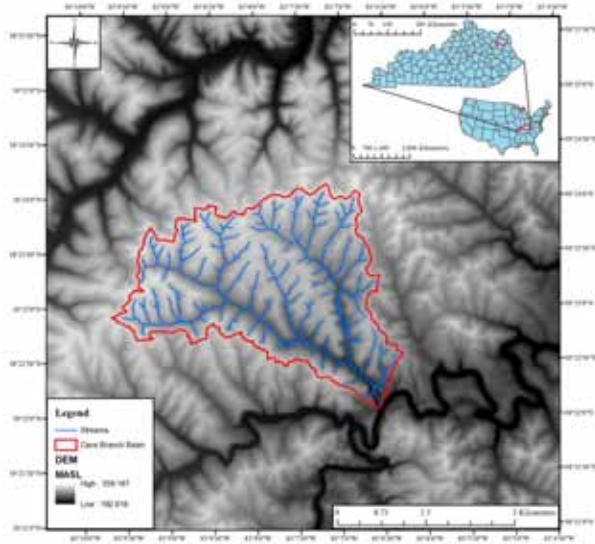


Figure 1. Cave Branch Basin, including its tributary Horn Hollow. Horn Hollow constitutes the northeastern branch of the watershed.

Jacoby et al., 2013; Peterson et al., 2011; Woodside et al., 2015), contain rocks of Mississippian and Pennsylvanian age, with approximately 25 meters of carbonate bedrock bounded by siliciclastic units (Figure 2). Engel and Engel (2009) provide a detailed description of the regional stratigraphy and salient descriptions of bedrock within the area. CCSRP includes surface exposure of three bedrock formations: the Borden Formation, the Slade Formation, and the Paragon Formation. The Borden Formation, the lower-most Mississippian unit, is a series of siliciclastic rocks, sandstones and shales. The Slade Formation is primarily carbonate rocks with interbedded chert, silt, and sand in the upper member. The upper most unit, the Paragon Formation, consists of siliciclastic rocks, primarily sandstones. The contact between the Slade Formation and the Paragon Formation is reported at 274 meters above sea level (MASL) (Jacoby et al., 2013). The headwaters of the basins originate in the Carter Caves Sandstone. Streams transition from clastic to carbonate to clastic moving towards the regional base level defined by Tygart's Creek, which flows along the Borden Formation and below all karst development.

Jacoby et al. (2011a) identified four cave levels within the CCSRP with the use of a 10-meter DEM (digital elevation model). The cave levels developed due to changes in base level associated with glacio-eustatic processes, which coincided with the formation of the Ohio River and the abandonment of the Teays River Valley.

Methods

To address the three objectives in this study, streams were evaluated using a stream power model. The integral method introduced by Royden and Perron (2013) and Perron and Royden (2013) was used to conduct the profile analyses. The main reach and the tributaries a watershed should erode at relatively the same rate. A benefit of the integral method is that it scales erosion with drainage area. This characteristic is crucial to this study because it allows the analysis of the watershed as a whole, or

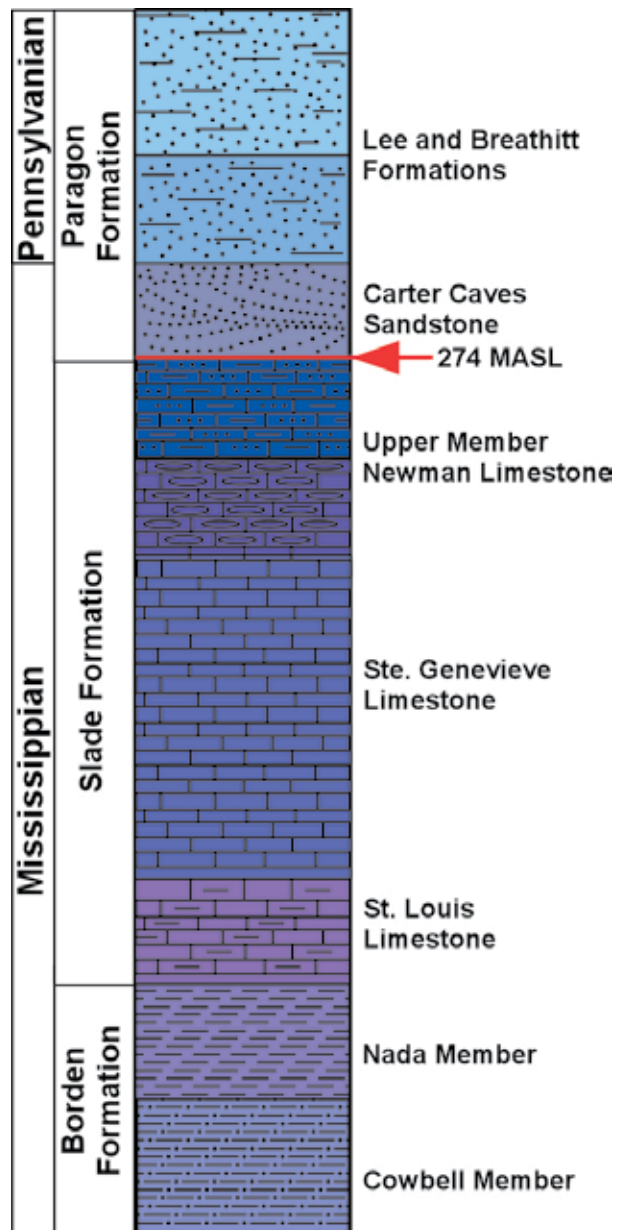


Figure 2. Stratigraphic column of CCSRP (modified from Engel and Engel, 2009). Red arrow represents 274 MASL.

as segments of streams, to assess if a system is in a state of equilibrium. Providing a comparison between upstream and downstream segments, the integral method allows assessment of the erodibility of the Carter Caves Sandstone and the Upper Member Newman Limestone.

Integral Method

Derived from Eq. 2, the integral method calculates stream power by using elevation instead of slope as the dependent variable and the spatial integral of drainage area as the independent variable (Perron and Royden, 2013; Royden and Perron, 2013). The slope of a transformed profile, or chi plot, represents the steepness index (SI), which is equal to uplift (U) divided by erodibility (K). The transformation of a stream profile is calculated from:

$$z(x) = z(x_b) + \left(\frac{U}{KA_0^m} \right)^{1/n} \chi \quad \text{Eq. 3}$$

where

$$\chi = \int_{x_b}^x \left(\frac{A_0}{A(x)} \right)^{m/n} dx \quad \text{Eq. 4}$$

The variables in Eq. 3 and 4 have been defined above in Eq. 1 and 2, with the addition of A_0 , which serves as a reference drainage area, and χ or chi, which is the integral of drainage area. The integral method also removes noise that is a side effect of calculating slope from uncertain topographic data. Thaler and Covington (2016) successfully used the integral method to investigate similar lithology sequences in the Buffalo River Basin.

For a single stream, the chi plot should be linear, and any deviation from that suggests a state of disequilibrium. Because erosion is scaled with drainage area, the chi plot for an entire stream network should exhibit streams with similar slope, or SI.

Geographic Information System (GIS)

Individual watersheds were generated in ArcGIS 10.3.1 (ArcGIS, 2011) from 10-meter DEMs downloaded from the USGS 3D Elevation Program (USGS, 2017). The Cave Branch watershed and sub-watersheds were delineated by employing the Raster Calculator to select

all cells with more than 1000 cells draining to it (e.g., the collection points for a significant amount of surface flow). With a 10-meter DEM, a 1000-cell drainage area represents 100,000 m². Thus, the threshold of 1000 cells signifies the transition from colluvial to fluvial, which occurs when the drainage area of a watershed ranges from 10⁵ to 10⁶ m² (Whipple and Tucker, 1999). Watershed boundaries were computed by identifying all of the cells with directional flow (from the flow direction layer) leading to that pour point. Watersheds were created for both Cave Branch, upstream from the confluence with Horn Hollow, and Horn Hollow (Figure 3a). Additional delineation of the Cave Branch watershed at the contact between the Carter Caves Sandstone and the Upper Member of the Newman Limestone at the elevation of 274 MASL generates three upstream sub-watersheds, which are named CB274 north, mid, and south (Figure 3b). Within the Horn Hollow watershed, two upstream sub-watersheds were created, HH274 west and east.

MATLAB

The individual watersheds were exported to and analyzed in MATLAB using the Topotoolbox (Schwanghart and Scherler, 2014) and Image Processing Toolbox (The MathWorks Inc., 2016). Topotoolbox is optimized to conduct stream power analysis and incorporates chi plot analysis in the functions.

An important aspect of the flow accumulation size is to determine where the transition from colluvial to fluvial conditions occurs. While the threshold typically occurs between 10⁵ and 10⁶ m², the transition for a given watershed can be determined by plotting drainage area against stream slope. The inflection in this graph represents where the transition from colluvial to fluvial occurs (Montgomery and Buffington, 1997). For the entire Cave Branch watershed, including Horn Hollow, the log of drainage area and the log of slope were plotted against each other. The point along the x-axis (drainage area) where the inflection occurs represents the drainage area that was used for the stream networks to be analyzed by the integral method via chi plots. We then modified the stream network to include areas above and below the 274 MASL.

To determine if variation in lithology was creating a state of disequilibrium within the fluvio-karst system, we compared the profiles of the sandstone segments above 274 MASL and the limestone segments below

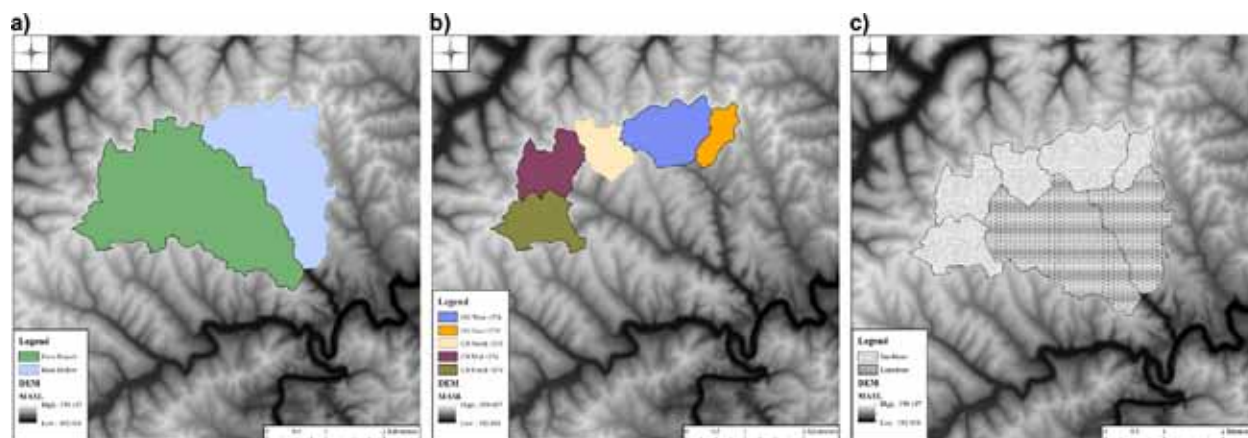


Figure 3. (a) Cave Branch and Horn Hollow watershed. (b) Sub-watersheds for Cave Branch and Horn Hollow above 274 MAS. (c) Individual watersheds with corresponding lithology. Limestone below 274 MASL, sandstone above 274 MASL.

274 MASL to the individual Cave Branch and Horn Hollow watersheds. To create the chi plots for all of Cave Branch and Horn Hollow, the chi plot function in the Topotoolbox was run to include all streams above the confluence of the two streams. To create the chi plots for limestone segments, χ analyses were completed on stream segments below 274 MASL. To create the chi plots for the sandstone streams, the upstream watersheds had to be created because an individual chi plot requires that streams drain to one point. The five upstream watersheds (Figure 3) were analyzed using the chi plot function including all streams above their pour point.

Before calculating the degree of equilibrium of watersheds or steepness index of streams, the m/n ratio must be determined. To reiterate, the m/n ratio represents the concavity of a stream. The m/n ratio used for a given chi plot can be established in one of two ways. The first way is to exclude the input value when running the chi plot, which is what is used to determine if variation in lithology was creating a state of disequilibrium. When this course of action is taken, the m/n ratio will automatically be determined by Topotoolbox by running a linear least-squares regression. The m/n ratio that produces the highest R^2 value will then be used. The R^2 value represents the degree of equilibrium for a watershed. The higher the R^2 value, measured on a scale from 0 to 1, the greater the agreement in slope among the streams. A system completely in equilibrium will have a R^2 of 1. We then compared the limestone streams and the sandstone streams to entire watersheds to see if there was a difference in the degree of equilibrium because of varying lithology.

To determine if the limestone or sandstone is more resistant to erosion (thus, having a greater SI) chi plots were analyzed in a different manner. First, subwatersheds were generated based solely on the lithology. The five watersheds with sandstone stream segments were compared to the two with limestone stream segments (Figure 3c). Upstream sandstone watersheds were determined by placing pour points above 274 MASL. The downstream limestone watersheds were created from the Cave Branch and Horn Hollow watersheds, only including streams below 274 MASL. Second, the m/n ratio was entered manually when running the chi plots. Finally, instead of comparing the chi plots of watersheds in terms of R^2 , the chi plots of individual limestone and sandstone streams were compared in terms of their SI.

To compare the SI of different streams, limestone against sandstone, the same m/n ratio must be used. The m/n ratio to be used was determined with a sensitivity analysis, run for each watershed to determine the m/n ratio that yielded the highest R^2 value. A range of m/n values between 0.1–0.9 was used because bedrock streams typically have a m/n ratio of 0.2 to 0.6 (Whipple and Tucker, 1999). Using the m/n value with the highest R^2 value, chi plots were generated for each of the watersheds. Once the SI of each individual limestone and sandstone streams were established, the values were evaluated with a t -test using an $\alpha=0.05$ to determine if there was a statistical difference between the limestone and sandstone streams.

Results

Before creating chi plots, the proper flow accumulation size is needed to be determined by creating a log-log

plot of drainage area against slope for streams within the watersheds (Figure 4). The inflection of the drainage area-slope graph around $10^{5.98}$ m² signifies the transition from colluvial to fluvial. Only streams with a drainage area greater than this value were used in the analysis.

Equilibrium Analysis

The equilibrium analysis revealed that the entire Horn Hollow watershed had a greater R^2 than its subwatersheds, and the entire Cave Branch had a lower R^2 than its subwatersheds (Table 1). For both Cave Branch and Horn Hollow, the sandstone segments exhibit a greater R^2 than the limestone segments. The m/n values for Horn Hollow and its subwatersheds ranged from -0.599 to 0.646 . The m/n values for Cave Branch and its subwatersheds ranged from -1.724 to 0.543 . A positive m/n ratio represents a stream in equilibrium, while a negative m/n denotes a stream not in equilibrium. Both watersheds exhibited a range of m/n ratios, but the m/n ratio of the entire Horn Hollow and Cave Branch watersheds differed by an order of magnitude. The chi plots of the individual watersheds can be seen in Figure 5. The more co-linear the chi plot, the higher the R^2 .

Sensitivity Analysis

The sensitivity analysis incorporated a χ analysis for the entire Cave Branch watershed, including Horn Hollow, using the previously mentioned range of m/n ratios (Table 2). The m/n value of 0.4 generated the highest R^2 value, making it the most representative of the entire watershed.

Steepness Index (SI) Analysis

Upon identifying an m/n ratio of 0.4 , individual chi plots for the 17 limestone streams and 16 sandstone streams generated SI values for comparison (Figure 6). The mean SI for the streams with limestone bedrock was 0.032

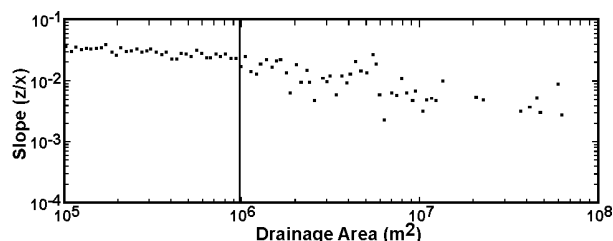


Figure 4. Log-log drainage area-slope plot used to determine the flow accumulation that constituted a stream in the Cave Branch Basin. The inflection occurs at $10^{5.98}$ m², which is represented by the vertical line.

Watershed	m/n	R^2
Cave Branch (SS&LS)	0.276	0.80
CB _{less274} (ls)	0.502	0.86
CB _{274south} (ss)	0.554	0.98
CB _{274north} (ss)	-0.599	0.79
CB _{274mid} (ss)	0.646	0.94
Horn Hollow (SS&LS)	0.050	0.92
HH _{less274} (ls)	0.543	0.80
HH _{274east} (ss)	-1.724	0.86
HH _{274west} (ss)	-0.093	0.86

Note: SS represents sandstone and LS represents limestone.

Table 1. Results from equilibrium analysis.

with a variance of 2.0×10^{-4} ; for the sandstone streams, the mean SI was 0.012 with a variance of 2.0×10^{-5} . A t -test indicates a significant difference in SI values between the limestone and sandstone stream segments ($t(31) = -10.10$, $p < 0.001$). The higher SI of the limestone indicates that the limestone stream segments are more resistant.

Discussion

The first objective of this study was to determine whether lithology was responsible for a state of disequilibrium. The results of the equilibrium analysis revealed that the degree of equilibrium varied from the sandstone to the limestone sections of Cave Branch and Horn Hollow. Within Horn Hollow (red line on the diagram on Figure 5f), a noticeable change in slope (SI value) occurs at the contact between the sandstone and limestone. The sandstone watersheds are closer to equilibrium, while the downstream limestone segments appear to be in a state of disequilibrium. At the watershed scale, all the factors that can affect the shape of a profile, which include climate, tectonics, changes in base level, are held constant among the sub-basins except for variation in lithology. The results of the equilibrium analysis suggest that the sandstone segments are in a greater degree of equilibrium than the limestone segments.

The second objective was to determine whether the sandstone or limestone reaches were more resistant to erosion based on SI. The statistical difference between SI values for the sandstone and limestone, with limestone stream segments having a greater SI, suggest that limestone in the Carter Caves area is more

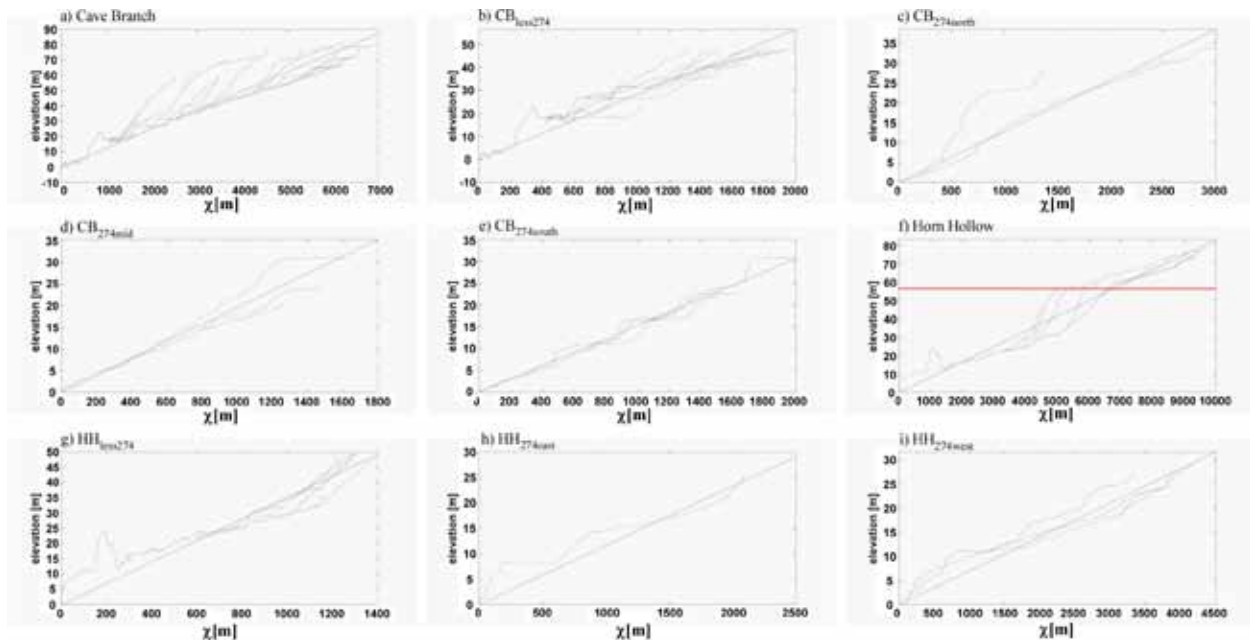


Figure 5. Chi plots for the Cave Branch and Horn Hollow segments. Gray lines represent chi plot individual streams and the blue line represents best fit for the watershed. (a) Cave Branch, including sandstone and limestone segments. (b) $CB_{274less}$ limestone streams in Cave Branch below 274 MASL. (c) $CB_{274north}$ sandstone streams in Cave Branch above 274 MASL. (d) CB_{274mid} sandstone streams in Cave Branch above 274 MASL. (e) $CB_{274south}$ sandstone streams in Cave Branch chi plot above 274 MASL. (f) Horn Hollow including sandstone and limestone streams—red line indicates 274 MASL. (g) $HH_{274less}$ limestone streams in Horn Hollow below 274 MASL. (h) $HH_{274east}$ sandstone streams in Horn Hollow above 274 MASL. (i) $HH_{274west}$ sandstone streams in Horn Hollow above 274 MASL.

m/n	R^2	Steepness index
0.1	0.76	0.008
0.2	0.80	0.011
0.3	0.82	0.015
0.4	0.83	0.021
0.5	0.80	0.028
0.6	0.74	0.037
0.7	0.63	0.047
0.8	0.47	0.595
0.9	0.25	0.073

Table 2. Sensitivity analysis of m/n ratio for the Cave Branch Basin.

resistant than the sandstone. Thaler and Covington (2016) identified high steepness values for limestone underlying a sandstone caprock. They conclude that the steepness values for the limestone are a result of shielding by the caprock. This is a possible explanation, but not necessarily the case when all variables are considered.

One explanation for the different observed SI in the sandstones and limestone is the difference in weathering processes. As previously stated, sandstones are vulnerable to physical weathering, and limestone can be weathered by physical and chemical processes. In the limestone segments, streams can be diverted to the subsurface. The reason streams are diverted into the subsurface in a specific location is that water moving from a sandstone to a limestone is going to be more dissolutionally aggressive, having yet to be neutralized. The more aggressive water is likely to encourage dissolution and subsurface piracy, once in contact with soluble limestone. In the subsurface, the stream maintains an equilibrium profile, leaving a ‘bump’ in the profile where erosion is not occurring (White and White, 1983; Woodside et al., 2015). Furthermore, the difference in SI between limestone and sandstone streams could be due to the continued denudation in the limestone areas of Cave Branch and Horn Hollow. As streams in the limestone sections are diverted into the subsurface, the continued downcutting along the flowpath in the subsurface increases the gradient between the tributary and main

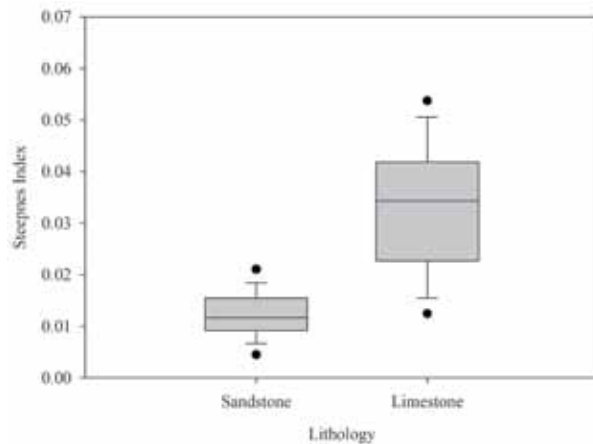


Figure 6. Box plot of SI values of sandstone and limestone streams. The ends of the boxes represent the 25th and 75th percentiles with the solid line at the median and the dashed line at the mean; the error bars depict the 10th and 90th percentiles and the points represent the 5th and 95th percentiles.

stem. Woodside et al. (2015) observed evidence of cave collapse in Horn Hollow. Instead of the typical v-shaped valley that develops along a bedrock stream, Horn Hollow displays vertical valley walls in areas. In areas where cave collapse has occurred, the steeper gradient is exposed to the surface. The existence of cave collapse would also explain the greater degree of equilibrium observed in the sandstone watersheds.

The third objective was to determine how erosional differences in the limestone and sandstone are related to the overall development. To answer this question, the assessments made from the first and second objectives must be considered concurrently. The greater degree of equilibrium in the sandstone watersheds and the greater steepness in the limestone streams is a function of both the soluble nature of limestone and the glacial-fluvial development of northeastern Kentucky. The rapid development of the fluviokarst system in northeastern Kentucky lead to the development of four distinct cave levels (Jacoby et al., 2013). The caves in the Horn Hollow and Cave Branch represent the levels of cave development linked to a common static base level. During these periods of stable base level, streams in the limestone segments were diverted to the subsurface. While in the subsurface, these limestone streams can maintain their equilibrium profile (White and White, 1983; Woodside et al., 2015). Over time, a subterranean stream can be exposed to the surface because of cave collapse. Woodside et al. (2015)

saw evidence of cave collapse in Horn Hollow Creek. The disequilibrium in the limestone sections of Horn Hollow and Cave Branch is the result of cave collapse, which exposes the elevation differences between surface reaches and subsurface reaches. The greater SI in the limestone streams is a result of the subsurface piracy and eventual cave collapse. As the main stem continued to erode in the subsurface, the gradient between it and the tributaries increased. The sandstone streams, which generally had a greater degree of equilibrium had started to develop prior to glaciation when the system was a part of the Teays drainage system.

Within fluviokarst system in southeastern Minnesota, Schroeder et al. (2015) reported the absence of anomalous segments along the limestone streams. The difference between the fluviokarst system in southeastern Minnesota and the one in northeastern Kentucky appears to be the influence of glacial-fluvial events. The disequilibrium of the fluviokarst system in Kentucky, as indicated by dissimilar m/n values among stream reaches, suggests rapid development associated with glacial and interglacial periods has created the anomalous sections and the difference in equilibrium between the limestone and sandstone watersheds.

Conclusion

The purpose of this study was to determine how the variation in lithology was influencing the development of the fluviokarst system in CCSRP in northeastern Kentucky. To do this, streams were compared using an integral approach to the stream power equation that allows for the degree of equilibrium of watersheds and SI values of streams to be compared. The analyses reveal that sandstone watersheds were generally in a greater degree of equilibrium than the limestone watersheds and that the limestone streams had a greater SI. SI is a measure of a streams resistance to erosion, but when the differences in weathering processes in limestone and sandstone are considered, SI reveals more than just resistance to erosion. The soluble nature of limestone lends itself to the development of karst, while sandstone is eroded only by physical processes. The difference between the limestone and sandstone segments is due to the rapid development of the Ohio River valley in response to the glacial and interglacial periods. The glacial-fluvial influence explains the difference between the fluviokarst system in northeastern Kentucky as compared to the one in southeastern Minnesota.

One uncertainty that remains from this study are the result of the equilibrium analysis. While there was generally a greater degree of equilibrium in the sandstone watersheds than in the limestone watersheds, the entire Horn Hollow watershed had a greater degree of equilibrium than the individual subwatersheds. In contrast, the entire Cave Branch watershed had a lower R^2 than three of its four subwatersheds. While the R^2 values indicated that the entire Horn Hollow watershed was in a greater state of equilibrium than its subwatersheds, the transition from negative to positive m/n values suggests that, as a whole, the system is in a state of disequilibrium. Further investigation is warranted to understand the difference and the significance of R^2 and the application of m/n . This would allow for a better understanding of the differences between Cave Branch and Horn Hollow.

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COMPREHENSIVE INVESTIGATION AND REMEDIATION OF CONCEALED KARST COLLAPSE COLUMNS IN RENLOU COAL MINE, CHINA

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Abstract

Coal mining in China has exposed numerous karst collapse columns of tens of meters in diameter and hundreds of meters in height. Hydraulically conductive collapses have functioned as groundwater pathways between the underground workings and the aquifers, resulting in water inrushes during coal mining. Over the last 40 years, water inrushes through these collapses have caused fatalities, economic losses, and degradation in the environment. Two such collapse features were unexpectedly encountered during operations in Renlou Coal Mine of China. The first encounter caused flooding of the entire mine. Although no serious damages occurred at the second encounter, because of timely and effective grouting measures, the production rate was reduced. Proactive detection of any concealed karst collapses and determination of their hydrogeological characteristics were essential components of a comprehensive investigation program in preventing water inrush incidents and ensuring normal coal production in the mine. The investigation program included surface and underground geophysical surveys with five geophysical techniques and directional drilling of three exploratory boreholes at completion depths ranging from 902 to 986 m. A new collapse feature was identified through systematic analysis of the data collected in the investigation program. Although the bottom of the collapse feature has not been determined, its total height is more than 135 m. The roof was at approximately 785 m depth, and there was an open void 1.5–2 m high at the top. Geotechnical properties, results from packer testing and tracer testing, monitoring of potentiometric pressures, and geochemical fingerprinting suggested

that this collapse column was hydraulically conductive and still actively developing. Water in the confined thin-bedded limestone and Ordovician limestone aquifer that either overlies or underlie coal seams could flow into the mining areas if this feature were not identified in advance but encountered during mining. A grouting program was designed and implemented to construct a water plug in the collapse that effectively cut off the hydraulic connections from the aquifers to underground workings. Successful construction of the water plug in the collapse was confirmed by water intake tests in the grouting holes, water flow measurements in the mining area, and groundwater level monitoring in the aquifer.

Introduction

Karst collapse columns are widely distributed in northern China. They have been found in over 50 coalfields and their total number exceeds 3,000 with an intensity of up to 70 collapses/km² (Zhou, 1997). In some mining panels, such collapse structures comprise 30% of the total mined areas. They are recognizable in plan view as patches of breccia with miscellaneous lithological composition, generally derived from overlying strata and completely enclosed in lower bedrock. Diameters range from tens to hundreds of meters with the largest measuring 1,050 m (Dong, 2016). In profile, they take the form of vertical cylinders several hundred meters deep. No bedding is apparent inside these structures and the different rocks are intermixed and poorly sorted. They generally contain higher proportions of displaced blocks and the adjoining strata are offset as a result of dissolution-collapse. Fragments tend to be sharply angular, typically rotated, show little sign of

wear and appear to have dropped from their original stratigraphic position.

Usually the infill materials in the karst collapse structures are tabular 5–40 cm angular fragments, which display random orientation. Sides are subparallel, and contacts between host and fills are sharp and irregular. In most cases, the matrix consists of clastic sediments without cement or mineralization. These structures are generally perpendicular to the ground surface. However, they can become inclined as a result of tectonic movements but remain perpendicular to the surrounding strata. Voids may be present at the top of the structures and drill bits can drop noticeably during borehole drilling. Closed depressions sometimes form in the surficial sediments without any apparent fluctuation in water level or any construction works taking place.

The karst collapses found in northern China are of different hydrogeological types depending primarily upon the lithology of their internal rock blocks, extents of weathering and cementation, and the secondary structures associated with the collapses (Zhou and Beck, 2011). Based on the exposed karst collapses from drillings and excavations, the karst collapse columns can be permeable, impermeable and poorly permeable. In different karst collapses or different locations of the same collapse, the rock blocks may have different hydrogeological properties. The permeable collapses consist of weathered rock blocks but they are typically unconsolidated and not cemented. The impermeable collapses consist of weathered rock blocks that are cemented by weathered shale and mudstone. The poorly permeable collapses consist of partially cemented rock blocks with secondary fractures around the border of the collapses.

Impacts of Karst Collapse Columns on Mining and the Environment

The sudden inrush of karst water from the Ordovician limestone have been encountered in the mines of the Permo-Carboniferous coalfields of northern China. Karst collapse structures functioned as groundwater pathways for some of these events. Figure 1 shows three scenarios in which the pressurized karst water in the Ordovician limestone flows into the mining areas through karst collapse columns. The relative location of a mine to the active flow zone or karst conduits in karst aquifers determines the amount of water that can flow into the mine. In the presence of a large water-pressure

difference, hydrofracturing will facilitate upward flow of the Ordovician karst water into mines. Apparently inactive karst collapse structures or those which have been cemented can be reactivated by activities such as mining, pumping water, dam construction, and landfill development. They may also be triggered by natural events such as neotectonic movements and earthquakes (Li and Zhou, 2015). Mining drifts do not have to intercept karst collapse structures directly to cause a geohazards but may instead intercept faults or fractures connected to them. However, once a water inrush occurs and significant water flows into the workings, the whole mine may become flooded. In cases where different aquifers, several hundred meters apart, become hydraulically connected, the impacts on safety, economy and the environment can be alarming.

Table 1 lists 14 water inrushes through karst collapse columns in coal mines, including the largest inrush in the world, which occurred in Fangezhuang Mine in 1984.

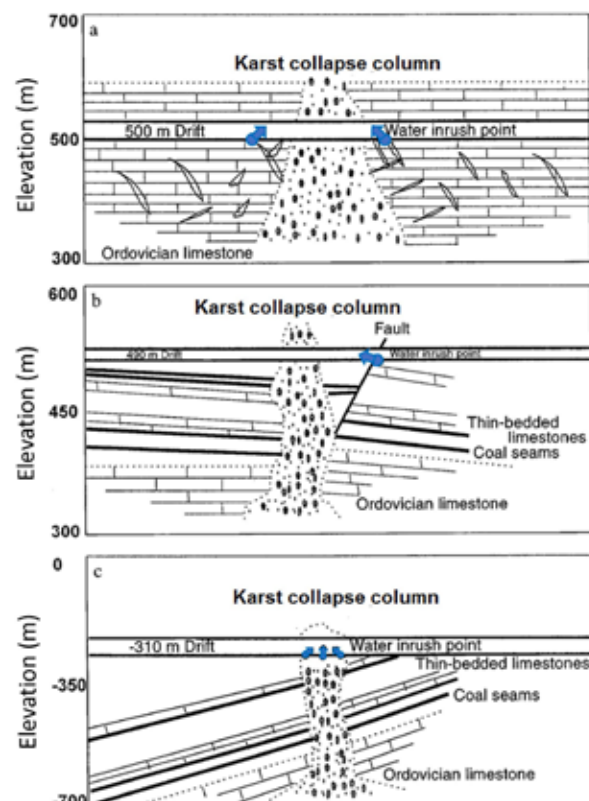


Figure 1a–c. Scenarios where karst water from Ordovician limestone flows into workings through karst collapse structures. (a) Through karst collapse-connected fissures; (b) through karst collapse-connected faults; (c) through karst collapse columns (modified from Zhou, 1997).

Mine	Date	Flow rate (m ³ /s)	Description	Damage
Taoyuan Coal Mine	2013	2.8	Karst water from the Ordovician limestone flowed into the cut-hole of 1035 working panel through a concealed karst collapse.	Mine was flooded with 1 person missing.
Shenjia-zhuang Coal Mine	2012	0.36	Karst water from the Ordovician limestone flowed into mine through a concealed karst collapse that has developed to 50 m below the coal seam.	Mine was flooded.
Huangsha Coal Mine	2011	3	Karst water from the Ordovician limestone flowed into working panel 112106 at depth of 800 m through a compound structure consisting of karst collapse column and a fracture.	Mine was flooded.
Luotuoshan Coal Mine	2010	2	Karst water from the Ordovician limestone flowed into mine via 870 m return airway of #16 coal seam.	Mine was flooded with 32 fatalities.
Dongpang Coal Mine	2003	19.5	Karst water from a karst collapse structure flowed into the mining area.	Mine was flooded.
Wucun Coal Mine	1999	0.67	Karst water from a karst collapse structure flowed into the mining area.	Panel was flooded.
Renlou Coal Mine	1996	19	Karst water flowed into 7 ₂₂ working face at depth of ~380 m through a karst collapse column. The collapse connected thin-bedded limestone and Ordovician limestone with the mining area.	Mine was flooded, shut down about 6 months.
Huaxian Coal Mine	1984	0.06	Karst water from a karst collapse structure flowed into surrounding fractures and then into the horizontal drift in the Ordovician limestone.	Drift was abandoned.
Fagezhuang Coal Mine, Kailuan	1984	34	This is the biggest water inflow incident in the world. The mining coal seam was 180 m above the Ordovician limestone but they are connected by a karst collapse structure. The reactivation of the collapse may be associated with a recent earthquake in this area. Grouting boreholes revealed that the top of the sinkhole was unfilled with sediments.	Mine was flooded, resulted in 9 fatalities, 17 cover sinkholes, and the adjacent three mines were threatened.
Fagezhuang Coal Mine, Kailuan	1983	0.23	A small fault with displacement of 0.2–0.5 m was intercepted by a working stope. Karst water flowed through a karst collapse structure into the fault and then to the working stope.	Working stope was flooded.
Fagezhuang Coal Mine, Kailuan	1978	1	Water flowed into the mine from the sandstone, which is 160 m above the underlying Ordovician limestone. A sluice gate was constructed to isolate the water inflow area and a 0.2-m fracture was revealed, connected with a karst collapse structure.	Part of a drift and a working stope (70,188 m ³) was flooded
Lifeng Coal Mine, Jiaozuo	1967	2	Karst developed very well in the area. Intensive mine water drainage reactivated the karst collapse structure.	A working stope was flooded and 1 fatality occurred.
Huoxian Coal Mine	1967	0.13	Karst water flowed into an excavating drift through a karst collapse structure and a connecting fault.	Drift was abandoned.
Tongyie Coal Mine, Anyuang	1965	0.39	A water inspection borehole drilled into a karst collapse structure from a drift. The initial water flow rate was 0.5 m ³ min ⁻¹ and water flow rate increased to 23.3 m ³ min ⁻¹ . An exploration borehole revealed 17 cavities within 50 m of the collapse with the maximum bit-drop of 2.59 m.	Mine was flooded.

Table 1. Case histories of water intrushes through karst collapse columns in northern China.

Karst water gushed into the mine at a flow rate of 34 m³/s at a depth of 313 m below sea level (bsl). The surface level is 27 m above sea level (asl). The whole mine was flooded within 21 h and as a result, the regional water table in the Ordovician limestone dropped from 5.94 m asl to 111.09 m bsl. The cone of water depression covered 84 km² with a north-south axis of 25 km. The fall in the level of the water table in the Ordovician limestone caused serious problems for local residents. These included the drying up of their water supply wells, contamination of the groundwater, and the formation of new sinkholes. The water intrush led to the development of 17 cover collapses, with resulting sinkholes ranging in diameter from 2.5 to 3 m and with depths of 3 to 12 m.

Table 1 also includes a water intrush that occurred at the study mine, Renlou Coal Mine, Anhui province in 1996. The water intrush occurred in working panel 7₂₂ at 380 m deep. Figure 2 shows the lithology in the mine and the water-inrush point. The panel was flooded within 10 h. The final water level was stabilized at 15.59 m asl, which is approximately the same elevation of the water level in the Ordovician limestone. The maximum water inflow was 19 m³/s. The water intrush resulted in a water level drop of 7.04 m in an Ordovician limestone monitoring well 16.2 km away. Investigations in response to the water intrush and subsequent grouting confirmed that the water pathway was a karst collapse column. The column was nearly vertical and oval-shaped with long

A second smaller water inrush occurred at working panel 7₂18 in the same coal mine in 1999. Timely recognition of water inrush indicators including pressure increase in front of the tunnel, deformation of tunnel support structures, water flow increasing from 5 to 9 m³/h allowed

These water inrush incidents suggest that the hydrogeological conditions in Renlou Coal Mine meet the three basic requirements for a water inrush through karst collapse columns:

1. Presence of a karst aquifer that can supply a sustainable or high volume of water;
2. Active karst collapse columns that are permeable to water; and,
3. Significantly higher water pressure in the karst aquifer than the elevation of the underground working area, providing the necessary force for water flow.

Therefore, proactive detection of any concealed karst collapses and determination of their hydrogeological characteristics have become essential components of a comprehensive investigation program in preventing water inrush incidents and ensuring normal coal production in the mine.

Detection and Remediation of a Concealed Karst Collapse Column

In June 2010, an anchor hole advanced in II 5₁ Tunnel encountered groundwater. The tunnel was at elevations from -718.6 to -720.1 m bsl and was excavated for mining #5₁ coal seam. The tunnel was 440 m below the Quaternary and Tertiary formations and at least 300 m above the Ordovician limestone. The stratigraphy encountered by the tunnel consisted of fine sandstone and mudstone with petrified plant parts. Under normal conditions, water in these formations was limited and did not pose a safety threat to underground workings. The tunnel also intercepted a normal fault, DF₈, with 5 m displacement. No water seepage was observed through the fault.

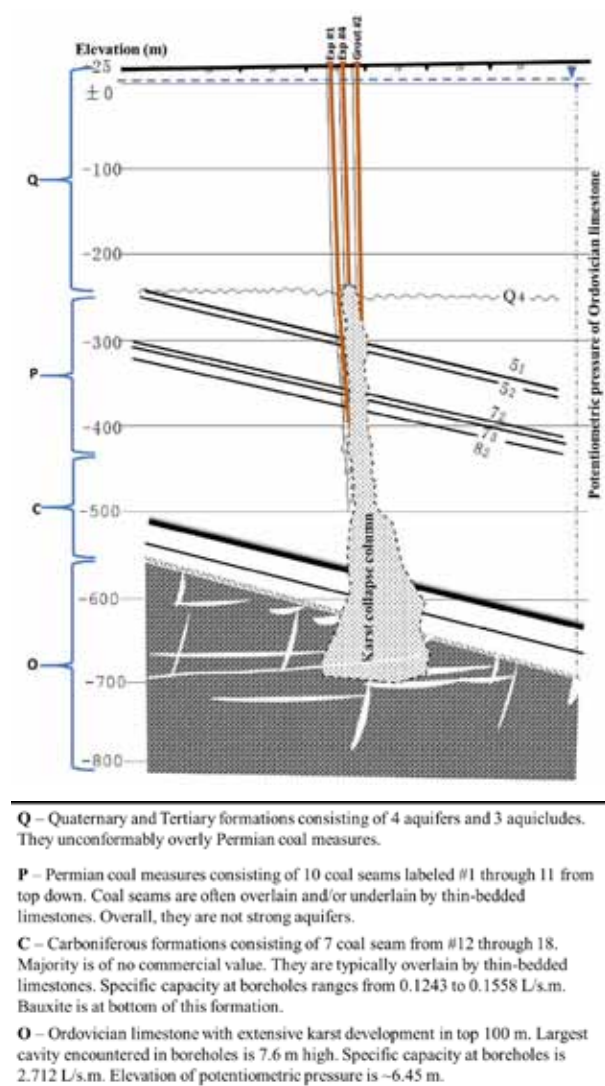


Figure 2. Schematic depicting lithology and 1996 water Inrush at Renlou Coal Mine, China.

Water Source Discrimination by Temperature and Hardness Measurements

As shown in Figure 3, two exploration boreholes, 4-3 and 4-3', were advanced at different angles to investigate the source and pathway of the groundwater encountered at the anchor hole. At an angle of 47° , borehole 4-3 intercepted fault DF_8 , whereas at an angle of 40° , borehole 4-3' intercepted a high-angled (75°) fracture. The maximum groundwater flow rate at borehole 4-3 was $2 \text{ m}^3/\text{h}$, and the maximum flow rate at borehole 4-3' was $16 \text{ m}^3/\text{h}$.

Figure 4 shows changes of water temperature and hardness at borehole 4-3 from June 2010 to November 2011. Data at borehole 4-3' had similar trends. Over a period of 17 months, the water temperature gradually increased from 33 to 41°C . The normal earth temperature at this elevation in the mine is approximately 35°C . The higher than normal temperature in the inflow water indicated that the water source was from deeper formations.

Two types of hardness are presented in Figure 4, the total hardness was measured prior to boiling and permanent hardness was measured after boiling. Their unit is degree of General Hardness or German degree (dGH). Both types of hardness show a general trend of increase. The total hardness increased from 8.34 to 60.58 dGH , whereas the permanent hardness increased from 0 to 48.81 dGH . The persistent increases in the hardness also suggest that the water sources were from the deeper formations. The measured temperature and hardness at end of the monitoring period were similar to those measured in the Ordovician limestone in the mine.

Geophysical Investigations

Geophysical surveys were conducted to investigate any geologically and hydrogeologically anomalous areas. Time domain electromagnetic methods (TDEM) and 3D seismic were used on the ground surface, while TDEM, 3D seismic, earth resistivity imaging, and ground penetrating radar were used underground in II 5_1 Tunnel. Areas identified and verified from multiple geophysical techniques were considered the targets for further investigations. Figure 5 shows an example of 3D seismic interpretation of the # 5_1 coal seam elevation. The rectangular is a geophysical anomaly in which the coal seam elevations were disconnected. A vertical profile

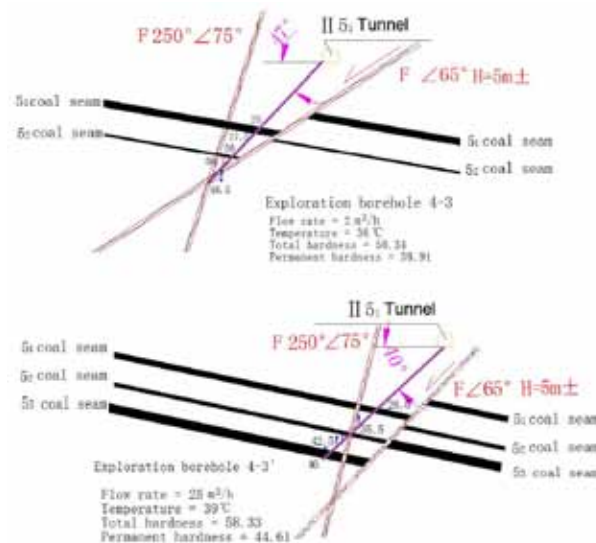


Figure 3. Layout of boreholes 4-3 and 4-3' for exploration of water sources.



Figure 4. Water temperature and hardness measurements at borehole 4-3.

of the 3D seismic is shown in Figure 6. The location of the cross-section is shown in Figure 5. The geophysical anomaly was interpreted to be associated with a karst collapse column.

Borehole Exploration

Figure 5 shows the locations of three exploratory and grouting boreholes #1, #2, and #3, and two monitoring wells #23 and #24. The monitoring wells were installed to monitor potentiometric pressures of the Ordovician limestone. The exploratory boreholes were drilled in the order of #1, #2, and #3. They were drilled in the geophysically interpreted anomaly to investigate the subsurface conditions, in particular, to determine presence of a karst collapse column. If the karst collapse column was confirmed, these boreholes were then used as grouting holes to construct a water plug within the collapse feature. Borehole #1 was vertical, while directional drilling was used in boreholes #2 and #3 to intercept the collapse feature encountered in



Figure 5. Contours of S_1 coal seam elevation as interpreted from 3D seismic survey.

borehole #1. Figures 7 and 8 shows the profiles across from borehole #1 through borehole #2 to monitoring well 24 and from borehole #1 through borehole #3 to monitoring well 23, respectively. Table 2 summarizes the pertinent parameters for these three boreholes.

Both boreholes #1 and #2 encountered drill bit drops and total loss of circulation. The bit drops at boreholes #1 and #2 were 1.5 m and 2 m, respectively. The loss of circulation was greater than 72 m³/h where the drill bit drops occurred. The drops occurred at depths between 773 and 787 m. Such characteristics were atypical of the formations at these intervals unless a karst collapse

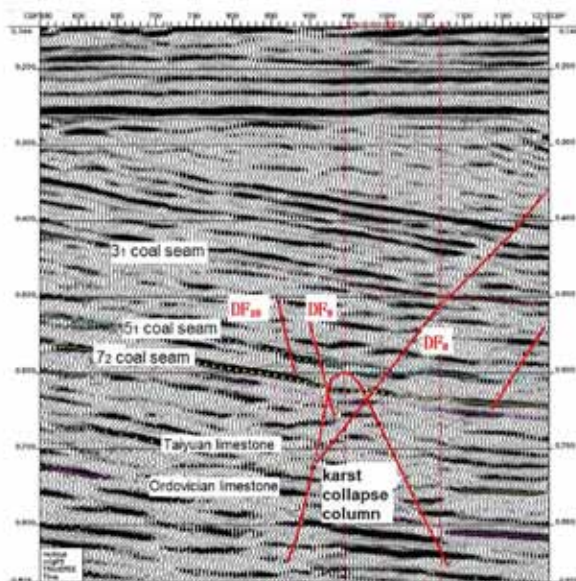


Figure 6. A cross-section of 3D seismic survey (location of the cross-section is shown in Figure 5).

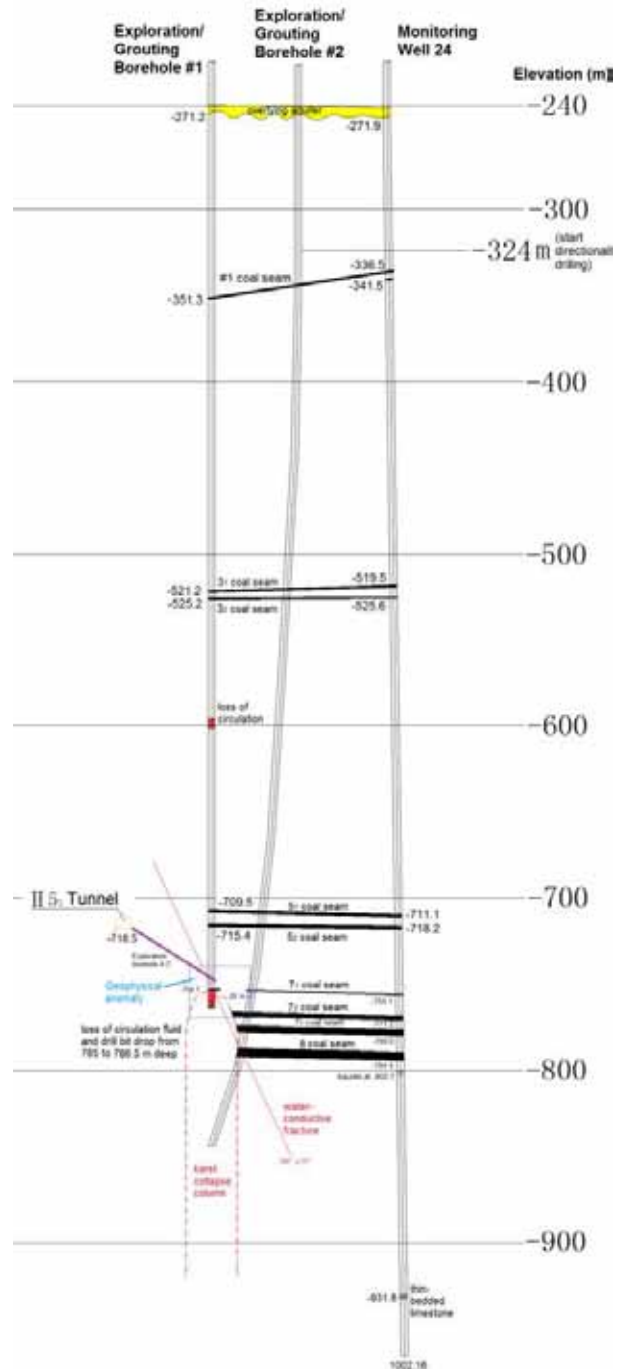


Figure 7. Profile of exploration/grouting boreholes #1 and #2.

column or large fracture was present. The exploratory and geophysical results suggested that this feature was likely a karst collapse column. The column had an oval shape, and its dimensions were estimated to be 55 m in the long axis and 40 m in the short axis. The bottom of the karst collapse column was unknown and its roof was approximately 20 m below #5 coal seam.

Figure 8. Profile of exploration/grouting boreholes #1 and #3.

Parameters	Exploration/Grouting Boreholes		
	#1	#2	#3
Total depth (m)	920.48	920.57	986
Directional drilling		At 350 m toward borehole #1	At 380 m toward borehole #1
Depth to bedrock (m)	271.2	273.7	273.1
Depth to #1 coal seam (m)	376.8	360.0–369.6	395.05
Depth to #5 coal seam (m)	740.8	764.9	758.7
Loss of circulation intervals (m)	627–694 785–787	609–619 773–775 863–865 885	739 983
Drilling bit drop (m)	1.5 m from 785 to 786.5; likely entering collapse body	2 m from 773 to 775; likely entering collapse body	
Grouting (t)	1,366 t (935 tons at 791 m; 81 t at 820 m; 159 t at 842 m; 191 t at 900 m)	1,920 t (445 t at 803 m; 245 t at 835 m; 180 t at 855 m; 110 t at 865 m; 270 t at 865.5 m; 140 t at 885 m; 70 t at 905 m; 420 t at 920.57)	295 t at 911 m
Post-grouting water intake capacity (L/ min.m.m)	0.00099	0.00091	0.00214

Table 2. Summary of drilling parameters at three exploration/grouting boreholes.

Grouting at boreholes #1 and #2 further confirmed that both boreholes intercepted the top of a collapse column. Grouting materials injected at borehole #1 were observed at borehole #2 as well as in II 5₁ Tunnel. Since borehole #3 was advanced after grouting at boreholes #1 and #2 was completed, it encountered cement-filled void and the amount of grout was significantly reduced in borehole #3. Water injection tests were conducted at all three boreholes before completing the grouting. The results (Table 2) demonstrated that the water intake capacity was less than the designed value of 0.01 L/min.m.m. The water intake capacity was calculated by water injection rate (L/min) divided by applied pressure (m of water) and test interval (m). Another indicator of the grouting success was that the post-grouting groundwater flow into II 5₁ Tunnel was minimal and the remaining water seeped from the overlying formations with their typical

water quality parameters. The water levels in monitoring wells 23 and 24 have been measured to ensure the long-term success of the investigation and remediation effort.

Conclusions

Karst collapse structures are karst features that were often encountered in mines of northern China. Because these karst features could be several hundred meters high, they can connect multiple aquifers and lead water to underground working under the following conditions:

1. The karst collapse column is active and permeable to water.
2. The karst collapse column is connected to an aquifer or a water body that can supply a sustainable water source.
3. The water pressure in the aquifer or water body is higher than the elevation of the underground working area.

Because of potential damages that can be caused by these structures in mines, proactive detection of any concealed karst collapses and determination of their hydrogeological characteristics are essential components of mine water control and prevention programs in China. Multiple techniques including geochemistry, geophysics, directional drilling, grouting, and water injection testing were used in this case study. The risks posed by a karst collapse column was successfully mitigated.

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THE EXTREME KARSTIFICATION OF THE KINTA VALLEY, WEST MALAYSIA

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Abstract

Surface limestone makes up only about 7% of the whole karst area; the greater subsurface area lies beneath thick alluvial sediments. The depth of the subsurface varies from 9 m to more than 60 m, and shows various topographies from platforms with flat concordant tops to jagged sharp pinnacles with rounded tops. The ratio of surface to subsurface karst can be used as an indication of the intensity of dissolution that occurs and of advanced degradation. Based on its association with tin-rich alluvium, it is believed that the karst in this area developed mostly under a pluvial environment and the humid tropical conditions since the Tertiary.

Introduction

The Kinta Valley in Perak, Peninsular Malaysia is important historically; the richest tin mine in the world was located here. A tin-rich placer sourced from two granitic highlands has been deposited across the wide valley. Tin-bearing alluvium elsewhere has been dated to as much as 700,000 years old based on the presence of tektites, e.g., in Gambang, Pahang (Gangadharam and Stauffer, 1978; Gangadharam, 1984). It is believed that the unique subsurface feature of planation with jagged surface formed by limestone pinnacles has trapped the alluvial sediments and prevented them from being washed away. Topography further has an effect on weathering; it has been suggested that the lowlands and extreme highlands of Southeast Asia were influenced by the Quaternary pluvial and inter-pluvial periods (Ashton and Ashton, 1972). Streams from these highlands flow into major rivers in the valley, fed by the high rainfall throughout the year. This has provided a constant allogeneic water source to the plain and transported the placer to the vast lowland. The north to south variation of bedrock depths indicates the slope of the bedrock is on the order of 1.9 m per km, also suggesting a fluvial origin for the valley and that stream activity has been very widespread (Newell, 1971). Many ponds are scattered throughout the valley, most of which are ex-tin mines that have been left after mining ceased in the 1990s.

Parts of lowland equatorial Southeast Asia are amongst the few areas of the world where possibly little or no climatic change has taken place during the Quaternary (Ashton, 1972; Gale, 1986; CLIMAP, 1976; Prell et al., 1980). Paramanathan (1982) considers lateritic soils formed during the Tertiary (Batchelor, 1979; Law and Leamy, 1966; Eyles, 1970 after Raj, 1982) to have developed during the Pleistocene through the deposition of iron-coated materials that were derived by erosion from weathering profiles formed by intensive tropical weathering. Some evidence for this Tertiary humid tropical climate is seen in Mueller (1972), whose palynological analysis led to the conclusion that there was a uniformly humid climate throughout the Tertiary.

However, it has been suggested that this study area was subject to repeated climatic variations and changes in erosional base levels in the late Pleistocene to Holocene, based on characteristics of the Young Alluvium (of Walker, 1956) or Alluvial Complex that blanket the subsurface karst. The Pliocene to early Pleistocene probably experienced more arid, seasonal climatic conditions during periods of low sea levels. The palynological record from Kuala Lumpur, which is about 180 km from the valley, indicates a cooler climate around 41–36 ka (Haile & Mohammad, 1968), while guano from nearby Batu Caves indicates an open-savanna type environment 35–60 ka ago (Wurster et al., 2010).

The surface dissolution rate of the limestone in the study area, obtained using a micro-erosion meter, was found to range from 224 mm/ka and 369 mm/ka for calm pond water, and running water environments, respectively (Muhammad, 2003). These dissolution rates are rather high when compared to the rates in other karst areas around the world, including in other tropical areas; their rates range from 15 to 99 mm/ka (Kukul, 1990), as shown in Table 1. The dissolution rate in the Kinta Valley, coupled with its topographic setting, provided a suitable environment for a high rate of karstification.

By looking at selected parameters such as rockheads, fissures, caves, and sinkholes, Waltham and Fookes (2005) suggested five engineering classifications for karst. “Malaya” karst is defined as an extreme karst kV (Figure 1). It shows characteristics of subsurface and surface karst similar to those found in Kinta Valley and Kuala Lumpur, there is no detailed explanation on how the conclusion was made.

Climatic zone and area	Rate of erosion (m ³ .km ⁻² .a ⁻¹) or (mm.ka ⁻¹)	Reference
Moderate zone		
Derbyshire, Great Britain	60–193	Smith and Atkinson, 1976
South Wales	16	Groom and Williams, 1965
North-West Scotland	88–100	Groom and Williams, 1965
Ireland	51	Groom and Williams, 1965
Yugoslavia	9–126	Corbel, 1965
Swabish Jura	98	Aubert, 1969
Krakow Platform	20	Corbel, 1965
Poland, average for karst	10–32	Oleksynowma and Oleksynowma, 1971
Tatra Mts, Poliss part	86–95	Kotarba, 1971
Moravian Karst, Czechoslovakia	25	Stelcl et al., 1969
Aggletek, Hungary	20	Balasz, 1971
San Antonio, Texas	4	Corbel, 1971
Eastern Siberia, USSR	1–32	Pulina, 1968
Southern England	40	Sweeting 1966
Tropical zone		
Indonesia	63–99	Balasz, 1971
Florida	15	Runnels, 1971
Jamaica	39–96	Smith, 1972
Puerto Rico	42	Corbel, 1971
Arctic and Alpine zone		
Alaska	8–530	Corbel, 1959
Canada	2	Smith, 1972
Spitzbergen Is.	16–30	Corbel, 1965
Tatra Mts, Polish part	96	Corbel, 1965
Tatra Mys, Polish part	36–38	Kotarba, 1971
Tropical desert zone		
Sahara	3	Corbel, 1971

Table 1. Rates of dissolution of karst in other parts of the world including in other tropical areas (Kukal, 1990).

The objective of this study is to describe the karst topography in Kinta Valley based on the morphological features on the surface and subsurface karst and its relationship to the overlying tin-bearing placer deposit.

Tower karst refers to a landscape of residual carbonate hills scattered across a plain, although the tower may not be necessarily be steep (Ford and Williams, 1989). The karst in this study was divided into two simply based on its expression relative to the ground level. The term *surface karst* is used to refer to topography that is present above the ground, while subsurface karst refers to topography below the ground. The topography of Kinta Valley is characterized by tower karst terrain comprising isolated limestone hills separated by alluvium and detrital sands, with subsurface karst dominating the rest of the area. Due to its setting on a plain, the term “residual hills” (Ford and Williams, 1989) applies here. However, unlike the Gunung Kidul area that features conical hills (Eko and Day, 2004), the residual hills in Kinta Valley are mostly steep-sided. Schist and shale outcrop as undulating hills throughout the plain, and dolines, described as small- to medium-sized closed depressions, range from metres to tens of metres in both diameter and depth (Ford and Williams, 1989). Beneath the alluvium, the limestone takes the form of limestone pavement with highly irregular surfaces and can be termed *buried karst* (Jennings, 1982).

The Study Area

The Kinta Valley is a triangular-shaped, low-lying valley in the Western Belt of Peninsular Malaysia (Figure 2) bounded by two prominent granitic ranges: the Main Range in the east, which rises to about 1464 m above mean sea level, and Kledang Range in the west, which rises to about 752 m (Figure 3). The valley widens from about 7 km in the north to 20 km in the south over a distance of about 45 km. The surface area of the valley is estimated at about 450 sq km. From north to south, the first tower karst observed in this area is Gunung Kanthan, and the last is Gunung Tempurung. The alluvial plain is located from 40 m to 80 m above mean sea level.

The karst in the study area was formed from Kinta Limestone of the Silurian to Lower Permian age. The hills are made up of pure crystalline limestone and are invariably marmorised due granitic intrusions; they mostly lack fossils (Ingham & Bradford, 1960). Farther away from the granite, the subsurface limestone at the

south of the study area is less recrystallized and contains Palaeozoic fossils. The granitic highlands are mostly made up of coarse-grained porphyritic biotite granite. Other common rocks include several relatively thin argillaceous beds, which exceed 3000 m in stratigraphic thickness (Ingham and Bradford, 1960; Suntharalingam, 1968); these were folded and recrystallised by regional metamorphism in the Late Triassic.

Methodology

The occurrence of carbonaceous rocks is documented in Ingham and Bradford (1973), the Mineral Distribution Map of Peninsular Malaysia (Yin, 1988), and the Geological Map of Peninsular Malaysia (Malaysia Mineral and Geoscience Department, 2014). The topography of the surface karst is indicated as limestone hills, while subsurface limestone is expressed as a topography underlain by alluvial cover (Yin, 1988). Hills were identified by observing 1:50000 topography maps produced by the Department of National Mapping Malaysia, including Series L 7010, Sheet 3562, 3563, 3463, and 3564; aerial photos from Colombo Plan 1960 were also used. Map data were compared to

recent Google Earth and satellite images, and numerous observations were carried out in the field to verify the results obtained in lab. Available data were combined using the Freehand software to reproduce the geological map with details of the outlines of the limestone hills (Figure 3). Each area of surface limestone was drawn and numbered, and the exposed subsurface karst and overlying alluvium material were also observed. The approximate ratio of surface to subsurface karst was measured by comparing subsurface limestone against surface limestone. In addition, solutional features on hill cliffs were observed and measured using a laser range finder, and selected profiles of these features were drawn. Due to the ready accessibility of Gunung Rapat, more detailed observation was carried out there compared to other hills; therefore, it was chosen as a representative limestone hill.

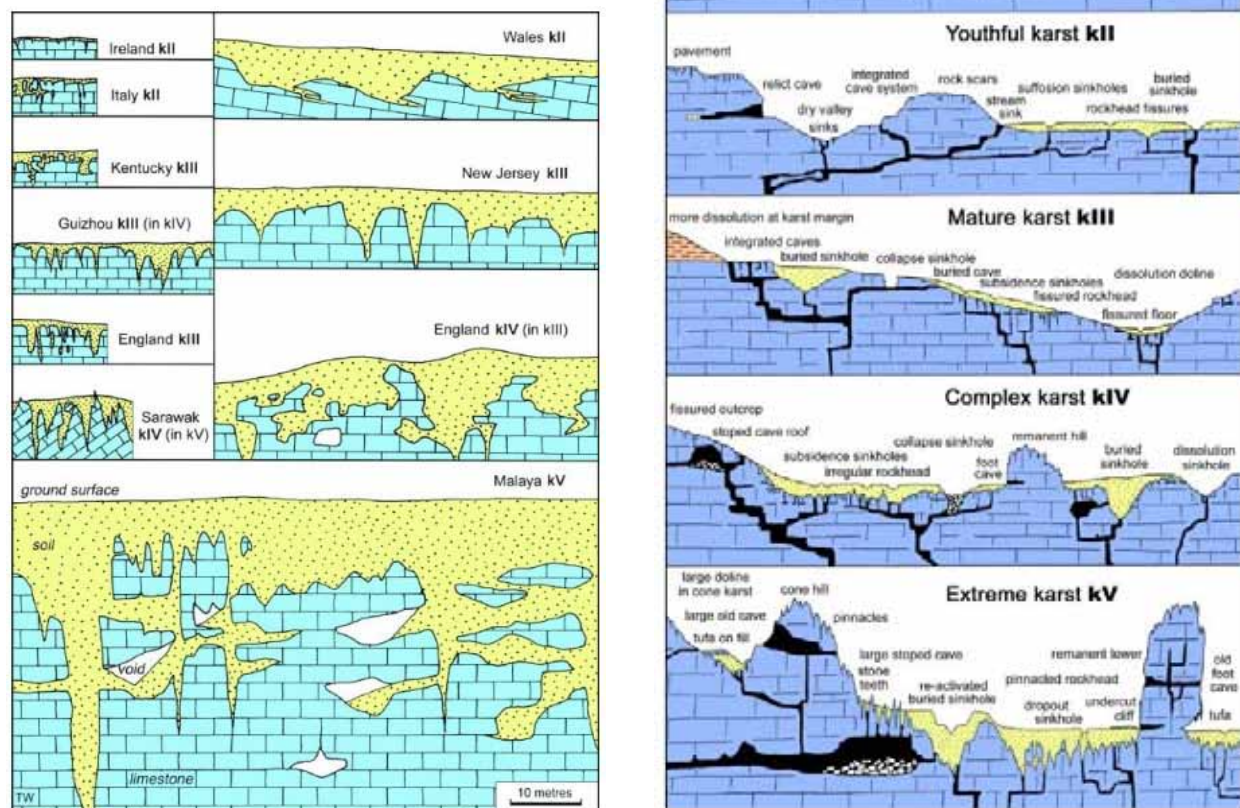


Figure 1. Engineering classification of subsurface karst development by Waltham and Fookes, 2005. Class kV is labelled “Malaya”, without further elaboration, and resembles karst in the study area.

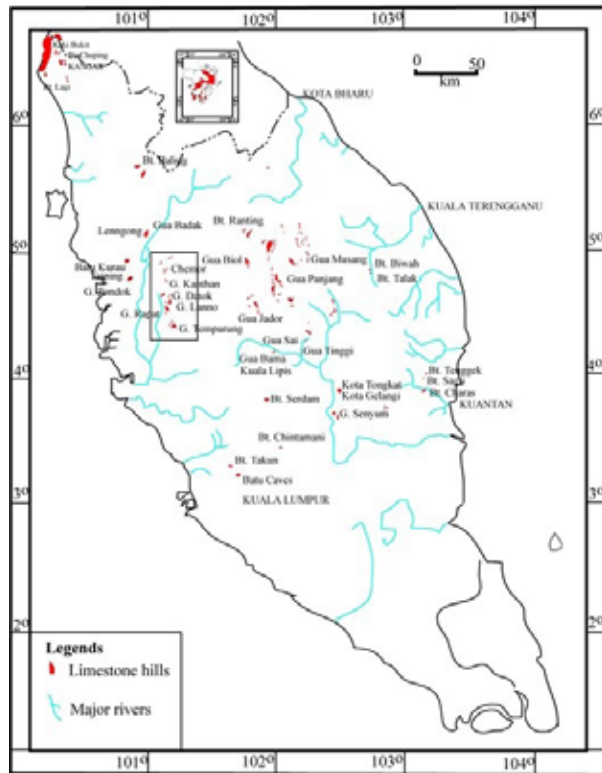


Figure 2. Map of Peninsular Malaysia showing the locations of limestone hills. The study area is indicated in the box.

The Karst of Kinta Valley

Surface Karst

There were a total of 34 towers in the study area, as shown in Figure 3. Studies on the morphostructure of these hills showed that pock marks and the alignment of dolines are controlled by the fault and major joints that can be seen extending from the granitic highland; most of these structural directions are in excellent agreement with the stress system on the Main Range side of the valley (Muhammad & Tjia, 2011). This feature is explained by the “Aligned or Intersecting corridor topographies” description of Ford and Williams (1989). The bases of the hills are connected to each other by lower connecting ridges and wind gaps. The hilltops and slopes are covered by vegetation or consist of bare slopes marked by a distinctively minimal terra rossa soil and organic hummus, while closed depressions are further deeply degraded to form dolines with concave floors covered by variable amounts of alluvial material, rock rubble, and soil. A number of hills showed more extensive vertical dissolution down to the base levels, and subsurface karst was present in certain doline platforms. Many of these platforms were blanketed by placer deposits, usually

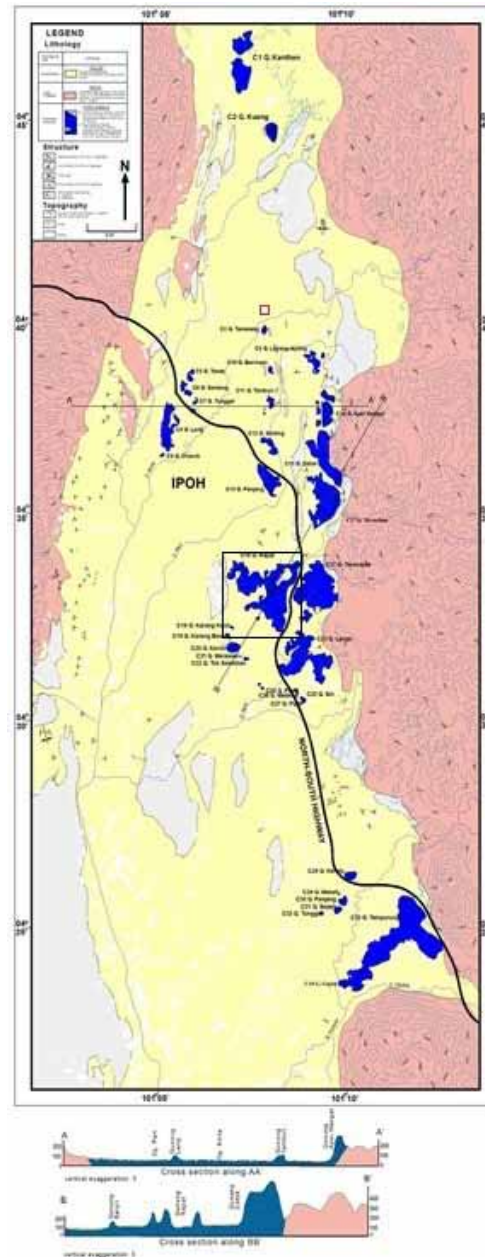


Figure 3. Geological map of the floodplain of the Kinta Valley in Perak, West Malaysia. 34 limestone hills (in blue) represent karst on the surface, while large areas of karst are buried under the alluvial cover (in yellow). Granites (in red) form two highlands on the east and west sides of the Valley, while grey areas represent metasedimentary rocks (mainly schist) and white areas are ponds that occupy most of ex-mining land. Gunung Rapat is located in the black box and the study location for the geophysical survey in the red box. This map is based on topography maps, Geology of Peninsular Malaysia Map (JMG, 2014) and Mineral Distribution Map of Peninsular Malaysia (Yin, 1988).

stripped for mining and later filled with water either naturally or by quarry operators (Figure 4).

Another important feature thought to play an important role in tower karst development is notching or indentation formed by normally horizontal dissolution aided by the presence of numerous ponds at the foot of the hills and throughout the valley. This feature has been reported in Peninsular Malaysia by various researchers (Walker, 1955; Paton, 1964; Jennings, 1976; McDonalds, 1976). Notches that are more extensive and create a flat roof regardless of geologic structure are termed corrosion bevels (Ford and Williams, 1989) or German '*laugdecke*' (Kempe et al. 1975 after Ford and Williams, 1989).

The occurrence of swamp slots and notches is often cited as field evidence of the effectiveness of lateral corrosion (Ford and Williams, 1989). Based on observations of tropical tower karst in many areas, including the Kinta Valley, Sweetings (1972) and Roglic (1972) have suggested that marginal corrosion had progressed at a very fast rate due to a swampy solution or corrosion



Figure 4. GoogleEarth image of Gunung Rapat. The outline of the surface morphology of the limestone hill can be observed in Figure 3. Extensive vertical dissolution coupled with the slicing off of vertical blocks are thought to be responsible for the advanced karstification of the hill. The red dot shows the location of multilevel notches and yellow dot shows the location of a subsurface platform. This image was captured after the doline was filled with water. The author has received permission from Google to use this image.

at the foot of the limestone hills. Sweetings (1972) additionally suggested that deep horizontal swamp notches intersected by vertical solutions resulted in the collapse or slicing off of vertical blocks of limestone, which fell into the swamp and were then quickly dissolved. Dolines were thus further enlarged, and the hills reduced in size. Thus, according to this hypothesis, notches play a very important role in the formation of steep-sided limestone hills in the humid tropics and in hastening the degradation process.

Many notches in the Kinta Valley were found to be preserved on cliffs in enclosed dolines within the limestone hills. Due to the collapse of limestone blocks, these notches can unfortunately no longer be seen on most of hill cliffs, only scars of collapse. Figure 5 shows a profile of these features. The notches can be as high as 20 m above ground, and show variable depths and shapes (Figure 5). Most higher-level indentations showed scalloped roofs, while lower-level ones had flat roofs. It is postulated that scalloped roofs form when pond water levels fluctuate rapidly, while stagnant ponds lead to the formation of flat roofs. These notches can be regarded as records of the climate during their formation. Detailed mapping is being carried out using terrestrial Light Detection and Ranging.

Subsurface Karst

The ratio of the surface to subsurface karst was calculated to be around 7%. While most of the subsurface topography is either covered by development or flooded after the cessation of mining, the various degree of degradation shown is important as evidence of the extent of karstification in this area. Some parts are prone to sinkhole occurrences and depression, and in certain areas the subsurface limestone is riddled with water conduits and cavities.



Figure 5. Profiles of multi-level karst notches in the study area.

A few locations show limestone in the pavement form with a very jagged surface created by subsoil downward dissolution; in some locations, further dissolution has produced pinnacles with flat, rounded, or sharp tops (Figure 6). An iron mine in a doline in Gunung Rapat has exposed part of the buried subsurface karst, extending up to 9 m below the ground. This subsurface karst is in the form of an almost concordant platform surface, but downward dissolution has further developed the pinnacles with flat to rounded tops. The platform was previously buried under iron-rich alluvium, of which a remnant can be seen up to 7 m above the ground. It was reported by Ford and Williams (1989) that the corrosion plain is commonly veneered with alluvium and, when uplifted, glaciated, or strip mined for placer deposits, removal of the clastic veneer reveals an impressively planar rock floor; particularly in the tropics, this floor can sometimes be rugged in detail because of etching down joints. Jennings (1972) commented on sections by Ingham & Bradford (1956) showing the floor of the Kinta Valley as corrosional karst plain, stating

that in detail there is elaborate solutional sculpture but overall the steeply dipping limestone beds are horizontally truncated.

Further away from the subsurface karst found in doline floors, geophysical studies showed uneven topography of the subsurface karst at various depths. The bedrock depths were observed to range from about 20 m to more than 60 m, exceeding the depth allowed by resistivity studies (Riyadh et al., 2014). One example of such a survey was carried out in the north of the study area (shown in Figure 3).

The basal limestone bedrock is covered by soil or sandy clay, and in some places by friable sand; it is dissected by cavities that are believed to be produced by further dissolution of solution-widened joints. Sinkholes and cavities found at this site are of tubular and cylindrical shapes, and most of the cavities appear to be channels for transmission of water and material from the surface (Figure 7). These observations may indicate that these sinkholes and cavities are newly



Figure 6. Right: Flooded subsurface limestone in a doline in Gunung Rapat, previously overlain by alluvial cover that has since been stripped off due to mining. This platform is 9 m below ground level. Left: Multilevel notches on the western flank of Gunung Rapat. Similar feature can be found throughout the valley.

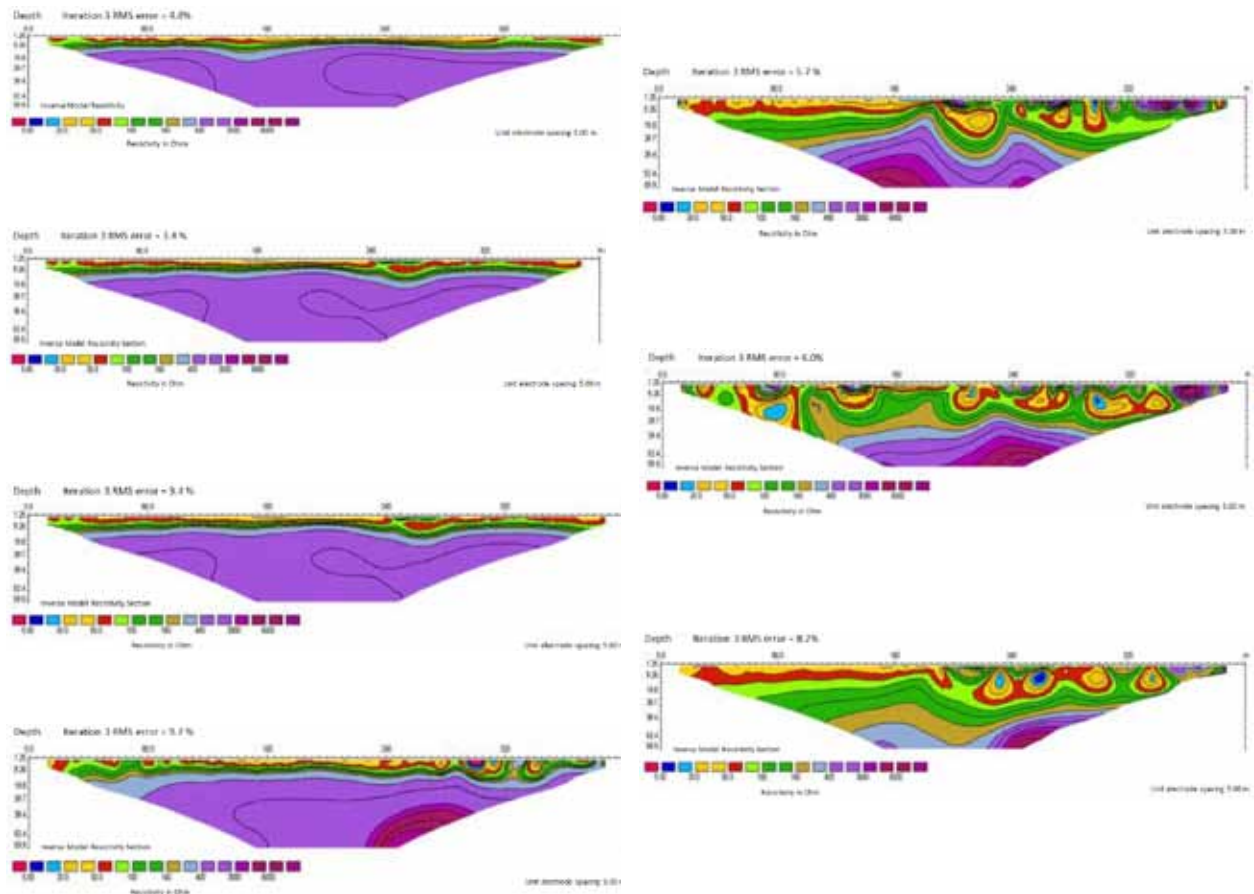
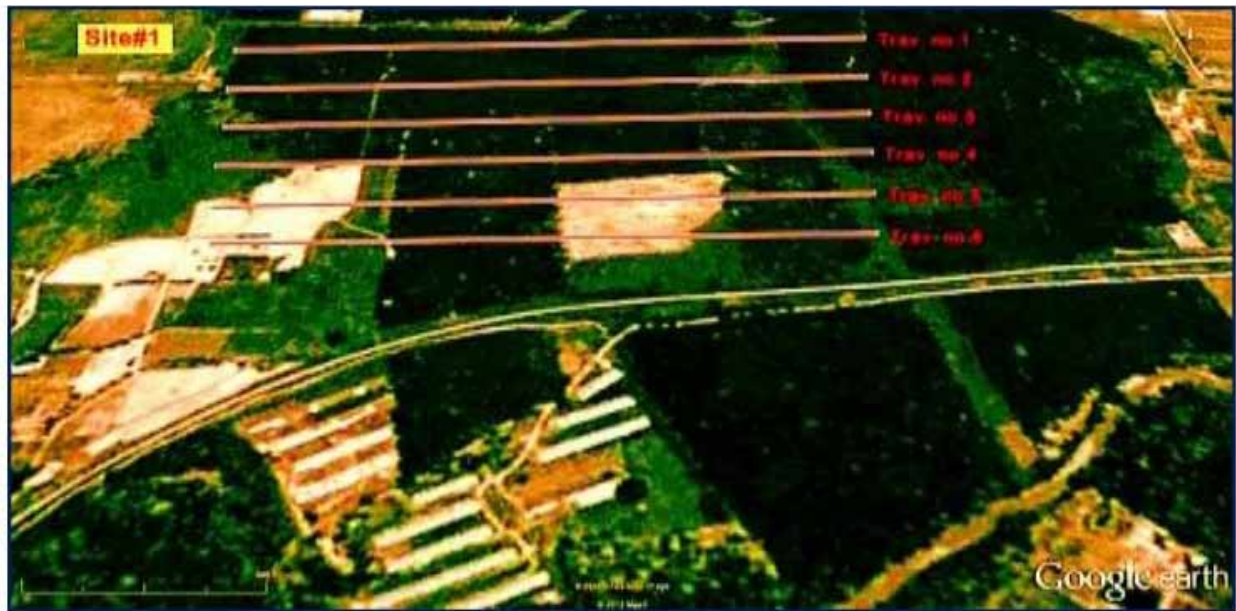


Figure 7. Satellite image of the area of resistivity traverses at the north of Kinta Valley (shown in Figure 3) and inverse models of the resistivity sections, showing highly irregular topography of the subsurface. Values ranging from 400 Ω -m to > 3000 Ω (purple) are interpreted as massive limestone. Circular features with lower resistivity are interpreted as conduits filled with sand and clay (modified from Riyadh et al., 2014).

developed from the collapse of features. This supports the thought that all these cavities originated from pre-existing joints and likely widened due to subsidence/collapse movements in the area that had rapidly filled with clay.

Conclusion

Overall, Kinta Valley karst shows advanced stage tropical karst maturity with a low surface to subsurface area ratio. This is due to the rapid degradation caused by wet conditions in the fluvial and floodplain environment, which continues to exhaust the surface karst and leaves behind a jagged, pinnacled subsurface platform under alluvial cover. The ratio of surface to subsurface karst shows that most of the surface karst in the study area has been extensively degraded. The local setting of the area includes a pluvial environment with constant allogenic water supplied by rivers that flow from the granitic highlands. Degradation is further fasten by the rock collapsing in blocks. The advanced stage of karstification in Kinta Valley could on the surface possibly represent almost the end of the karstification process, with continuous dissolution of the subsurface ongoing from the Tertiary to the present.

Acknowledgement

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SINKHOLE IMAGING AND IDENTIFICATION OF FRACTURES WITH S_H -WAVE REFLECTION SEISMIC

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Abstract

Subrosion can result in depressions and sinkholes, which are a geohazard. To improve the knowledge of subrosion processes, high-resolution geophysical imaging and a detailed characterization of subsurface structures are required. One of the main subrosion areas in Germany is along the Kyffhäuser-Southern-Margin-Fault (KSMF) in Thuringia. Two shear wave (S_H) reflection seismic profiles of 300 m length in total were carried out along two sinkholes. The near-surface down to ca. 100 m depth was imaged with a resolution of less than 1 m down to 15 m depth and a resolution of 1 m to 3 m at 50 m depth. The internal structures of the leached anhydrite and gypsum were imaged. The reflection patterns indicate a heterogeneous near-surface geology around the sinkholes, with mainly lateral and vertical variations of discontinuous reflectors and small-scale fractures, which are necessary for percolation of meteoric water and sinkhole development, especially in areas with a deep groundwater table and no faults. This is the case for one of the two sinkholes. The other is located at a fault with a shallow groundwater table at 37 m depth. The sinkhole margins are characterized by reflectors, which dip towards the focal points of the sinkholes. Previous sinkholes probably generated fractures, which act as additional fluid pathways. As a result, a collapse can be triggered more easily. Indicators for continued collapse are observed in the profile of the fracture-induced sinkhole by the continued migration of focal points of consecutive collapse events over time.

Introduction

Subrosion, the underground leaching of rocks, requires the presence of soluble rocks (e.g., evaporites), water (e.g., groundwater), and fractures or faults enabling water flow through the subsurface to form cavities (Smyth, 1913; Martinez et al., 1998). Different kinds of structures can evolve, and the two main types are (1) sinkholes and (2) depressions (for a detailed classification see Waltham et al. (2005); Gutierrez et al. (2008)). Subrosion is a natural process, but it can be influenced by, e.g., manipulation of the aquifer system (Bell, 1988) and extraction of saline water (Getchell & Muller, 1995). Reflection seismic (e.g., Steeples et al., 1986) delivers a high-resolution image of the underground for a detailed characterization of the subsurface structures, especially using shear-waves, because the near-subsurface surrounding sinkholes often consists of loose sediments and strongly fractured, and therefore not compacted rocks (Krawczyk et al., 2012; Wadas et al., 2016).

Germany suffers from widespread sinkhole problems because soluble deposits, exposed to natural and man-made subrosion processes, are close to the surface in many areas. One of the main subrosion areas is located along the Kyffhäuser-Southern-Margin-Fault near the town of Bad Frankenhausen in Thuringia. For a detailed analysis of the local subrosion processes, two shear wave (S_H) reflection seismic profiles with a total length of 300 m were carried out along two sinkholes. The aim was to obtain detailed images of the sinkhole structures and to detect possible fluid pathways.

Geological Setting

Bad Frankenhausen is a town in northern Thuringia in Germany located at the southern border of the Kyffhäuser hills (Figure 1). The southern part of the hills is bounded by the northward-dipping and W-E striking Kyffhäuser-Southern-Margin-Fault (KSMF), a major thrust fault in this region (Schriel & Bülow, 1926a,b).

The sediments in the south of the Kyffhäuser hills are deposits of the Zechstein Sea, an epicontinental ocean during the Permian. The main Zechstein formations are the Werra-, Staßfurt- and Leine Formations (z1–z3) consisting of anhydrite, gypsum, limestone, shale, and conglomerates, which were cyclically deposited (Richter & Bernburg, 1955). The anhydrite and gypsum of the Staßfurt and the Werra Formations represent the main subsidence horizon in the research area. Triassic deposits are only found at isolated locations, and Cretaceous and Jurassic rocks were completely eroded. Tertiary deposits are exposed only at a few locations at the southern and western margins of the Kyffhäuser hills, e.g., brown coal. Quaternary sediments, like silt and loess, cover a large area (Schriel & Bülow, 1926a,b; Reuter, 1962; Beutler & Szulc, 1999).

The entire area south of the Kyffhäuser hills is affected by subsidence. The presence of salt springs and the occurrence of numerous sinkholes and depressions at the surface are indicators for the long lasting and still

ongoing subsidence processes. The Äbtissinnengrube sinkhole (Figure 2b) that developed in the 16th Century, is one of the largest sinkholes of the region with a diameter of 160 m x 120 m and a depth of ca. 40 m. The forest sinkhole has a diameter of ca. 20 m and a depth of ca. 7 m. Other famous subsidence-induced tourist attractions are the Barbarossa Cave situated in anhydrite of the Werra Formation westward of the town and the leaning church tower of Bad Frankenhausen.

Field Survey

Two shear wave reflection seismic surveys were carried out (Figure 1), the first, with a length of 180 m, along a sinkhole in a forest north of the town (Figure 2a), and the second, with a length of 120 m, west of the town of Bad Frankenhausen at the Äbtissinnengrube sinkhole (Figure 2b). To generate horizontally polarized shear-waves (S_H), we used the micro-vibrator ELVIS 7 (Polom, 2003; Druivenga et al., 2011) with a sweep frequency of 20 Hz to 120 Hz and a duration of 10 seconds, as seismic source. As receivers, we utilized 120 horizontal geophones in 1 m spacing combined to a landstreamer and Geometrics Geodes recorded 12 seconds of raw signal. For the profile of sinkhole 1, we used a variable split-spread geometry with the source and the receivers moving forward, which is designed for near-surface reflection seismic profiling. For more information about the equipment, see Krawczyk et al. (2013); Polom et al. (2013).

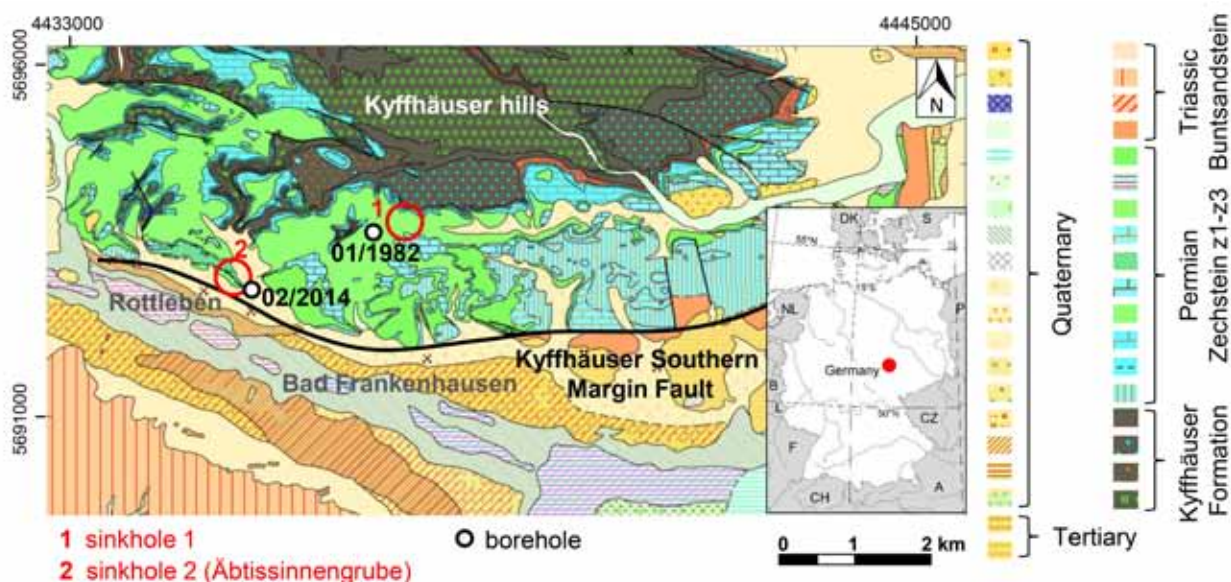


Figure 1. Geological map of Bad Frankenhausen (after Schriel & Bülow, 1926a,b). Red circles mark the investigated sinkhole areas and the insert map shows the location of Bad Frankenhausen in Germany.

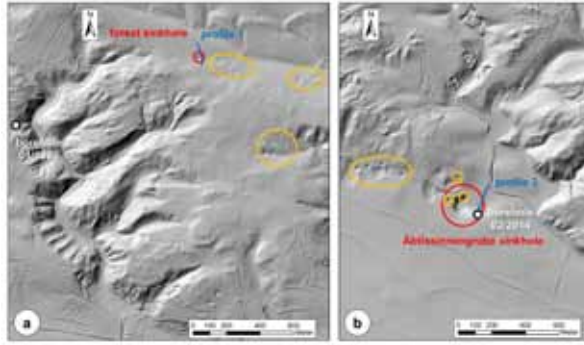


Figure 2. Digital elevation models (DEM; TLUG, 2017b) with positions (red circles) of the investigated sinkhole 1 (forest sinkhole) and sink hole 2 (Äbtissinnengrube sinkhole). Sinkholes nearby are marked orange and white dots indicate bore hole locations.

Data Processing

S_H -wave reflection seismic data processing was carried out using the VISTA software (version 10.028) by Gedco (Schlumberger).

The vibroseis correlation using the pilot sweep was applied to the recorded traces to compress the time-stretched signal to a short wavelet such as an impulsive signal (Figure 3a). This is followed by amplitude and spectral editing with automatic gain control (AGC) of 200 ms, bandpass filter (16/18–120/122 Hz) and trace normalization to enhance the reflection response and to attenuate noise to improve the resolution and the data quality. Improvement of signal-to-noise ratio is important

for investigations of subsrosion structures, in order to image the small-scale vertical and lateral variations, which are typical for these kind of structures. Two records of each source location were vertically stacked subsequently to reduce statistically distributed noise and to amplify the seismic response (Figure 3b). The survey geometry setup was applied using a crooked-line binning with a 0.5 m bin interval. A top mute was used to remove data irrelevant for further data processing, in this case signals above the first breaks. The processing steps described above were applied identical to profile 1 and profile 2 (Äbtissinnengrube sinkhole).

This was followed by individual filtering in the frequency-wavenumber domain (FK filter) and an additional bandpass filter (p1: 16/18 Hz–100/102 Hz, p2: 16/18 Hz–94/96 Hz) to remove surface Love waves, harmonic distortions, and noise. To compensate for attenuation and energy loss of the seismic waves an offset-dependent, time-variant logarithmic scaling was applied on profile 1 (Figure 3c). The loss of reflected energy and the reduced amplitudes result from the fractures and possibly small-scale cavities induced by subsrosion, which lead to scattering of the seismic waves and attenuation of especially higher frequencies (Boadu & Long, 1996; Barton, 2007). Since the energy loss with increasing offset was less pronounced for sinkhole 2, an offset-dependent and time-variant logarithmic scaling was not required for profile 2. After sorting the data by common midpoints (CMP), a manual, interactive velocity

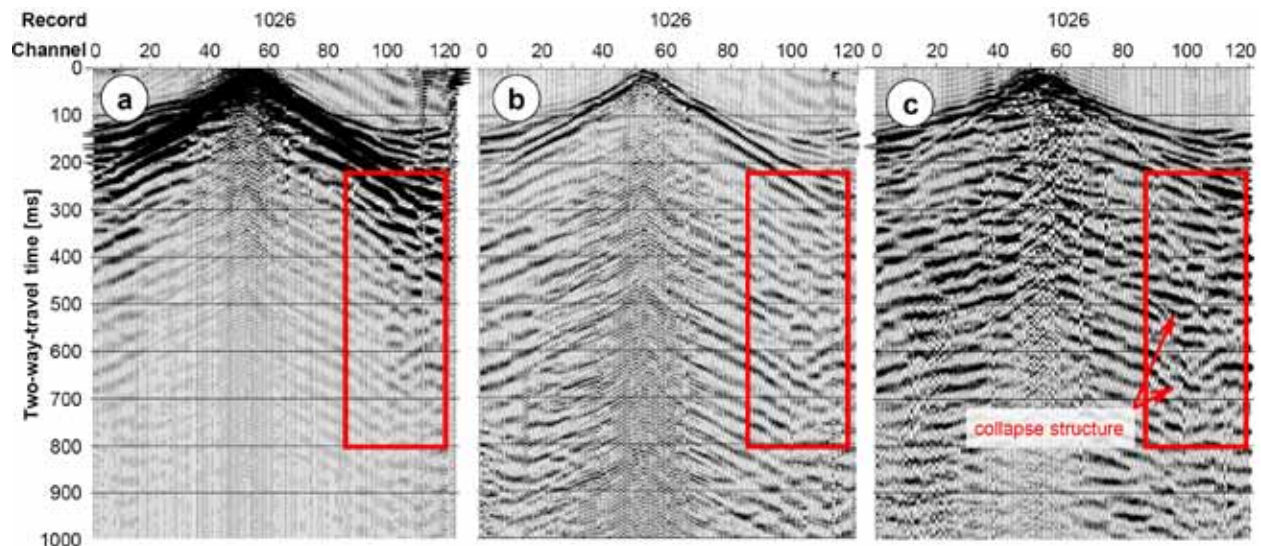


Figure 3. Pre-stack data processing of profile 1 using vibroseis correlation (a), vertical stacking, amplitude and spectral editing (b), and FK filtering and offset-dependent, time-variant logarithmic scaling (c).

analysis was carried out using semblance, offset gathers and constant velocity stacks. The lateral intervals for the velocity analysis were generally 2 m to 10 m in order to resolve the lateral velocity variations. After normal-moveout (NMO) correction and residual statics correction, a CMP-stacked section in time domain was generated (Figures 4a, 5a). To remove remaining noise, an additional FK filter was applied to the stacked data. To compensate the frequency attenuation, spectral balancing was applied on profile 1 (Figure 4b). The main parts of the reflection signals were between ca. 20 Hz and 60 Hz for profile 1 and ca. 20 Hz and 80 Hz for profile 2. The spectral balancing boosted the frequency range of profile 1 to 20 Hz to 75 Hz, which improved the resolution.

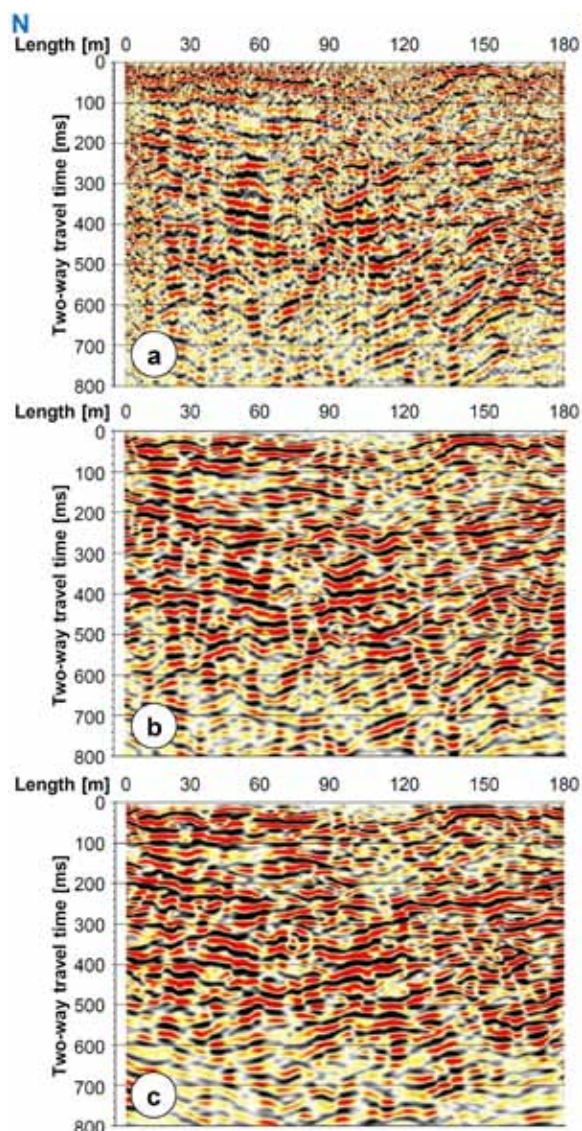


Figure 4. Post-stack data processing of profile 1 with CMP stack (a), FK filter, spectral balancing (b), and FD time migration (c).

Coherency enhancement and further noise suppression were accomplished by applying a trace weighting function. Finite-difference (FD) time migration shifted the reflectors to their origin subsurface position and removed diffractions (Figures 4c, 5c). The last step was time-to-depth conversion to generate a seismic depth section. All processing steps were performed iteratively, for a detailed description of the processing procedures, see e.g., Hatton (1986) and Yilmaz (2001).

Interpretation

S_H -wave reflection seismic profile 1 (180 m length), was carried out from north to south along sinkhole 1.

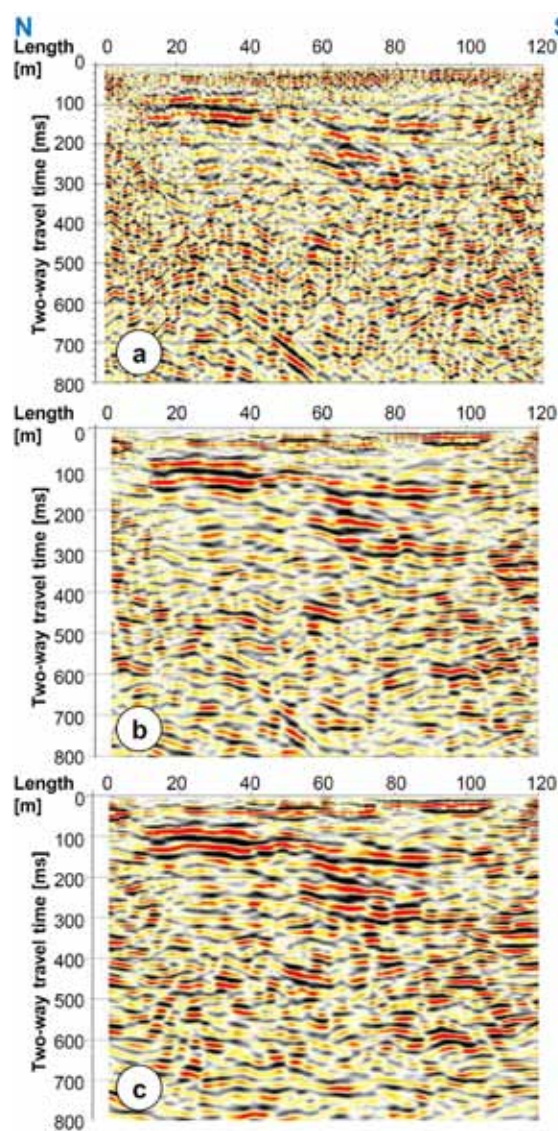


Figure 5. Post-stack data processing of profile 2 with CMP stack (a), coherency enhancement (b), and FD time migration (c).

For correlation of reflectors and stratigraphy, borehole Ky 01/1982 (BGR, 2017) was used, located ca. 600 m west of profile 1 (Figures 1, 2a). At ca. 5 m depth, a continuous reflector with high amplitudes is traceable between 0 m and 80 m and between 135 m and 180 m profile length (Figures 6a,b). The strong impedance contrast represents the boundary between silt of the Pleistocene and Werra Anhydrite of the Permian. The

area between ca. 5 m to 70 m depth shows a semi- to discontinuous reflection pattern within the karstic Werra Anhydrite. Shallowly-dipping reflectors, which form three bowl-shaped structures of ca. 30 m to 50 m diameter are visible at three different depths. The three structures are interpreted as subrosion-induced collapses. The deepest collapse is labeled number 1 and the collapse at the surface is labeled number 3. Collapse 1 (at 60 m

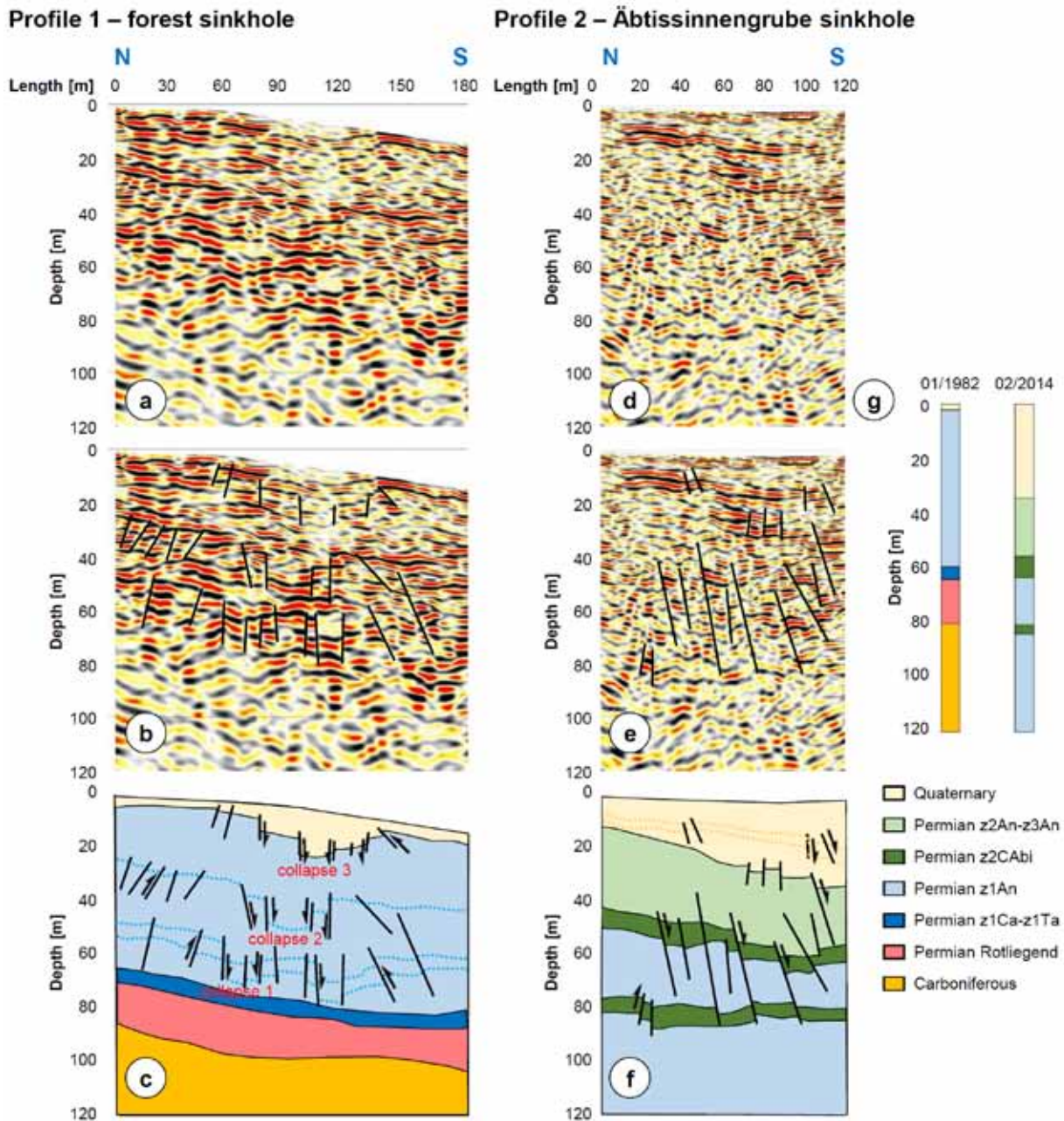


Figure 6. Depth sections of profile 1 (a,b) and profile 2 (d,e) with interpretation (c,f). Two boreholes were used to correlate reflectors and stratigraphy (g), for borehole location, see Figure 1. Fractures and intraformational faults are shown as black lines.

depth) has a height of ca. 10 m and collapse 2 (at 40 m depth) and 3 (at 15 m depth) have a height of ca. 20 m (Figure 6c). All three collapse structures are formed within the karstic Werra Formation (Figure 6g), while collapses 2 and 3 were generated above the southern margin of the collapse beneath. As a result, a shift of the collapse focal points towards south can be observed. The focal point of collapse 3 shows weak reflectivity and the area directly beneath from ca. 20 m to 40 m depth is almost transparent compared to the neighbouring reflectors at the same depth. The center and the margins of the three consecutive collapse events are characterized by fractures and intraformational faults on the seismic- and probably subseismic scale. They have small-scale vertical offsets of ca. 1 m to 5 m.

S_H -wave reflection seismic profile 2 (120 m length), was carried out along the forest sinkhole. For correlation of seismic reflectors and stratigraphy borehole Ky 02/2014 (TLUG, 2017b) was used (Figures 1, 2b). At ca. 10 m to 30 m depth, partly continuous, high amplitude reflectors are visible. They represent the internal layering and the base of the Quaternary deposits (Figures 6d, e). In contrast the area below, down to 120 m depth, is characterized by a heterogeneous reflection pattern with mostly discontinuous reflectors. Numerous fractures are identified of which only a few are drawn into the interpreted section (Figure 6f). This strongly fractured area is part of the Permian Zechstein Formations (Werra- to Leine Formations (z1–z3)). They are characterized by anhydrite and gypsum (z1An, z2An, z3An). From the surface to ca. 70 m depth the displaced reflectors dip to the south towards sinkhole 2. In this profile only the sinkhole margin is imaged compared to the profile of sinkhole 1, which displays the entire cross-section next to a sinkhole.

Discussion

Shear wave reflection seismic has been shown to be a valuable tool to image sinkholes and the surrounding near-surface like the internal structures of the leached anhydrite and gypsum of the Permian Zechstein Formations z1–z3. The horizontal resolution achieved was less than 1 m at 20 m depth and 1 to 3 m at 60 m depth.

Several aspects regarding data acquisition and processing have to be taken into account for investigation of sinkholes or subsrosion areas with

shear wave reflection seismic. For the identification of the lateral, structural variations and steep reflectors a dense receiver spacing should be chosen (e.g., 1 m or smaller). The seismic source must provide a sufficient force and good ground coupling for good energy transmission into the ground, even on unpaved ground. This helps to partly compensate for energy loss due to strong seismic wave attenuation induced by the fractured subsurface.

Important steps of data processing were filtering, spectral balancing and offset-dependent, time-variant logarithmic scaling, due to the poor signal-to-noise ratio and attenuation of especially high frequencies (e.g., 120 Hz). Partly poor reflection hyperbolas due to discontinuous reflectors are another issue. An improvement might be the use of the common reflection surface (CRS) stacking method instead of CMP stacking, because the CRS stack is independent of the velocity model and uses more traces, which can increase the signal-to-noise ratio (Yilmaz, 2001).

Both profiles reveal a heterogeneous near-surface below a sinkhole and in the surrounding area with many fractures and intraformational, non-tectonic, faults induced by subsrosion. These are necessary for percolation of meteoric-water and groundwater and therefore sinkhole development, especially in areas with a deep groundwater level of e.g. 110 m depth (TLUG, 2017a) for the area of sinkhole 1. Neither a tectonic fault nor artesian-confined groundwater are found at this location, as a result the near-surface subsrosion of anhydrite and gypsum is unlikely to be caused by contact with groundwater. Instead meteoric water that percolates through the near-surface dissolved the soluble rocks and generated the three collapses. In contrast the Äbtissinnengrube sinkhole (sinkhole 2) is located at the KSMF with a shallow groundwater level at 37 m depth (TLUG, 2017a). The fault serves as a fluid pathway for groundwater and probably enhanced subsrosion, which eventually resulted in the occurrence of such a large sinkhole with a dimension of 120 m x 160 m. The digital elevation model (DEM; Figure 2b) shows two smaller sinkholes at the northern and western margins of the Äbtissinnengrube sinkhole. Similar observations were made for the seismic profile of the sinkhole 1, but not in the corresponding DEM, due to a poor resolution limit of 5 m.

Three subsrosion-induced collapse structures were identified in the profile of sinkhole 1. Each collapse is suspected to have generated additional fractures within the overlying material, due to stress redistribution in the area surrounding a cavity, because cavities can not transfer stress (Holohan et al., 2015; Schneider-Löbens et al., 2015). In this study, fracture migration is observed especially at the collapse margins (Figure 7), which serve as fluid pathways for e.g., meteoric water.

As a result multiple collapses can be triggered more easily at the margins. The collapse events have consecutively moved to the south, which correlates with the direction of the drainage system of the Kyffhäuser hills. From these observations, we assume that the margins of an underground collapse or a sinkhole are predestined for a subsequent collapse.

Conclusions

Sinkholes and their surroundings are characterized by a strongly heterogeneous near-surface with semi-continuous to discontinuous reflectors, vertical and lateral variations, and fractures and intraformational faults, which result in vertical displacements on the order of ca. 1 m to 5 m. These openings serve as fluid pathways and can trigger a collapse.

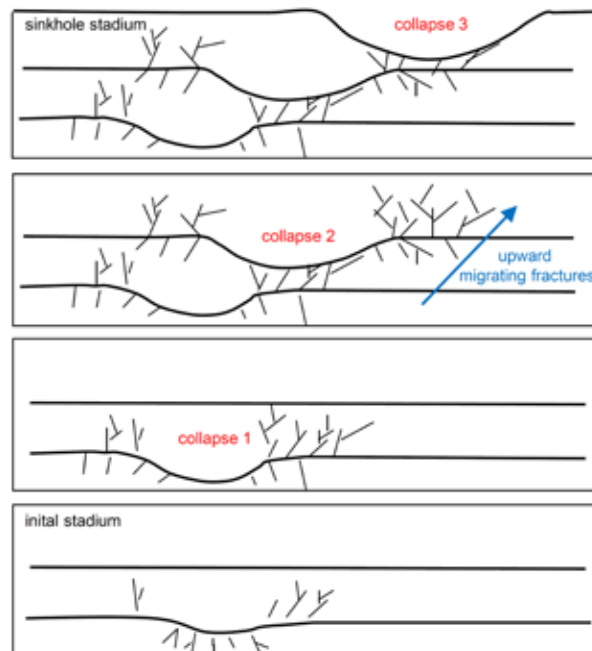


Figure 7. Sketch illustrating the process of the upward migrating fractures and collapse events of sinkhole 1.

We have shown that the margins of an initial underground collapse or a sinkhole are predestined to form another collapse event, due to the generation and the upward migration of additional fractures and intraformational faults into the overlying material. They may enhance the percolation of water, and therefore trigger a subsequent collapse. These collapse events can constantly migrate upwards until they reach the surface forming a sinkhole. The migration direction of collapse events follows the general water flow direction of this area, e.g., it follows the direction of the natural drainage system.

Since sinkholes and collapse events form very small features (even <1 m), the chosen imaging method must be capable of resolving these scales. S_H -wave reflection seismic is well suited to image the underground to a depth of ca. 100 m in high resolution, which is an important depth zone for investigation of subsrosion processes.

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JOINT PROJECT SIMULTAN - SINKHOLE CHARACTERIZATION AND MONITORING WITH SUPPLEMENTING GEOPHYSICAL METHODS

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Abstract

The joint project SIMULTAN (Sinkhole Instability: integrated MULTi-scale monitoring and ANalysis) develops and applies an early recognition system of sinkhole instability, unrest, and collapse in Germany. The research approach combines structural, geodetic, geophysical, petrophysical, and hydrogeological mapping methods, accompanied by sensor development, multi-scale monitoring, modelling, and an information platform. Two focus areas are investigated in Germany, for which sinkhole unrest has been identified. The surveyed areas are representative of evaporitic sinkhole formation, and are highly relevant since located in densely populated areas.

Shear-wave reflection seismics enables high-resolution structural imaging of critical zones, while additional vertical seismic profiling (VSP) provides hints on subsurface zones by velocity analyses. Spatial detection thresholds for microseismic events were calculated using a combination of synthetic event signals and noise recorded in the field. Improvements of the detection and localization capability due to additional borehole stations and surface mini-arrays were investigated. The potential to detect mass dislocations in the upper subsurface is proven by repeated gravimetry and levelling campaigns, that are supplemented by micro-gravimetry. How combined direct-push and SIP-monitoring will characterize sufficiently the soil-water-interaction in the upper 40 m is still in the testing phase, but stable inversion schemes are yielded.

All these petrophysical parameters are fed into modelling and simulation studies that describe dissolution initiation and explain realistic collapse scenarios in the light of overburden strength. These shall support decision processes, and the cooperation with geological surveys will advance the development of sinkhole instability recognition systems.

Introduction

Scientific key questions in sinkhole research encompass the geophysical characterization of subsidence areas, the control of void evolution and sinkhole formation at depth, or if micro-earthquakes are precursors for larger rock fall or collapse events.

Close to surface, sinkholes manifest in a variety of ways, depending on both process stage and rate (Figure 1). While collapse structures occur rapidly and within a few minutes, continuous subsidence is observed in many sinkhole areas, that progresses slowly and for many years with only a few mm/year. Individual process components may be simple and can easily be understood, but the interaction of different processes ahead a collapse and precursor phenomena with different rates and dimensions impede full process understanding. In addition, the variability of controlling parameters and its consequences are not well understood. Therefore, multi-scale observation and integrated analyses are essential for early recognition systems, especially for shallow exploration in urban areas (Krawczyk and Dahm, 2011).

First steps were undertaken in Thuringia (Katzschmann et al., 2015) and Hamburg, where staggered faults and subsidence are observed on top of a salt diapir (Krawczyk et al., 2012). Such characteristics are also seen in Kansas (Miller et al., 2008) or Texas (McDonnell et al., 2007), where collapse structures were investigated with different geophysical methods. In Germany, combined approaches are rare (Gebregziabher, 2011; Wiederhold et al., 2008; Reuther et al., 2007) but receive growing importance (Wadas et al., in review). Combined seismic reflection-refraction measurements were tested in urban areas in Canada (Hunter et al., 2010). SIMULTAN therefore applies an integrated approach for sinkhole process understanding.



Figure 1. Different process stages of sinkholes: slow subsidence in Hamburg (a), developing fracturing at surface in Jordan (b), and a 10 m deep hole at collapse initiation in Northeim (c).

Initial Position

The local governments in Germany provide individual information and maps about areas of potential sinkhole hazard, but a collective hazard map does not exist. The sinkhole areas are generally located on top of salt highs in northern Germany, or within sulfate karst or carbonate karst, which is dominant in middle and southern Germany (Figure 2). Since urban population growths, and also growths towards and into sinkhole areas, the understanding of sinkhole occurrence and processes is of increasing relevance.

Depending on soil structure and the onset and evolution of the process, sinkholes can cause continuously growing subsidence of the Earth's surface (e.g., Flottbek/Hamburg; Ochtmissir Kirchsteig/Lüneburg) or collapse abruptly, thereby opening holes with diameters of 10th of meters (e.g., Schmalkalden and Tiefenort/Thuringia, 2010; Quickborn/Schleswig-Holstein, 2010; Münsterdorf/Schleswig-Holstein, 2003–16). In Figure 2 the specific locations are marked, where also part of our research focuses. Further examples of sinkhole types can be found in Waltham et al. (2005). Both sinkhole types can cause large infrastructure damages (ca. 93 Mill. USD were spent by insurance companies in Florida in 2009; 38 Mill. USD were lost by the Arab Potash Company within 30 minutes by sinkhole-induced collapse in Dead Sea evaporation pans).

Geophysical Surveying

The research approach of SIMULTAN is structured in several components, that encompass geophysical field surveys, integrated analysis of data, model development, and simulations. Finally, we combine the information of past and ongoing activity with prognoses for possible sinkhole collapses, serving for knowledge transfer and decision processes. Our concept comprises interconnected work packages that investigate large- to

small-scale phenomena and consider time-dependent data. These are presented in the following.

Seismic Investigations

To study near-surface subsidence structures, shear-wave reflection seismic profiling provides high-resolution structural depth sections in the focus areas Hamburg and Bad Frankenhausen (e.g., Krawczyk et al., 2012; Wadas et al., 2016). The seismic profiles were acquired with the



Figure 2. Simplified geological map of Germany showing areas that can suffer sinkhole hazard (modified after Krawczyk et al., 2015). In the north, salt is dominant, while in the middle and south carbonates crop out. Hexagons: working areas of SIMULTAN.

horizontal micro-vibrator ELVIS developed at LIAG and a landstreamer equipped with horizontal geophones (for further technical details see Krawczyk et al., 2012, 2013). This setup allows for ca. 1 m vertical resolution in the uppermost 10 m subsurface, and 1–3 m further below.

The geological underground of Hamburg and Thuringia is characterized by soluble rocks of Permian age, especially Zechstein deposits. The various seismic lines gained show subsidence-induced structures to a depth of ca. 100 m. While Hamburg is characterized by surface subsidence, slightly sagging sediments and a fault system at 80 m depth (Krawczyk et al., 2012), the Thuringian investigation area is rather finely fractured close to surface and exhibits collapse structures in the surrounding (Wadas et al., 2016, 2017). A common feature is identifiable in the velocity fields of both regions: the laterally and vertically varying seismic velocities and low-velocity zones. These presumably delineate areas of enhanced fracturing and upward migrating cavities. Borehole measurements corroborate the idea of high porosity and cavities by decreased specific electric resistivity and low shear-wave seismic velocities (Tschache et al., 2017).

Micro-Seismic Monitoring

The monitoring of the seismogenic characteristics of a study area can improve the description of its deformational behavior. Therefore, the setup of a quality-controlled monitoring network in Hamburg was performed. Due to the high ambient noise level in the urban environment in combination with the complex waveforms of these shallow events traditional detection and localization approaches often fail (Becker et al., 2017). Using a combination of synthetic event data utilizing information about the source mechanism of known sinkhole events and the local velocity model (Dahm et al., 2011) and ambient noise data recorded at the network stations, the spatial detection capability was investigated and triggering routines adjusted (Becker et al., 2017). In addition to routine localization approaches also stacking algorithms using characteristic functions of the waveforms are investigated. Here, an algorithm incorporating time shifts derived from synthetic STA/LTA (Short Time Average over Long Time Average) maxima improves the results when compared to traditional travel time stacking. The use of geophone surface mini arrays, in addition to improving the characterization of the noise

field, also has the potential to better constrain the source localization (Becker et al., 2017).

Apart from compromising event detection and localization the ambient noise field can also be used to investigate possible changes of underground parameters and check the timing accuracy of seismic stations. From investigations of the ratio of the horizontal to vertical component of the ambient noise spectra (H/V method) a station specific diurnal and annual variation is observed which hints at variable noise sources but might also contain information about possible changes of physical subsurface parameters. If such developments are incorporated in monitoring systems, early recognition of underground movement is strongly enhanced.

Gravity Repeats, GNSS, and Levelling

The effect of Zechstein evaporite leaching in Thuringia is investigated with geodetic time-lapse observations. Figure 3 shows the monitoring network that has been set up. It consists of 15 gravity stations and additional levelling locations which cover the main sinkhole areas in the city of Bad Frankenhausen (Kobe et al., 2017; Kersten et al., 2017). Starting with the baseline survey in 2014, network points are monitored by quarterly campaigns. The last three years provide gravity acceleration changes ranging between 0–15 μGal , accompanied by subsidence of 0–15 mm indicated by levelling (Kobe et al., 2017).

To monitor the long-term stability of the gravity reference an absolute gravimeter point was established in 2015 (Kersten et al., 2017). Furthermore, micro-gravimetric measurements provide a structural model of the area necessary for the interpretation of geodetic signals.

Additionally, semi-annually GNSS (Global Navigation Satellite System) campaigns provide estimates for the monitored network locations. Therefore, a star-like network has been established and is fixed at the local reference station (c.f., station SL03 in Figure 3). The local reference station is tied to the national SAPOS (Satellite Positioning Service, Germany) network with the Geodetic Datum of December 1, 2016. It gives evidence that deformation is limited to local subsidence areas. Displacements of GNSS network points are obtained with respect to the local reference station.

Accuracies of the final monitoring network coordinates, processed with combined GPS and GLONASS

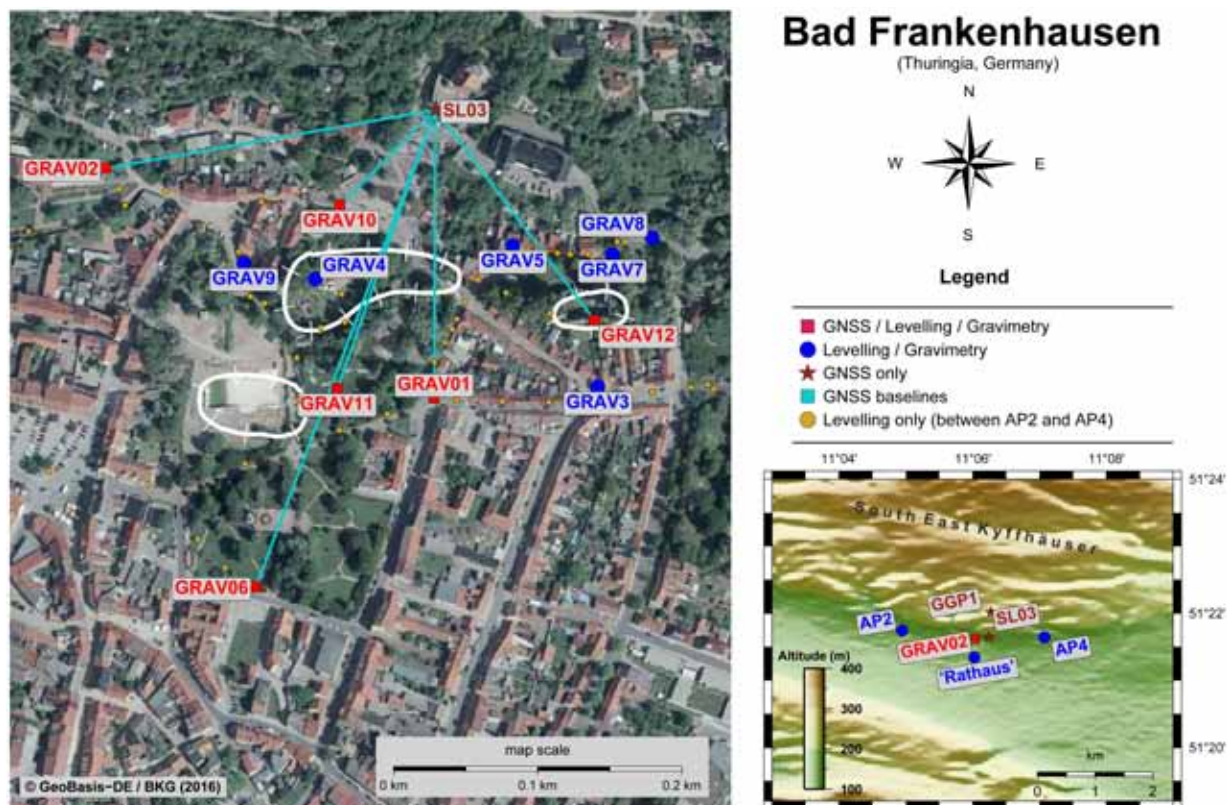


Figure 3. Field setup of geodetic monitoring network in Bad Frankenhausen.

(the satellite navigation system run by the Russian Federation) observations, are estimated to 0.8–1.5 mm for the horizontal component and to 0.8–3.5 mm for the vertical component, depending on the individual satellite sky distribution at each location (Kersten and Schön, personal communication, 2017).

A similar geodetic network is operated in the sinkhole area in Hamburg since two years. First results indicate that possible long-term trends due to leaching are often overlain by seasonal effects, most probably hydrogeological variations, which require correction models.

Rock-Soil-Water Monitoring

Soil parameters relevant to dissolution and speleogenesis are measured in the Münsterdorf area in northern Germany (c.f. Figure 2, located approximately half-way between Hamburg and Flintbek). The aim is to develop a concept integrating 3-D electric and electromagnetic tomography plus in situ probing like direct push (DP). Electrical conductivity and Cone Penetration Testing (CPT) were combined along a profile crossing a known and active sinkhole (Tippelt et al., 2017). A 2 m thick layer of increased conductivity is found at ca. 10 m depth consistently along the entire profile. This marks a compact clay layer at the transition from sand to

till. Within the sinkhole area we observe with direct push profiling tools material of higher hydraulic conductivities above the chalk.

With spectral-induced polarization (SIP) the complex electrical resistivity at electrode strings in two boreholes (21 m and 23 m deep) of 5 m distance and at surface is monitored (Mai et al., 2017). The aim is to detect slight variations of electrical polarizability caused by the interaction of a time-dependent groundwater flow with soluble rock (chalk) and adjacent material, for instance due to changing pore water chemistry or rock texture. Equivalent to the CPT results, low values are visible for the sand-till transition at ca. 11 m depth. Here, continuous groundwater monitoring will help clarifying the hydrological situation over time, which initially shows a high groundwater pressure at 10–12 m depth.

Collapse and Cavity Modelling

Combined modelling and geophysical field work of a collapse sinkhole provides the numerical verification of a stepwise collapse from void growth at depth and chemical dissolution in the overburden (Kaufmann and Romanov, 2016). These processes may be aided by fractures and faults nearby (see above).

Such mechanical interaction is constrained with the DEM (distinct element modeling) approach that is adapted for incrementally increasing dissolution zones and cavity growth (Al-Halbouni et al., 2017). The scenarios for Münsterdorf reveal for instance that a medium to high overburden strength is required to produce the mechanical collapse structure present. Low-strength scenarios yield a fully different structure.

Thus, the integration of soil properties describing the overburden in more detail puts local boundary conditions to such scenario calculation. According to a study of Grube et al. (2017), glacio-tectonics as influencing factor in areas of stronger karstification could be considered in the future, too.

Feasibility and Recommendation

The geophysical surveys, monitoring campaigns, and modelled scenarios provided so far by the integrated project SIMULTAN show both the feasibility and limits of approaches chosen.

In general, sinkhole processes with its end members subsidence and collapse develop with different rates and under a vast variety of boundary conditions. The scales to be evaluated range between 100 m to cm, as well as decades and seconds (Figure 4). While geophysical imaging defines the structural layout in the subsurface, borehole monitoring and hydrological tools above cavities can help analyzing indicative changes in the subsurface. If it comes to collapse, the surface itself reacts latest but fastest.

With SIMULTAN we explore the applicability of a combination of methods and approaches dedicated to sinkhole early recognition. The reduction of seismic velocities and irregularities in wave-propagation behavior in the presence of subsrosion are an important attribute that should be further evaluated with respect to its sensitivity and the technical implementation of it into a prediction tool. The calibration from geotechnical parameter studies is essential to develop monitoring concepts from invasive studies to non-invasive tools. The combination shown here seems to provide a first step towards this direction of geotechnical hazard assessment.

Reliable seismicity monitoring and especially the determination of the directivity of a subsurface signal is

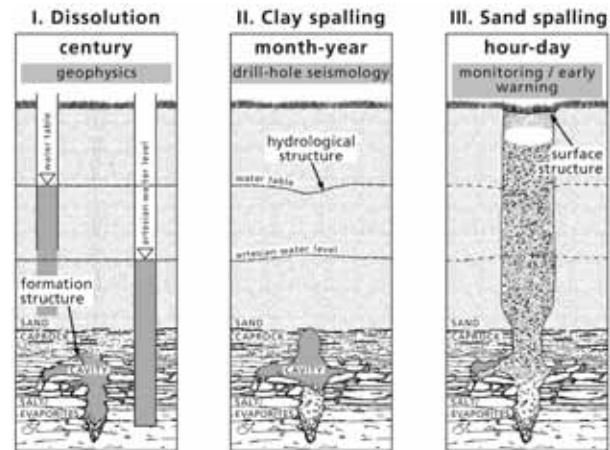


Figure 4. Scales to be considered in sinkhole research and adapted methodical layout.

challenging. Together with geodetic indicators for mass movements these can better be evaluated and possibly trends of cavity breakdown identified.

After a 2-year period of surveying only, we recommend that time-lapse and monitoring surveys shall be maintained during the next years to explore attribute sensitivity. InSAR monitoring should complement the geodetic monitoring setups, to better rate the sinkhole process and its stage in an area.

If we would use in turn the modelling results for prediction of parameter values that can be surveyed in the field, setups for field measurements with time-lapse or monitoring components should persist for at least five years to stabilize the prediction potential and reliability of trends. The approach here suggests acoustic emissions are related to microseismic monitoring of the seismic moment, interparticle forces may be used for stress field predictions, and strain simulation could be evidenced by extensometer measurements.

The combination of the above results with scenario modelling finally yields background and basic information for decision makers. Feeding these into a data base that encompasses also the quality control of specific methods and details provided, early warning in areas prone to enhanced sinkhole risk appears feasible.

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REMEDIAL INVESTIGATION OF LARGE SCALE KARSTIC FLOW CONDUITS WITH BRINE-ENHANCED RESISTIVITY IMAGING AND DOWNHOLE COLLOIDAL BORESCOPE METHODS

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Abstract

Locating conduit-type permeability in karstified limestone and dolomite and measurement of flow velocity and flow direction are key requirements for remediation of groundwater contamination, and sealing of massive inflows to pits, quarries, and underground mines. The massive rates of water inflow to a mine can cause catastrophic flooding in days to weeks, requiring a rapid reconnaissance method that can locate deep karstic permeability in a shortened timeframe as compared to traditional geophysical and drilling methods. Off-site migration of groundwater contaminants can occur by conduit flow in days to weeks as compared to much longer timeframes for diffuse flow permeability, and remediation often requires rapid remedial planning, and strategic grouting of selected conduits to eliminate the major transport pathways.

Resistivity profiling was used in conjunction with salt brine enhancement of the conduit flow to locate and image deep-lying karst flow conduit features using the Advanced Geosciences, Inc. (AGI) SuperSting R8 earth resistivity geophysical equipment. The equipment consists of the meter, external power supply, and 112 electrodes at 3 m spacings, for a surveyed length of 333 m (1,092 ft). Ambient resistivity conditions were measured throughout the surveyed area, and the average depth to karst bedrock was determined. Constant-rate injection of saturated NaCl brine solution into the flow conduit was commenced after the background survey was completed, and the conductivity of the conduit water was increased by roughly 10 times background. A second resistivity survey was conducted in which the resistivity readings above the top of bedrock were not collected to reduce the duration of data collection, and to reduce the brine volume requirement. The volume of saturated brine that is required is typically about 57,000 L (15,000 gallons) at a continuous pumping rate of 757 L/min (200 GPM). The 2-D models of subsurface resistivity from the pre-brine, and brine-enhanced surveys are subtracted to produce a conductive anomaly map. For a project site

in Hagerstown, Washington County, Maryland, a 2-D anomaly of roughly -500 Ohm-m, with a cross-sectional area of about $1,860$ m² ($20,000$ ft²), was detected. The total survey area was roughly 12X this size. The conductive anomaly was drilled with multiple boreholes, and conduit flow to a nearby mine was identified within weeks. The brine-enhanced 2-D electrical resistivity survey is believed to be the first application of its kind at this scale. The preliminary methodology and initial results from two case studies have been presented in Lolcama and Stuby (2015).

The colloidal borescope instrumentation by AquaVision utilizes natural colloidal particles which are suspended in the conduit flow past a video camera to determine groundwater flow velocity and direction. The system is capable of analyzing flow measurements every 4 seconds, and produces a very large dataset of several thousand particles tracked during an hour long test. The borescope can measure groundwater velocities from near zero up to 1.6 m/min (5 fpm). Testing of deep conduit flow that was encountered by drill holes was completed at a site in south-central Pennsylvania, which is different from the Hagerstown, MD site. Testing showed that the average direction of horizontal flow through the karst conduit features lies at about azimuth 64 degrees, or towards the east-north-east, with an average groundwater velocity of roughly 0.002 m/s (0.3 fpm), with occasional spikes in velocity to 0.01 m/s (1.7 fpm). The velocity is similar in magnitude to point dilution testing results for the same karstic flow field. The results were instrumental in achieving a better understanding of the locations of conduit flow features beneath the site, and the flow velocities and directions which were needed for remedial planning purposes.

Introduction and Background

Both sites are located in the Mid-Atlantic State region where the karst is typical of a mountainous setting, with carbonate bedrock encountered within regional scale geologic structures, such as plunging, tightly folded

synclines and anticlines and other forms of deformation. The preferential groundwater dissolution of limestone leaves terra rossa clay fill, sand, and rock debris in the karst voids and caverns. The interconnection of the karst voids has formed regional-scale karst channels in the bedrock, and we have encountered these pathways to depths of up to 137 m (450 ft), and several kilometers in length (Bruce et al., 2001).

Seepage and groundwater infiltration that results when mines, tunnels, and other deep excavations intercept a transmissive karst conduit can result in headward scouring of terra rossa clay, silt and other residuum filling the feature, effectively enhancing the transmissivity of the feature. Groundwater flow along these scoured conduits can increase rapidly and overwhelm dewatering pumps, and in extreme cases can cause catastrophic flooding of below grade excavations.

When a geotechnical or environmental crisis occurs in karst geology, where the groundwater flow is predominantly through deep-lying and isolated massive flow conduit features, remedial location of the flow features within very tight timeframes can seem nearly impossible to the individuals responsible for identifying a solution. Engulfed in the crisis, the owners of these properties all too often attempt a repair which does not suit the ground conditions, because they have been unable to complete a meaningful investigation to understand the problem in the time available. If too large of an area is targeted for remedial treatment, the crisis can turn into a seminal event if not turned around, by triggering the expenditures of huge sums of money without the likelihood of success. Paradoxically, crisis management guidance for these types of geotechnical problems (Bruce, 2004) teaches us that understanding the hydrogeologic and geotechnical scope and details of the problem is the key to selecting the correct repair strategy, and achieving a successful outcome.

This paper presents two different remedial case studies in the rapid, reconnaissance, location and characterization of large scale, karst conduit-type groundwater flow through bedrock using a novel brine-enhanced electrical resistivity surveying (BEERS) method, and a downhole colloidal borescope (CB) method.

Methodology

Colloidal Borescope Method

The colloidal borescope was first introduced to the commercial market by AquaVision in 2000 for direct, borehole measurement of laminar and turbulent groundwater flow velocity and average flow direction, using quantitative video particle tracking methods. The application described here is a delineation of contaminant transport directions and velocities in a complex karst aquifer, in which conduit flow pathways are embedded within a fractured carbonate aquifer. The dissolved phase contaminant mass in the aquifer is being removed by pump and treat methods, to depths of up to 250 feet. Our conceptual model is that contaminant mass is transported rapidly through an anastomosing network of conduits, and more slowly through the fracture networks. The purpose of the testing is to determine if the contamination is evading the capture wells by migration within the nested flow conduit features.

A portable borescope instrument system package includes the borescope and controller, communication/data cable and reel, and field computer with controller software. From Wilson et al. (2001), the natural colloidal particles which are scoured from clay-fill in karst become suspended in the groundwater flow which flows across the field of view of the video camera/borecope, which is suspended in the borehole and stationary. Particles are digitized and tracked by computer for speed and direction of movement. Only horizontal particle movement is considered, as particles with a substantial vertical movement tend to become unfocussed over time, and the tracking software eliminates their trajectories. An on-board compass, or flux-gate magnetometer, is utilized to determine particle directions. After AquaVision (2000), the system is capable of analyzing flow measurements every 4 seconds, resulting in a large data base of several thousand particles tracked during a typical one to two hour long testing period, adding to the accuracy and reliability of the results. The borescope is capable of measuring velocities up to 1.5 m (5 ft) per minute, which is applicable to turbulent flow. The provided AquaLITE software creates a data file with colloid speed and horizontal direction, number of particles tracked, and the date and time of a measurement. A statistical summary is created with average speed and direction, and data variability about the arithmetic mean statistic. Roughly 1 megabyte of data is collected per one to two hour test period; a typical test measures several thousand particles.

RockWorks software (Rockware, 2012) was used to create a circular histogram plot for each test location in the borehole. Each of the petals in the circular histogram is a 5 degree increment in the flow direction of the karst groundwater. An example plot of the directional data, with test statistics, for a test containing 2,854 particles is shown in Figure 1.

Example of CB Implementation and Data Interpretation

For the application site described above, where karstified limestone and dolomite bedrock underlie an industrial site in south-central Pennsylvania, optical televiewer logging was completed in several boreholes, and the example provided is from a test interval in a deep borehole that penetrated a zone of karst from roughly 61 m (201 ft) to 67 m (218 ft) depth below grade. The borehole log showed an open karst void from 65 m (213 ft) to 67 m (218 feet). The borehole was cased and sealed from grade to 61 m (200 ft) depth. No other voids were exposed in the borehole during testing. Testing was performed in an open hole section of the borehole below 61 m (200 ft). Vertical flow was minimal. After testing for roughly one hour, the

average horizontal flow direction through the borehole was azimuth 43 degrees, or north-east, with a 5 degree envelope about the average direction comprising the 95% confidence interval. The other directions shown are most likely caused by a slight swirling action to the groundwater in the borehole immediately after borescope insertion. The average groundwater velocity is 0.021 m/min (0.07 fpm), and the median velocity is 0.015 m/min (0.05 fpm), with occasional particle velocities up to 0.52 m/min (1.7 fpm). By comparison, point dilution testing at this depth showed groundwater velocity of 0.39 m/min (1.28 fpm). The results demonstrated a potential for deep-lying turbulent flow beneath the site. Future refinement of the field methods for CB will focus on minimizing the slight swirling effects caused by the insertion of the probe.

Requirements

A minimum set of requirements are provided as a guide:

1. 4 inch or larger open borehole access to the flow conduit feature of interest. Do not perform the testing through a well screen, either filtered or not filtered.

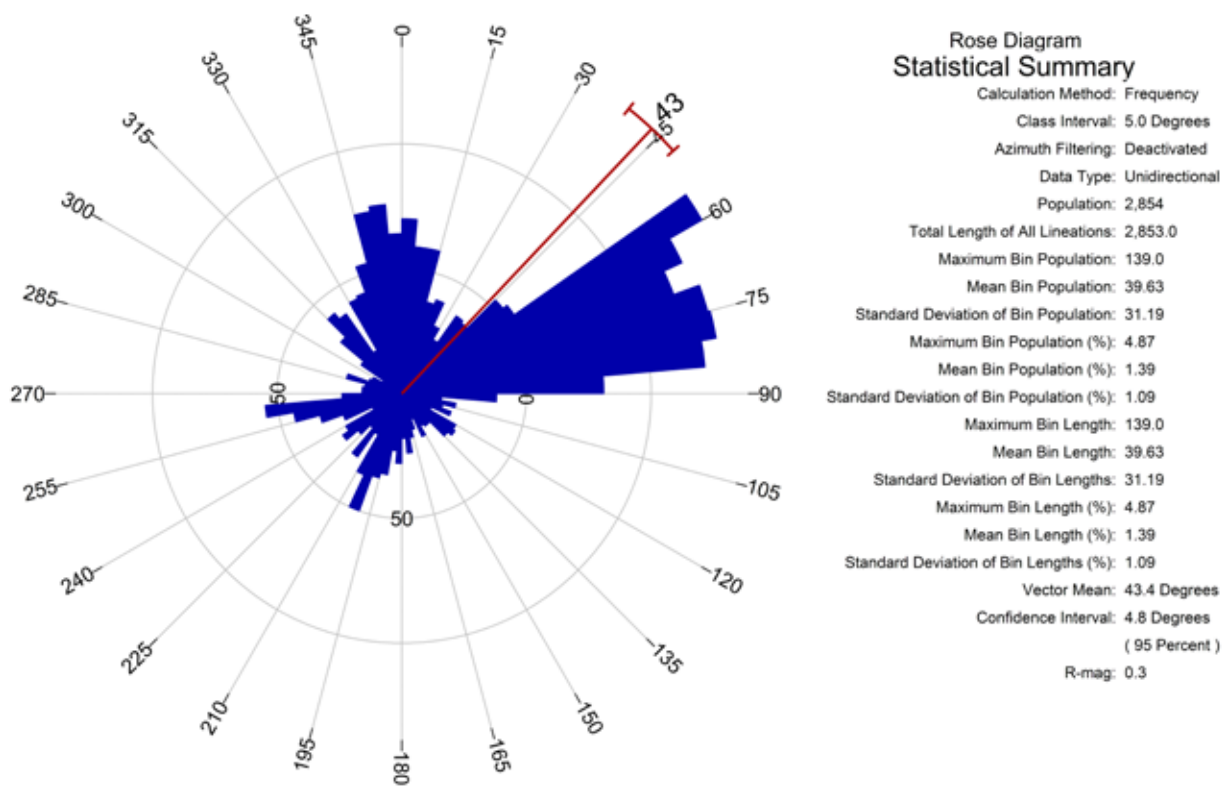


Figure 1. Summary of CB test results for one conduit feature from 65 m to 67 m deep. 2,854 colloidal particles tracked during a roughly one hour test period.

2. Perform the borescope work in natural flow conditions undisturbed by, for example, aggressive pumping nearby.
3. If equipment allows, measure the groundwater turbidity of the test zone, and compare with other test locations. Anomalous turbidity can cause random scattering effects, thus reducing the quality of the data.
4. Allow a period of time to pass after setting the borescope at the required depth before commencing logging, to reduce eddy effects in the colloid movements.
5. Make the necessary equipment adjustments to minimize edge effects/video interferences prior to the start of logging, and during logging. This is not a 'set it and forget it' technology.
6. Set a goal of several thousand particles tracked, if time allows, for best direction and velocity results.

BEERS Method

After Nettles et al. (2007), at-grade electrical resistivity technology (ER) provides two-dimensional information on the electrical properties of subsurface materials, which can be used to infer geologic structures such as top of rock and overburden thickness, presence of fractures, and the presence of voids and cavernous formations. However, the turbulent flowing water of a karst flow conduit cannot be differentiated from either the stagnant water in storage in an isolated void or cavern, or the diffuse flow of a fractured bedrock system. This differentiation of turbulent flow from diffuse and laminar flow is required for remedial planning purposes. AquaTrack™ technology by Willowstick (2006) is useful for locating water-seepage zones through the subsurface, such as might be afflicting a dam structure, however the method cannot differentiate between seepage and turbulent flow. The heat pulse flow meter (Kerfoot, 1988) is a direct measurement for flow velocity for borehole use which is limited to much less than 1 foot per minute, which is laminar to sub-turbulent flow. Point dilution testing methods are limited in not being able to discern the direction of the tracer movement.

The BEERS method incorporates saturated salt brine injection into the groundwater recharge through the geophysical test zone, enabling the method to differentiate the large, turbulent-type flow through

bedrock from otherwise conductive karstic features such as clay or water filled voids and caverns with laminar flow, to depths of up to 76 m (250 ft). The new method significantly decreases the time required to locate conduit flow, enabling a more focused and successful remedial treatment.

The brine-enhanced electrical resistivity survey is a time-lapse geophysical method first attempted by the authors in 2007 at a mine site in West Virginia that was taking on water from an adjacent river at large flow rates. Water was flowing through a known entry point in the river bottom and emerging in the quarry bottom as confirmed by a saline tracer test. An electrical resistivity profile could easily be acquired between the entry point and quarry. A background measurement was initially made to assess the steady-state subsurface conditions along the profile. The approach of the technique was to actively change subsurface electrical properties by injection of a large volume of saline solution (brine) through the entry point, and measuring the subsurface again while the saline solution was below the electrode array. Differences between the background measurement and the post-injection measurement were expected to be caused only by the brine which was travelling through the conduit between the river and quarry. In this way the horizontal location and depth of the conduit were determined.

The technique was subsequently applied twice at another quarry in Maryland with similar conditions. The first use was to identify the subsurface location of the conduit as in the WV quarry. The second use followed a major program of grouting activity, which had partially grouted closed a deep flow conduit network, and the owner was attempting to understand the extent of the remaining area to be grouted. These case studies are described in Lolcama and Stuby (2015).

Resistivity profiles were acquired using the SuperSting R8 Earth Resistivity Meter by Advanced Geosciences, Inc. (www.agiusa.com/supersting). In this BEERS survey case study, the SuperSting controlled a set of 112 electrodes spaced between 3.4 and 5.2 m (11 and 17 ft), depending on available space for the array. This resulted in arrays of lengths from 372 to 575 m (1221 to 1887 ft), which provided subsurface resistivity results to approximately 76 m and 122 m (250 ft and 400 ft) respectively.



Figure 2. Brine solution addition to the river water recharge to the subsurface conduit.

The brine itself was a saturated solution of NaCl, and volumes of up to 56,781 L (15,000 gal) were injected over a period of 60 to 90 minutes (Figure 2). The travel time of subsurface water through the conduit was known from tracer testing, so that the approximate time of arrival of the brine below the electrical resistivity array could be calculated, and resistivity measurements did not begin until this time in each case.

A detailed discussion of the geophysical test design, field data collection methods and processing of the data is provided in Lolcama and Stuby (2015).

The resistivity values for the test area with brine-injection were subtracted from the corresponding values in the background (no brine) model. In this way the drop in subsurface electrical properties caused by the presence of the brine appeared as negative values, and these negative values represent the location of the subsurface conduit connecting the river to the mine.

The negative anomaly observed on the second survey at the Hagerstown, Maryland mine site was the most clear and intense of those observed on the three surveys. The survey was completed across a deep faulted zone which interconnected a nearby river and quarry, and the river provided recharge to the fault zone. The left-half of the surveyed zone had been grout-sealed with cement-based grout, whereas the right-half has yet to be grouted. The anomaly is shown as “A-A” on Figure 3, and demarcates the area of conduit flow that remains after grouting. Note that positive anomalies are also observed on either side of the central negative anomaly. These are almost certainly artifacts of the iterative inverse modeling algorithm. The anomaly was confirmed to be the flooding flow conduit by drilling several boreholes through the anomaly and tracing the karstic flow connection to the nearby mining operation using the boreholes for tracer injection.

Requirements

A set of requirements are provided as a guide:

1. A naturally-occurring inlet point to the conduit would normally be located, such as a sinkhole throat in an adjacent river, or upstream of the dam

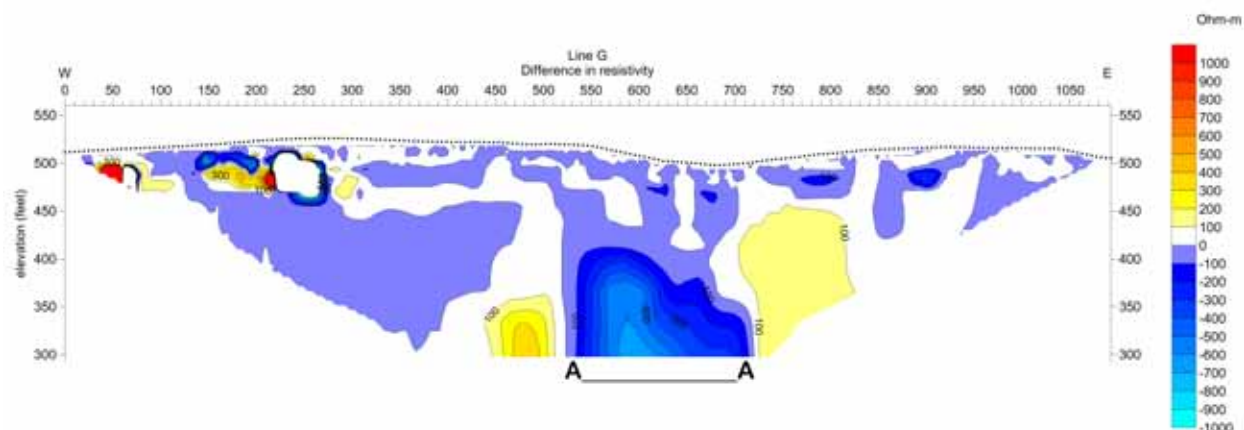


Figure 3. Resistivity profile showing differences in modeled subsurface resistivity between background and brine-injection models. The dotted line is the ground surface, and distances are in feet. “A” indicates the significant drop in resistivity of over 500 Ohm-m presumed to be caused by the brine, and which indicates the location of the flow conduit. Anomalies (positive or negative) above 450 ft elevation were above the river level and could not represent flow conduits.

structure. Otherwise, an injection borehole or two would be installed through the top of the conduit.

2. The rough strike of the flow conduit feature through the bedrock should be determined to guide the investigation.
3. The average flow velocity inside of the conduit should be determined by quantitative tracing.
4. Environmental State Agency-permission to inject salt brine may be required, and their requirements for salt-monitoring in local waterways must be adhered to, including establishing background, and demonstrating no impact during injection and for several days post-injection.
5. Locate allowable space to place a 300 m + (1,000 ft +) resistivity profile between the inlet and quarry, oriented perpendicular to the flow direction, and preferably in a straight line (although some curvature is allowable).
6. Stage sufficient brine at the project site to inject into the flow conduit over a period of roughly one hour with a pumping rate of at least 379 L/min (100 gpm).

Conclusions and Perspectives

The hydrogeology of the SE Pennsylvania project site is highly complex with large scale karstic flow conduits nested within a fractured carbonate aquifer. The contaminant transport directions and fast velocities of the conduit features are uniquely different as compared to the fractured bedrock matrix with diffusion-controlled migration. Earlier adoption of the colloidal borescope could have characterized the conduit flow for inclusion in the site hydrogeologic model.

The West Virginia mine site location discussed above, was the location of the largest multi-material grout curtain to halt a major inflow through karst bedrock in North America, completed during 1997 and 1999 (Bruce et al., 2001). The reconnaissance exploration program to locate the flow pathway, while successful in the end at centering the grout curtain on the main body of the conduit flow, required over 7,620 m (25,000 linear ft) of 2-D resistivity work through densely wooded terrain, and drilling of roughly 60 deep test borings to 76 m (250 ft). Access roads had to be cut through the dense brush for geophysical surveying, and for the drilling equipment. Several hundred additional

boreholes up to 107 m (350 ft) deep were drilled to plumb the karst bedrock to accept grout, with each borehole being tested for evidence of conduit flow. The conductive anomalies in the bedrock that were targeted for drilling without knowledge of flow velocity, were water and clay-filled karstic voids. With the highly karstified nature of the dolomite bedrock, due largely to structural deformation and breakage of the rock, very few of the many karstic voids were interconnected. The main body of the flow conduit was restricted to a relatively small cross-sectional area, which eventually was distinguished from static groundwater in storage by water temperature logging of the boreholes. Had the brine-enhancement method been available at the time, countless hours would likely have been saved by targeting the active flow conduit earlier in the program, resulting in less geophysical surveying, less drilling time and expense, and saved pumping costs by the mining client.

Site characterization programs for karstic aquifers would benefit from the application of the colloidal borescope method and BEERS. The direct measurement of flow velocity and direction information using boreholes helps us to understand the preferential karstic flow pathways, and whether the directions of groundwater flow through these karstic pathways differ substantially from averaging techniques for prediction of aquifer flow direction and discharge rate. Specifically, the testing can be used to detect off-site conduit flow that is by-passing a pump-and-treat remediation system.

Three different applications of the brine enhanced electrical resistivity survey method have been completed, and one of the surveys is presented in this paper. The results of these surveys clearly demonstrate that enhancing the electrical conductivity of conduit flow in a karstified bedrock aquifer will create a strong geophysical anomaly which can be detected to depths of at least 91 m (300 ft) and possibly deeper. The method provides a rapid and cost-effective tool for remedial-locating of water flow pathways during the early period of a flooding crisis for a mine owner, or a leakage crisis for a dam operator. If designed and implemented properly, the exploration time leading up to grouting repair of the flooding pathway, can be shortened to several weeks from several months, which should translate into substantial cost savings.

Recommendations

The application of the colloidal borescope system would benefit from additional setup time for the borescope to minimize edge effects, which is a software operational issue. The borescope should be positioned within the conduit flow to avoid particle swirling action, which will require additional time and prior knowledge of exact depths of karst conduits through other borehole logs. Elevated turbidity levels in the test interval can overwhelm the borescope particle tracking software, therefore the method would benefit from some turbidity screening prior to test startup. For testing of karst for horizontal flow direction and rate, the method seems to produce good data, provided that the test duration is long enough to overcome swirling action in the borehole, and the borescope is placed into the void and away from the wall or clay-fill material, and a large population of particles is tracked. The placement of the borescope should be guided by geologic logs and optical televiewer logs, as available. A test duration of 1 to 2 hours seems appropriate.

Acknowledgments

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COMBINATION OF 2D SHEAR WAVE REFLECTION SEISMICS AND TRAVEL TIME ANALYSIS OF BOREHOLE GEOPHONE DATA FOR THE INVESTIGATION OF A SINKHOLE AREA

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Abstract

In November 2010, a 30 m wide and 17 m deep sinkhole occurred in a residential area of Schmalkalden, Germany. Subsequent geoscientific investigations showed that the collapse was naturally caused by the dissolution of sulfates below 80 m depth. In 2012, the Thuringian State Institute for Environment and Geology (TLUG) established an early warning system including 3C borehole geophones deployed in 50 m depth around the backfilled sinkhole.

During the acquisition of two shallow 2D shear wave seismic profiles in the vicinity of the sinkhole, the signals generated by a micro-vibrator at the surface were additionally recorded by the four borehole geophones of the early warning system and a vertical seismic profiling (VSP) probe in a fifth borehole. Travel time analysis of the direct P- and S-wave arrivals enhances the understanding of wave propagation in the area. Seismic velocity anomalies are detected and related to the structural seismic images of the 2D profiles. In case of travel paths perpendicular to faults, the velocity is decreased, whereas the velocity of waves travelling parallel to the strike direction of faults is not significantly lowered.

The combination of receivers located at the surface recording reflected seismic waves and distributed

downhole receivers recording direct waves, enables analyzing of seismic wave propagation and velocities in more detail and beyond 2D. Therefore, the experiment setup will be further extended in future. The presented method shows the potential to locate instable zones in a sinkhole area. In our further research we propose to evaluate the suitability of the method for the time lapse monitoring of changes in the seismic wave propagation, which could be related to subsrosion processes.

Introduction

Early recognition of sinkhole hazard is an important and challenging topic. The approach of the joint project SIMULTAN (Sinkhole Instability: integrated MULTi-scale monitoring and ANalysis) is the combination of multi-disciplinary methods across different scales. One major step which is addressed by the project is the detection of unknown critical zones. Another one is the monitoring of suspect zones.

The shear wave reflection seismic method enables high-resolution imaging of the near-surface particularly in urban areas (Inazaki, 2004; Pugin et al., 2004; Polom et al., 2010; Krawczyk et al., 2013). This technique has already been applied with success in sinkhole related studies (Krawczyk et al., 2012; Wadas et al., 2016; Wadas et al., 2017). Krawczyk et al. (2012) propose

a low shear wave velocity combined with a chaotic reflection pattern as an indicator for subsrosion areas. Depression structures, strong scattering of seismic waves and discontinuous reflectors are further features in the seismic data that indicate leaching of soluble rocks in the subsurface (Wadas et al., 2016). The detailed mapping of the local fault and fracture system enhances the understanding of groundwater flow, which is a key factor of subsrosion (Harrison et al., 2002; Closson & Abou Karaki, 2009; Wadas et al., 2017). Tomographic studies using seismic waves in karst and subsrosion areas were successfully applied to image zones of decreased P-wave velocity related to karstified fracture zones (McDowell et al., 1993; Karaman et al., 2004). The aim of our study is to combine high-resolution 2D shear wave reflection seismic imaging with a survey similar to multi-offset multi-azimuth VSP.

Study Area

The study area is located in Thuringia, Germany. In 2010, a circular 30 m wide and 17 m deep collapse sinkhole occurred in a residential area of the town Schmalkalden (Schmidt et al., 2013). Fortunately, nobody was harmed, but infrastructure and private property were damaged. The sinkhole was backfilled immediately to stabilize the sloping terrain. Subsequently, various investigations were conducted on behalf of the Thuringian State Institute for Environment and Geology (TLUG) to clarify the cause of the sinkhole and to evaluate further sinkhole hazard. These included drilling of 5 cored boreholes and 2D P-wave reflection and refraction seismics amongst others (Schmidt et al., 2013). As no evidence for a large man-made cavity could be found, a natural origin by subsrosion of sulfate rocks was concluded being a sinkhole forming process known from neighboring areas (Schmidt et al., 2013).

Starting at depths of 80–90 m, a 30–40 m thick layer consisting of gypsum, anhydrite, and claystone acts as subsrosion horizon (Schmidt et al., 2013). It is overlain by a 15–25 m thick massive dolomitic limestone layer, which allows unnoticed cavity formation below, and sandstones and claystones of Permian and Quaternary age (Schmidt et al., 2013). Karstification of carbonate rocks is observed to be very low in the study area (Schmidt et al., 2013). The presence of a regional fault zone and intensive fracturing benefit the subsrosion process (Figure 1; Schmidt et al., 2013; Wadas et al., 2017). In 2012, an early warning system was established.

It includes, amongst other elements, four 3-component (3C) borehole geophones deployed in 50 m depth in four shallow boreholes surrounding the backfilled sinkhole (Figure 1; Schmidt et al., 2013).

Concept and Data Acquisition

Two 2D reflection seismic profiles (Figure 1) with a length of 192 m (Profile 1) and 226 m (Profile 2) were acquired along streets during daytime in the vicinity of the backfilled sinkhole. During the acquisition of Profile 1, a VSP probe clamped in 30 m depth in borehole KB5 (Figure 1) recorded the arriving signals simultaneously. Due to a technical problem, it could not be used during the acquisition of Profile 2. The four 3C borehole geophones of the early warning system located in boreholes KB1–4 (Figure 1) recorded data continuously throughout the survey of both profiles. As seismic source, the electrodynamic micro-vibrator ELVIS 7 developed at LIAG was used in SH-wave mode

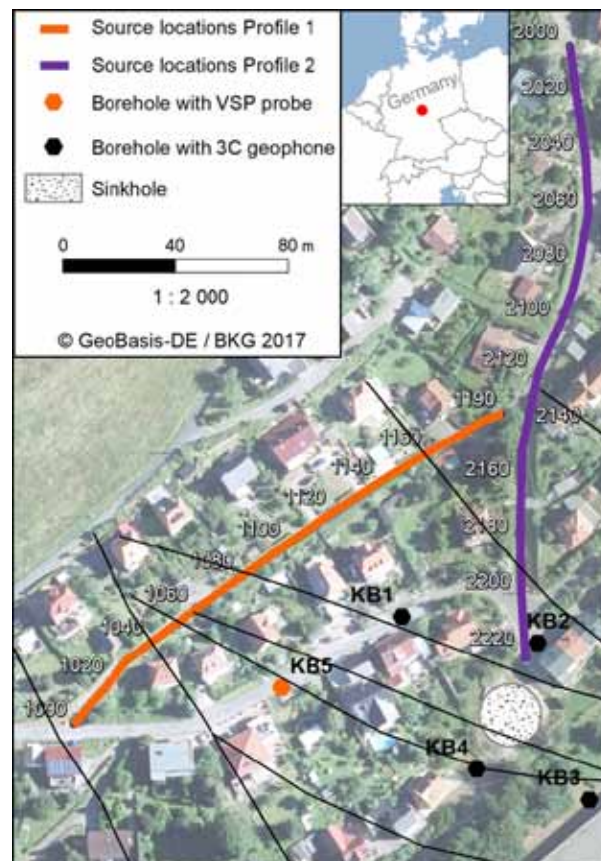


Figure 1. Location of profiles, boreholes and sinkhole in the study area Schmalkalden (red dot in map). Interpreted faults from previous seismic studies (Schmidt et al., 2013) are shown as black lines.

(Polom, 2003; Druivenga et al., 2011). At each vibration point, two 20–120 Hz sweeps of opposing polarity were excited to suppress compressional wave energy on the SH-component records. The source point interval was 2 m and 4 m at the end of Profile 1. For the two reflection seismic profiles, a land streamer developed at LIAG was used (Krawczyk et al., 2013). It is equipped with 120 1-component geophones in a 1 m spacing recording the SH-component. The VSP probe used consists of three geophone elements and the horizontal components can be oriented using an internal compass. In contrast, the orientation of the horizontal components of the permanently installed borehole geophones in KB1–4 is unknown. Another issue encountered is the time synchronization of all receivers. We achieved to determine exact shot times in an accuracy of 1 ms by simultaneous recording of GPS time signals during seismic data acquisition. However, the permanent borehole geophones of the early warning system (KB1–4) only use an internal time base, but no GPS sensor. Thus, the actual time difference between exact GPS time and the internal clock of the warning system is unknown and can only be roughly estimated.

Using the known distance between source and borehole sensor locations, an average velocity of the directly arriving P- or S-wave is determined after picking of the arrival time. For calculation, a straight ray is assumed.

Data Processing

Reflection Seismic Data

The reflection seismic datasets show a good data quality. In some shot gathers significant 50 Hz noise is observed due to power supply lines. An established shear wave processing flow similar to those described by Krawczyk et al. (2012) and Wadas et al. (2016) was applied. The first data processing steps comprised cross correlation of the raw vibration type data, trace editing, vertical stacking of shot records and a crooked line geometry setup. For noise suppression, a 20–25–90–100 Hz bandpass filter was applied and an individual notch frequency filter (e.g., 50 Hz) to some of the shot gathers. An automatic gain control (AGC) with a 300 ms window was applied to the data of Profile 1. In case of Profile 2, an exponential gain of $\exp(2t)$ yielded better results. Source noise dominant at near offset traces was reduced by FK filtering. After top muting and common midpoint (CMP) trace sorting, velocity analysis was performed in a 20 m interval. The stacking velocity field was iteratively enhanced by visual

brute stack evaluation. Normal move-out correction and stacking was performed using the final velocity model. Subsequently, a finite difference time migration and FX-deconvolution were applied. The data were transformed to depth domain using a 1D velocity field. A CMP-dependent static trace shift was applied to incorporate topography in the final seismic sections.

VSP Probe Data

The recordings of the VSP probe contain useful signal between source locations 1000 and 1144, which corresponds to a maximum travel path of 92 m, but are heavily affected by crosstalk, especially the Y component. Due to the very similar behavior on all traces, it could be combated by subtraction of a bottom-muted average trace for every single component. The data processing comprised cross correlation with pilot sweep, component separation, vertical stacking, crosstalk noise suppression and bandpass filtering using a 15–20–55–60 Hz filter. The horizontal components were rotated towards the source based on the derived azimuth of the known source position, component orientation and a straight ray assumption for the travel path. First arrival energy is concentrated well on the Hmax component. Rotation of Hmax and Z components towards the source did not yield improved results so that first arrival picking was carried out on the Hmax component (Figure 2b). In seismic data acquired by vibration sources, the first arrivals are commonly located at the maximum of cross correlation of raw data and pilot sweep (Crawford et al., 1960). According to that, the first strong peaks were picked.

The travel time curve of the first break picks shows a linear alignment for the picks of an offset greater than 60 m. The linear regression functions show a delay of the first arrivals of 85 ms. This indicates that the picked arrival times are too late when assuming body waves propagating from source to receiver on a straight travel path with a velocity of 580–710 m/s as indicated by the travel time curve slopes. It was not possible to pick consistent earlier arrival times which might also be caused by the strong crosstalk noise interfering the first 200 ms of the data. To concentrate on velocity differences along the profile rather than absolute velocities, a constant time shift of –85 ms was applied to the first break picks (see also dashed line in Figure 2b).

Continuous Borehole Geophone Data

The first data processing steps involved extracting of the relevant parts of the continuous recordings and

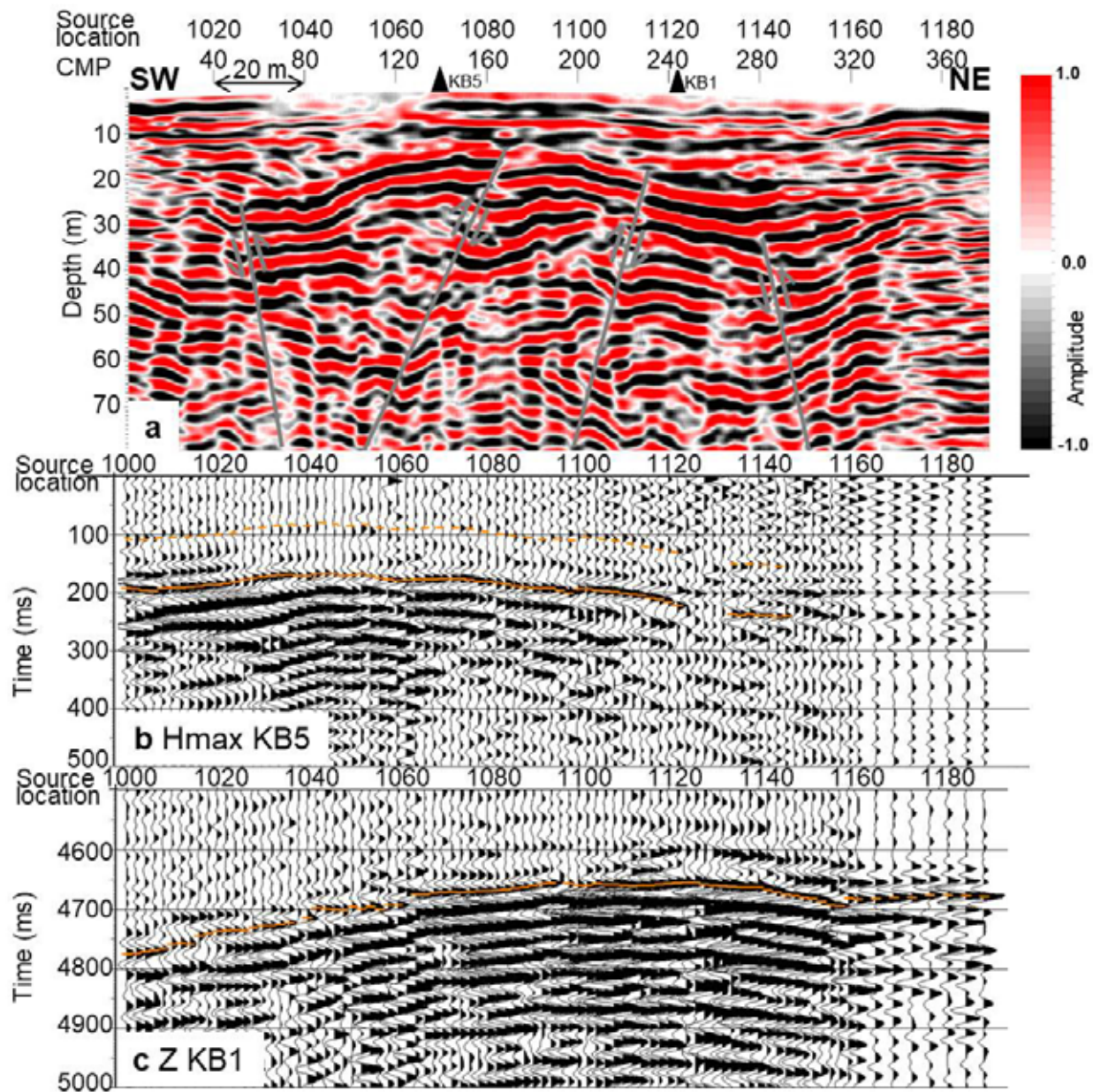


Figure 2. Seismic section of Profile 1 in depth below 327 m with interpreted faults. Borehole locations (full black triangles) are shown projected to the closest source location, respectively. (b) First arrivals (solid orange line) picked on the Hmax component measured in borehole KB5 and shifted 85 ms (dashed orange line). (c) First arrivals (solid orange line) picked on the Z component of the measurements in borehole KB1. Different time axes in b and c are due to time window used for extracting the data in c from continuous recordings.

conversion from MiniSEED to SEG-Y data format. We extracted 20 s long time windows starting 5 s before shot GPS time and assembled them in receiver gathers. Examination of the raw and cross correlated data revealed that, in case of Profile 1, only the geophone located in KB1 provided useful data and in case of Profile 2, the geophones in KB1 and KB2. The other

borehole geophones are located too far away or are not sensitive enough to record the signals.

The raw data were cross correlated with the pilot sweep, vertically stacked and lowpass filtered with cutoff frequencies of 50 or 55 Hz. Finally, a trace normalization was applied. First arrival times of source locations on

Profile 1 were picked on the Z component data of the receiver in KB1 (Figure 2c). The signals of source locations 1160 and greater do not belong to a directly arriving body wave and these picks were excluded from further analysis.

At source locations 2172 and greater on Profile 2, the records of both receivers in KB1 and KB2 are dominated by a very strong ringing (Figure 3b,c). The high amplitudes, early arrival times and travel time curve analyses indicate probably vibrations of the whole borehole casing excited by surface waves propagating

along the sealed ground and hitting the top of the borehole. This behavior is consistently confined to the closest source locations and stops at source location 2172 for both receivers, although the ground conditions between source locations 2170 and 2172 do not show a visible difference.

First arrival times were picked between source locations 2012 and 2170 on the Z component of the receiver in KB1 (Figure 3b) and between source locations 2116 and 2170 on the Y component of the receiver in KB2 (Figure 3c).

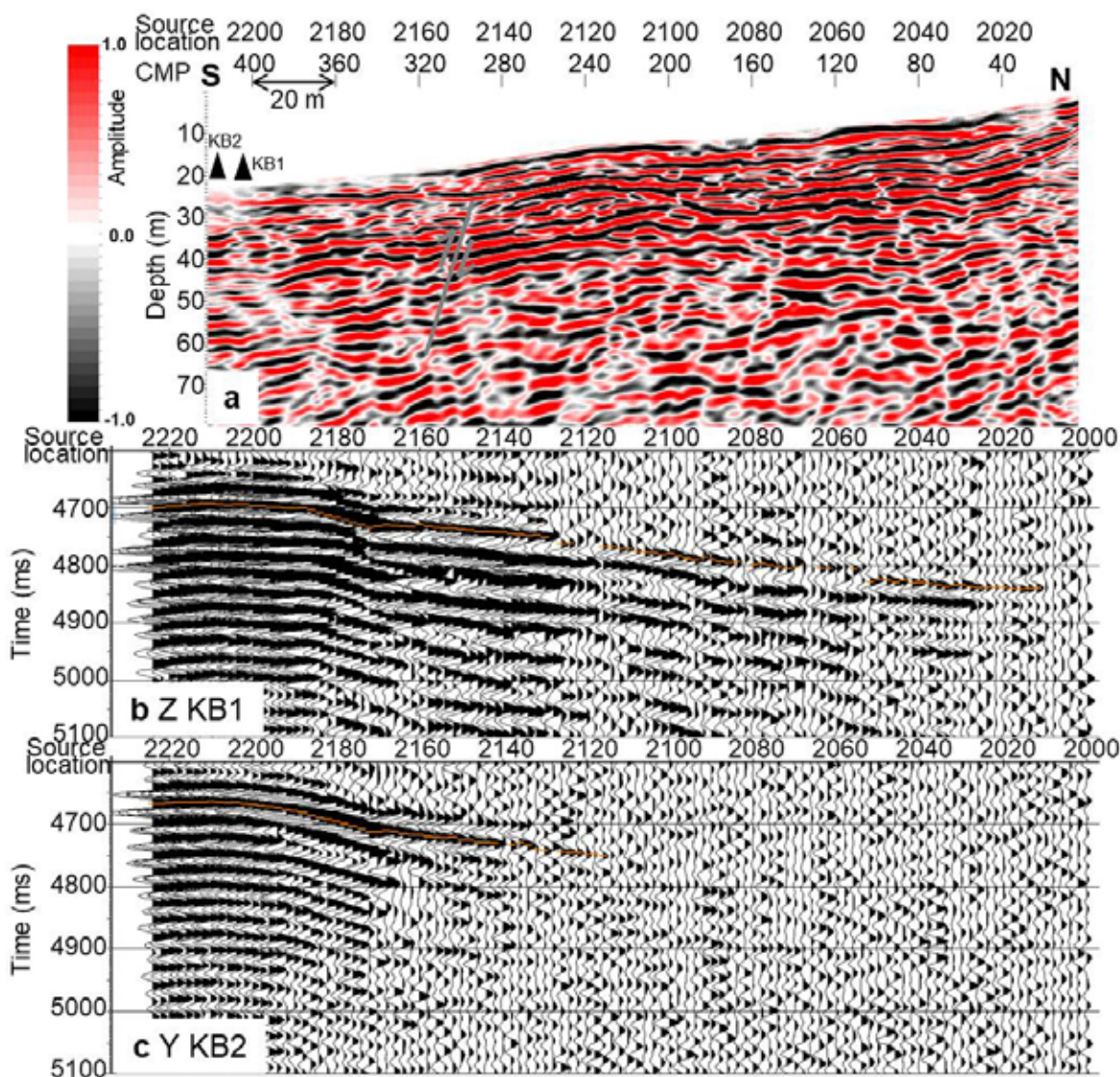


Figure 3. (a) Seismic section of Profile 2 in depth below 336 m with interpreted fault. Borehole locations (full black triangles) are shown projected to the closest source location, respectively. (b) First arrivals (orange line) picked on the Z component measured in borehole KB1. (c) First arrivals (orange line) picked on the Y component of the measurements in borehole KB2. Note that only first arrivals of source location less than 2172 were used in the analysis of velocities.

In travel time curves, the first arrival picks align very well to a linear function. The estimated shot time is 4670 ms (note that the time windows were cut 5 s before shot GPS time to allow for a clock difference of several seconds between GPS time and the internal time of the early warning system). As it cannot be derived with certainty, we assume a tolerance of ± 20 ms in the following. The influence of the picked phase and a typical period of 35–40 ms is one reason for uncertainty.

Results and Discussion

Profile 1

The reflection seismic section of Profile 1 (Figure 2a) reveals a strong and undulating reflector at 20–30 m depth. With respect to borehole profiles of KB1 and KB5 (kindly provided by TLUG), we interpret this as a reflection between sandstone and claystone layers. Two depressions are shown between source locations 1020 and 1060 as well as between 1110 and 1170. Several faults can be interpreted. The reflections between 50–70 m depth are less continuous and a strong fracturing is obviously present there.

The resulting velocities derived from the VSP probe data (orange dots in Figure 4) are between 700 m/s and 800 m/s for the western part of the profile (up to source location 1046 approx.), followed by a lowering of the velocity in the intermediate part and values of 500–600 m/s in the eastern part (starting at source location 1060 approx.). A comparison with data of a later study, in which P- and S-waves were excited at the same location, confirmed that the observed first arrivals are most likely S-wave arrivals.

The velocities derived from the receiver in KB1 (blue dots in Figure 4) are between 500 m/s and 700 m/s and are interpreted as S-wave velocities. The behavior of the S-wave velocity along the profile is different: medium velocities of 600–650 m/s in the western part (up to source location 1062) and between source locations 1098 and 1126, higher velocities of 650–700 m/s between source locations 1064 and 1096, and low velocities below 600 m/s in the eastern part (starting at source location 1130). This shows that the travel path and its direction affect the observed velocity. In general, we expect the average velocities derived from KB1 data to be slightly higher than those derived from KB5, because the borehole geophone in KB1 is located deeper and S-wave velocity tends to increase with depth. However, this is only observed for source locations 1058 to 1140.

Figure 5 shows the location of faults interpreted from the seismic sections shown here and further P- and S-wave reflection seismic studies (Schmidt et al., 2013; Wadas et al., 2017) and their dominant strike direction of NW-SE. We observe that travel paths parallel to the fault strike direction coincide with higher velocities and travel paths going through several faults more or less perpendicularly coincide with decreased velocities.

Profile 2

The reflection seismic section of Profile 2 (Figure 3a) shows strong reflections of the sandstone and claystone beddings in the uppermost 20 m. In the southern part of the profile the reflection pattern is more chaotic than in the northern part. Indications of faults and fracturing are present.

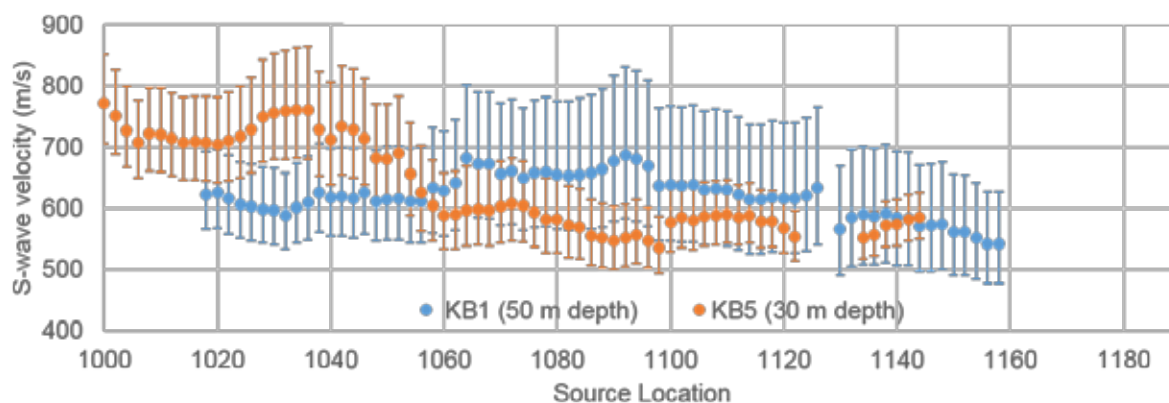


Figure 4. S-wave velocities derived from arrival times recorded by receivers in borehole KB1 (blue) and KB5 (orange) during survey of Profile 1. Error bars shown correspond to estimated inaccuracy of derived shot time of KB1-4 recordings (4670 ± 20 ms) and estimated inaccuracy of time shift applied to arrival times of KB5 recordings (-85 ± 10 ms).

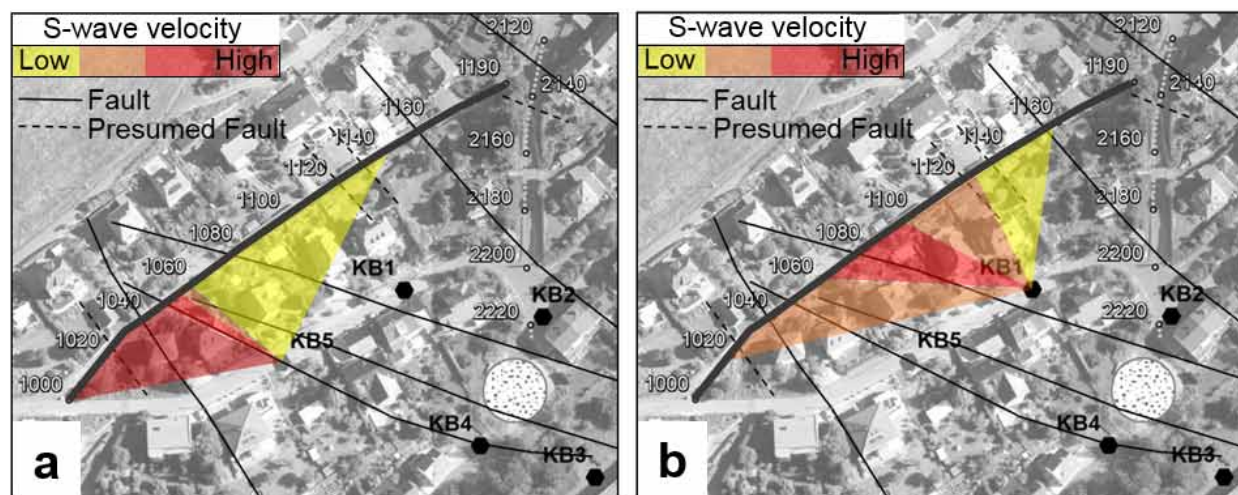


Figure 5. Section of the map shown in Figure 1. Solid lines mark faults interpreted in previous studies, dashed lines mark additional faults interpreted from seismic sections of this study. The colors indicate high and low average S-wave velocities observed using receivers in borehole KB5 (a) and KB1 (b). For velocity values see Figure 4.

The observed average velocities for Profile 2 (Figure 6) are significantly higher compared to those of Profile 1. From this and the comparison with data of a later study, in which P- and S-waves were excited at the same location, we conclude that P-wave first arrivals were picked. We assume that P-waves were directly generated at the source. The P-wave velocities observed at the receiver in borehole KB1 range from 1100 m/s to 1350 m/s and do not show significant changes along the profile. Higher velocities are derived from data of the receiver in borehole KB2. This might be due to inaccuracy dependent on the phase of the wavelet used for picking. The southern part of the profile close to the sinkhole could not be included in the analysis due to strong interfering signals.

Outlook

At this stage, we did not try to invert for tomograms, as the ray coverage is too low. This could be a solution for future studies for improved localization and analysis of low velocity zones. In a subsequent study, we investigate subsurface velocities in more detail by distributing source locations throughout the whole study area and generating SH-, SV- and P-waves. Also, we propose to test the suitability of the described method for time lapse studies. The permanently installed borehole geophones enable a good repeatability and the quality of signal repeatability of the micro-vibrator source is usually high. In the past, offset VSP surveys were successfully applied for the detection of man-made fractures (Stewart et al., 1981; Hardage, 2000) by comparing data of transmitted waves acquired before and after fracturing. The authors

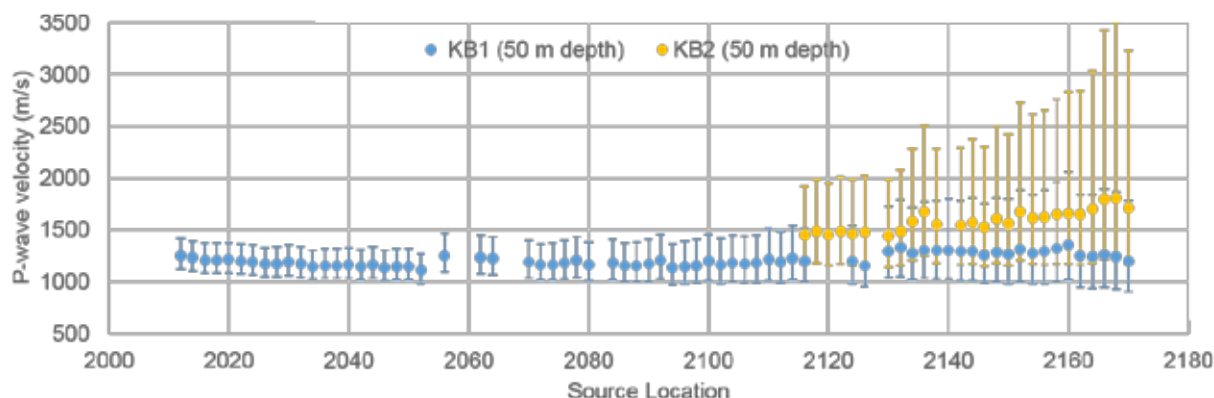


Figure 6. P-wave velocities derived from arrival times recorded by receivers in borehole KB1 (blue) and KB2 (yellow) during survey of Profile 2. Error bars shown correspond to estimated inaccuracy of derived shot time of KB1-4 recordings (4670 ± 20 ms).

observed lowered propagation velocities, amplitude decay, increased scattering and change of S-wave polarization due to the man-made fracturing. This might also be an approach to monitor the evolution of natural fractures and cavities. However, it should be kept in mind, that, in the study area, all permanently installed borehole geophones are located above the actual subsidence horizon. Thus, with this setup it will only be possible to investigate indirect features of subsidence, e.g., increased fracturing on top of cavities, but not the dissolution of rock itself.

Conclusions

We achieved to analyze the velocity of directly arriving P- and S-waves at the borehole geophones closest to the source locations. Although the estimation of absolute velocities involves a remaining uncertainty due to unknown receiver clock difference and the influence of the wavelet phase used for picking of arrival times, the analysis of velocities along the profiles reveals that the average velocity from source to receiver location depends on the travel path and its direction towards the main fault strike direction. If travel paths are perpendicular to several faults, the average velocity is decreased. Travel paths parallel to fault strike directions are less affected resulting in higher average velocity. The described method enables the analysis of velocities in more detail and beyond 2D. The combination of reflection seismic and travel time analysis of borehole sensor data enables to relate velocity anomalies to structural features. It is therefore a useful approach in near-surface and karst related investigations.

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IMAGING OF DEEP SINKHOLES USING THE MULTI-ELECTRODE RESISTIVITY IMPLANT TECHNIQUE (MERIT) CASE STUDIES IN FLORIDA

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Abstract

Surface geophysical methods have been extensively utilized for sinkhole investigations. While surface geophysical methods can penetrate to depth where sinkhole development occurs the resolution is typically poor. A detailed understanding of deep raveling zones into sinkhole throat through a new and novel geophysical technique was developed by the authors.

The authors performed over 750 sinkhole investigations on residential properties over a five year period of time, in each case geophysical methods of Ground Penetrating Radar (GPR) or Electrical Resistivity (ER) were performed. Over 1500 confirmatory Standard Penetration Test (SPT) drillings were performed of the geophysical anomalies. In a very large percentage of the geophysical surveys performed, the location, size and depth of the raveling zones into the sinkhole throat could be clearly identified.

The authors developed a novel geophysical technique called The Multi-Electrode Resistivity Implant (MERIT) to address the need to image deeper into karst formations to help identify the location of deep raveling zones and sinkhole throats. The purpose of this paper is to present case studies of the application of MERIT technology. Three case studies are presented in this paper.

The first case study focuses on the first application of MERIT at the Bordeaux Village in Tampa, Florida where a sinkhole swallowed a car in 2010. The MERIT survey was able to image the car in the sinkhole throat. This case study demonstrates the ability of the MERIT technique to identify the location of the sinkhole throat by identifying the depth and location of the car, a large conductive ER anomaly.

The second case study focuses on a pipeline in Orlando, Florida being threatened by sinkhole development on

the adjacent property. MERIT was able to identify size and depth of raveling of soils into the sinkhole throat near the pipeline. The results of the MERIT image were critical in engineering design to address the treatment to the pipeline.

In the third case study MERIT technology was applied to a proposed roadway through an extensive karst region of Lake County, Florida. Initial geotechnical investigation indicated a potentially large and deep sinkhole feature. MERIT was able to provide a concise geologic structure including the identification of the locations sinkhole throat at 52 m deep.

MERIT has been shown to identify details of the complex geology and geometry of karst formations. In particular the techniques ability to provide improved image capabilities of the raveling zone and sinkhole throats has significant engineering applications for assessment, risk analysis, and remediation of sinkholes.

Introduction

Multi-Electrode Resistivity Implant Technique (MERIT) is a technique that utilizes a tomographic configuration (Figure 1) that combines measurements with surface and deep electrodes that improve geophysical surveys using electrical resistivity (Harro & Kruse, 2013).

The tomographic arrangement of electrical resistivity data required new algorithms the development of new optimal array geometries and extensive laboratory and field research (Loke et al., 2015). The buried arrays are identical in length and electrode spacing as the surface array creating a mirror image in the subsurface. The tomographic configuration creates a vertical stacking of the electrical resistivity data resulting in the ability to reduce the survey length, increase penetration and increase image resolution at depth. MERIT has been shown to significantly improve resolution over

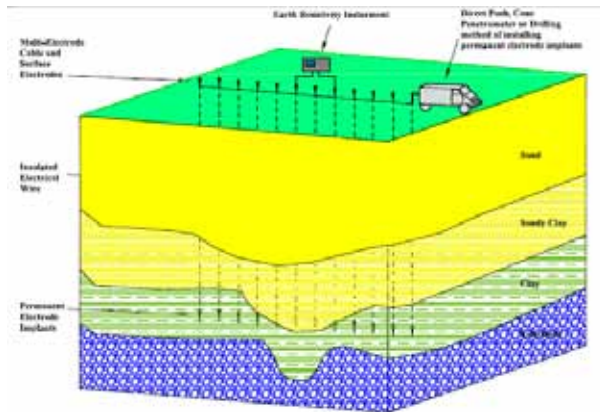


Figure 1. Deployment of implants for MERIT, note tomographic configuration of identical spaced surface and lower arrays.

basic arrays adapted from traditional 2D ER surface geometries (Kiflu et al., 2016).

Three case studies are used to illustrate the benefits of the MERIT technique. While all case studies represent cover-collapse conditions in west central Florida, each case study has some unique conditions that include surface limitations, buried utilities/infrastructure and changes in depth of targets. These case studies include:

- Revisit to the Bordeaux Village apartment complex in Tampa, Florida where the full scale trial of the MERIT technique was deployed. Measurements were repeated in the same area with improved array geometries and processing algorithms.
- A large sinkhole and area of subsidence developed on residential property on Salmon Drive in Orlando, Florida. The area of subsidence covered a 60 m radius that extended off the property toward the Florida Turnpike impacting the sound barrier and two lanes of the highway.
- A relic sinkhole in Lake County, Florida along a proposed Wekiva parkway

Case Study – Revisit Bordeaux Apartments Tampa, Florida

The Bordeaux Village apartments in Tampa, Florida received national news coverage in July 2010 after a car in the parking lot was swallowed by a 6 m diameter cover collapse sinkhole (Figure 2).

The MERIT first full scale field trial was performed to help identify the potential geometry of the sinkhole in



Figure 2. Bordeaux Apartments sinkhole, Tampa, FL, aerial photo showing car being swallowed by a sinkhole.

2012. The Bordeaux Village apartments were revisited with improved array geometries and algorithms.

The second set of data was acquired using the original MERIT survey configuration that comprised 18 surface electrodes and 18 implant locations at 3 m spacing adjacent to the location of the sinkhole. The MERIT implants were positioned at a depth of 9 m and were in contact with Hawthorn Formation clays and clayey sands and were within 3 m of the average depth of the top of rock (Harro & Kruse, 2013).

The MERIT survey data were collected using an AGI super sting resistivity instrument and was inverted using Res2Dinv software from Geotomo, Inc. The MERIT image shown in the Figure 4 profile details an upper sand unit that is resistive (red) that overlies conductive Hawthorne Formation sandy clay grading to clay that is conductive (blue), which in turn overlies the resistive (red) limestone formation. From the MERIT image vertical variations in limestone layers as well as the sinkhole throat can be seen.

The original investigation included two SPT and their locations are shown in Figure 3. The SPT encountered fine sand to 4 m, after which sandy clay to clay ranging in thickness from 3 to 6 m thick was recorded overlying the top of the limestone at depths between 10 m and 13 m with competent limestone starting at 15 m.

In the MERIT image the upper resistive unit (sand) has an average depth of 4 m. The conductive unit (sandy clay to clay) below this has an average thickness of 6 m. The top limestone (resistive) in the MERIT image can be seen at an average depth of 12 m.

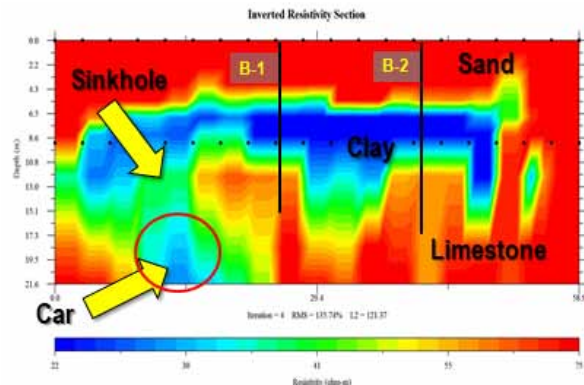


Figure 3. MERIT image showing a highly conductive anomaly inside the sinkhole throat. The location of the sinkhole and car was verified by measurements taken during the initial sinkhole collapse.

The depth position of the car was measured before it disappeared into the sinkhole. The car was vertically positioned, measuring 4 m in length and was last seen at a depth of 6 m in the sinkhole. In the MERIT image a highly conductive anomaly appears at 17 to 21 meters inside the sinkhole throat. The conductive anomaly is aligned with the last known position of the car.

Case Study Sinkhole Florida Turnpike

A large sinkhole developed on a residential property located on Salmon Drive in Orlando, Florida. The sinkhole feature was located on the eastern side of the residential property adjacent to the Florida Turnpike (Figure 4).

After the sinkhole development, a 60 m radius affected area extended from the sinkhole on the residential property and impacted two of the southbound lanes of the Florida Turnpike. Significant signs of ground subsidence included slumping of the two lanes and up to 15 cm of differential movement of the sound barrier. A section of a pressurized reclaimed water transmission main is located in the area of ground subsidence.



Figure 4. Location of the MERIT survey, pipeline, and sinkhole on the adjacent property.

Concerns that the sinkhole could pose a potential risk to the pipeline prompted the geotechnical investigation, and a geophysical survey using MERIT was requested. The MERIT geophysical survey consisted of 28 surface and 28 implanted electrodes over 165 m (540 feet). Implants were positioned at a depth of 15 m (50 feet) in order to obtain a depth of 45 m (150 feet).

The results of the MERIT geophysical survey of Line 1 identified a distinct geophysical anomaly located in the subsurface between 54 m (180 feet) and 85 m (280 feet) (Figure 5). The anomaly was located within the area of the highest concentration of distress/ground subsidence observed on the roadway and the sound barriers as well as being adjacent to the corresponding sinkhole development on the adjacent property.

The geophysical anomaly identified suggests that the sand unit has in the past or has recently moved downward and laterally into the underlying clay unit in the direction of the sinkhole. This would correspond with the sinkhole development type called cover-collapse. Cover-collapse sinkhole formation occurs when the underlying limestone is covered by a significant layer of clay. Dissolution of the limestone creates a void in the clay which will eventually collapse. If the clay has significant amounts of sand material covering it, the sand will infiltrate the voids created.

Three SPT borings were performed by the geotechnical consultant along a profile in the affected area prior to the implementation of the MERIT survey. SPT borings encountered sands grading to more silty sands to a depth of 24 m (78 feet) transitioning to sandy silty clay to silty clay to depths of 40 m (130 feet). No limestone was encountered in the borings.

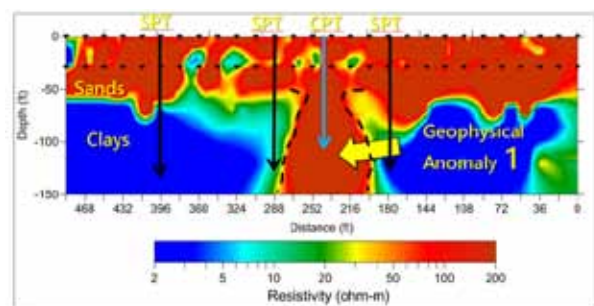


Figure 5. MERIT image shows vertical raveling of sands downward into clay unit. SPT were performed before the MERIT image and the CPT was performed after.

The results of MERIT shows the initial SPT borings did not intersect the area of concern. After the MERIT survey was performed it was determined a CPT should be performed in the anomalous area. The results of the CPT did indicate loose soils but not direct sinkhole conditions. Therefore based on the location of testing and the distress to the surrounding area, the MERIT geophysical anomaly most likely represented lateral movement of the upper sand unit into the sinkhole to the west.

Additional MERIT Line 2 was performed along the sound barrier adjacent to the sinkhole. The results of the MERIT Line 2 could not be verified by drilling due to physical constraints.

Based on the results of MERIT the risk to the pipeline was evaluated as to be enough potential to redesign the pipe line by constructing a bridge for the pipeline over the length of area of 21 m identified by the MERIT geophysical survey.

Case Study Wekiva Parkway CR46A

A new roadway was to be established by the Florida Department of Transportation (FDOT) in Lake County, Florida called CR46A or the Wekiva Parkway. The area of the road is well known to have karst geology. A review of aerial photographs along the alignment identified several potential karst features. These were investigated by the FDOT geotechnical consultant. After the initial SPT boring was completed in the area (referred to as site B) it was determined the potential large relic sinkhole was present (Figure 6).

A preliminary geotechnical investigation was conducted by others at Site B which included: GPR and in total the drilling of 26 SPTs and CPTs to better define the depth and extent of the relic sinkhole. SPT boring R-1 performed in the alignment encountered loose to medium dense fine sand to fine sand with silt to a depths of 8.5 m (28 feet); followed by a layer of loose to medium dense mucky fine sand to a depth of 13 m (43 feet); underlain by very loose to loose silty sand to clayey sand to a depth of 25 m (85 feet); followed by medium dense to very dense limestone to the boring termination depth of 45 m (150 feet) below existing ground surface. Drilling fluid circulation loss occurred at depths between 21 m (70 feet) and 41 m (135 feet).

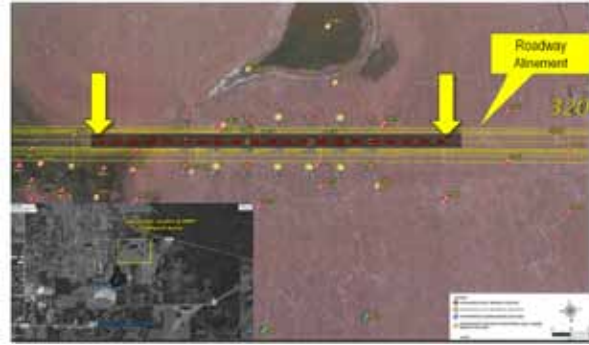


Figure 6. Google Earth image showing the alignment of new roadway CR46A and the location of the MERIT geophysical survey as well as SPTs and CPTs.

The MERIT geophysical survey was recommended after the geotechnical results indicated the size of the depth of the relic sinkhole required greater understanding.

Based on the geotechnical investigation performed by a consultant and the FDOT, the limestone formation was encountered at depths between 18 m and 45 m. The high degree of variability of the limestone formation encountered in the geotechnical investigation identified the potential for karst or sinkhole conditions that are considered to be a concern for this project. The application of the MERIT techniques' abilities to provide deep geophysical images was deemed beneficial to the project.

A complete profile across the relic sinkhole was performed using 28 surface electrodes and 28 implants over a 165 m linear distance at 6 m spacing. The implants were installed to an average depth of 14 m bls. Based on the subsurface geometry, MERIT data collection took over 5 hours to complete and encompassed over 3000 data points (Figure 7).

The MERIT survey of the sinkhole clearly identified the sinkhole throat of 52 m with a span of 45 m. The throat can be seen along the profile length between 120 and 300 foot intervals. Adjacent to the sinkhole throat is highly resistive and competent limestone Stratum 4 (red) of varying geometry along the profile between 0 to 37 m and on the other side of the sinkhole throat at 91 m to 152 m. A large section of weathered limestone (Stratum 3) can be seen as the greenish area between 85 m and 165 m extending upward to nearly 15 m. Of note is where CPT was performed to 45 m at profile distance 134 m, through a void in Stratum 3 material. Stratum 2 is comprised of

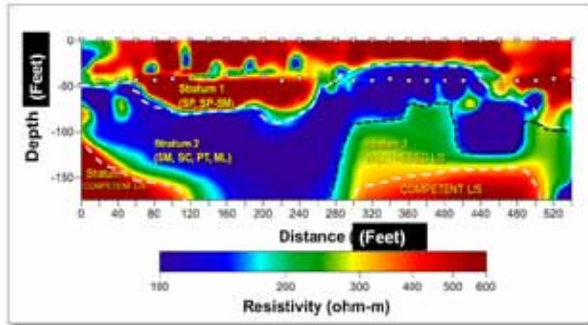


Figure 7. MERIT image showing geometry, and the sinkhole throat at 170 as well as a depressive area in the upper (resistive) sand unit into the conductive unit of material that infilled the sinkhole.

conductive material silts, clays, and organics that are associated with material that infilled the sinkhole after initial collapse. This conductive material provides a sharp contrast to the resistive sand and limestone to help define the geometry of the sinkhole. Overlying are the highly resistive sands of Stratum 1. Of special note is the depression located in Stratum 1 between 15 m and 73 m along the profile. This suggests a reactivation of the sinkhole resulting in the Stratum 2 material that was filled in by sands of Stratum 1. CPT testing in the area of the depression clearly showed a significant reduction in tip pressure located at the Stratum 1/ Stratum 2 boundary, and the SPT confirmed the thickness and boundary of the depression as well.

The results of the MERIT profile indicated a very good correlation with SPT and CPT data obtained during the geotechnical investigation. A comparison of deep SPT borings indicated similar depths of all strata as the MERIT profile.

The CPT results taken along the center line were compared with the results of MERIT along the primary line. There is a good correlation between the MERIT Stratum boundaries and the results of the CPT's soil behavior type and noticeable changes in tip resistance.

Conclusion

The case studies presented here are intended to provide a general understanding and view of the potential of implant technology for geophysical surveys, especially in regions of karst. While the MERIT technique is minimally invasive and requires more investment in time and cost, the results are significantly improved over surface geophysical methods. The ability to clearly

identify sinkhole geometry, geology, raveling zones and potentially the locations of the throat at depths of over 30 m (100 feet) can lead to much greater understanding or engineering applications of risk analysis, monitoring and remediation of sinkholes. If we are to gain a greater understanding of the enigmatic geology we call "karst", implant technology such as MERIT can lead the way to increase our understanding which will result in better decision-making.

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AVOIDING CAVERNS IN THE ARBUCKLE MOUNTAINS USING ELECTRICAL IMAGING METHODS

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Abstract

The Arbuckle Mountains in Oklahoma are a unique province with nearly vertical dipping beds of the Upper Cambrian to Lower Ordovician Arbuckle Group. The Arbuckle Group consists of intercalated sequences of thick carbonates and thinner shales and sandstones. Syn-Pennsylvanian mountain building steeply tilted these beds. Subsequently, caves and voids developed within the carbonate beds, presumably by hypogene speleogenesis.

Numerous dissolution cavities and several major cave systems have been mapped within the Arbuckle Mountain Wind Farm located 19 km north of Ardmore, Oklahoma. Electrical resistivity imaging was determined to be the most effective method of mapping subsurface voids and caverns due to the strong electrical contrast between carbonate units and void-filling sediments and groundwater.

Electrical resistivity imaging during early stages of the wind farm development identified numerous caverns and voids beneath proposed turbine sites; consequently, several wind tower locations were moved. This report addresses the East Access Road to six proposed turbine wind tower sites where three towers and access road near the towers were relocated south of their original proposed locations. Further, the Main Access Road to these six tower sites had to be rerouted due to the presence of two previously unidentified sinkholes and a major cavern system, the Wild Woman Cave Complex.

Electrical imaging method identified subsurface anomalies along the proposed access roads and at four of the six towers. The towers were moved away from the subsurface anomalies and the access roads were relocated to positions where subsurface anomalies would not pose a hazard to the heavy crawler cranes, used to erect the towers. The 50-tower Anadarko Mountain Wind Farm was successfully completed in 2016.

Introduction

Oklahoma ranks 8th for wind energy potential and maintains over 2,000 wind turbines in over 27 wind

farms. As of 2016, Oklahoma has 3,134 megawatts of installed wind capacity (AWEA, 2017). Monies (2017) reported that as of 2017, Oklahoma had 6,600 megawatts of wind power that supply one quarter of Oklahoma's generated electricity.

The permitting process for a wind farm provides limited tower relocation potential without an extensive repermitting process; however, most permits provide for some limited relocation of a tower within an approximately 30 m radius of the tower without going through the repermitting process. Wind turbine towers consist, from the ground up, of the foundation, stalk, nacelle, and rotor blades. The foundation, in general, is a 15 m wide by 3 m deep steel-reinforced concrete subsurface slab. Unstable foundations can cause the towers to topple so the location of a stable foundation is critical to the installation of a tower.

The wind turbine towers are erected by crawler cranes that are slow (1.4 km/hr), 187 m tall, and very heavy with a ballast weight of approximately 600 t (Liebherr, 2017). Crawler cranes are erected at a staging area and crawl to the individual towers for construction of the wind turbine towers. Further, crawler cranes due to their height can only tip up to 5° from vertical before catastrophic collapse. Consequently, the road upon which the crane travels must be stable.

Areas with poor agricultural potential create ideal opportunities for wind power development, since the land is often remote and underutilized. One of these areas is located in the southern portion of the Arbuckle Mountains, eponymously named after General Matthew Arbuckle (1778–1851). The 6,000-hectare Arbuckle Mountain Wind Farm consists of 50 wind turbine generators that can produce 100 MW of electricity. Construction of the wind farm was challenging due to the presence of karst topography within the steeply dipping beds of limestone and dolostone sediments (Figure 1).

Caverns and passages at the site have been mapped by various grotto groups for decades and provided a useful characterization of the subsurface anomalies in the study area. For example, Harrel (1959) published a detailed cave map of Wild Woman Cave (Figure 2).

Geology

Arbuckle Mountain Wind Farm is situated in the western portion of the Arbuckle Mountains of south central Oklahoma (Figure 1). This portion of the Arbuckle Mountains is noted for having karst topography. The rock units consist predominantly of limestone, dolomite and rhyolite, with minor amounts of shale and sandstone. The carbonate units are characterized by having sinkholes, dolines, and caverns.

The rocks in this portion of the Arbuckle Mountains are part of the Arbuckle anticline and are contiguous with a south-dipping thrust fault, the Washita Valley Fault Zone (Johnson, 1990). The sediments at the wind farm site strike N45°W and dip up to 45°SW. Deformation or mountain building occurred during the Middle Pennsylvanian time and ended during the Late Pennsylvanian as flat-lying upper Pennsylvanian and Permian rocks overly the steeply inclined lower Pennsylvanian rocks in other areas nearby.

The predominant rocks of interest at the site are the karst-forming limestones and dolostones. These carbonate rocks are estimated to be many thousands of feet thick (Ham, 1973). Surficial karst features observed in the field consisted of solution weathered vugs, bedding plane fractures, and voids.

Three geological groups lie within the footprint of the Arbuckle Wind Project. They are listed in order of decreasing age: middle Cambrian Colbert Rhyolite; upper Cambrian/lower Ordovician Arbuckle Group; and middle Ordovician Simpson Group.

The Colbert Rhyolite, located in the northern portion of wind farm, is a "...pink porphyritic rhyolite, locally flow-banded..." (Ham, 1951).

The Arbuckle Group contains 8 Formations, the Fort Sill Limestone, Royer Dolomite, Signal Mountain Formation, Butterfly Dolomite, McKenzie Hill Formation, Cook Creek Formation, Kindblade Formation, and the West Spring Creek Formation. These formations are composed of limestone and dolomite with a maximum thickness of 2,000 m in the Arbuckle Mountain region (Ham, 1973). Thin sandstone beds are present within the

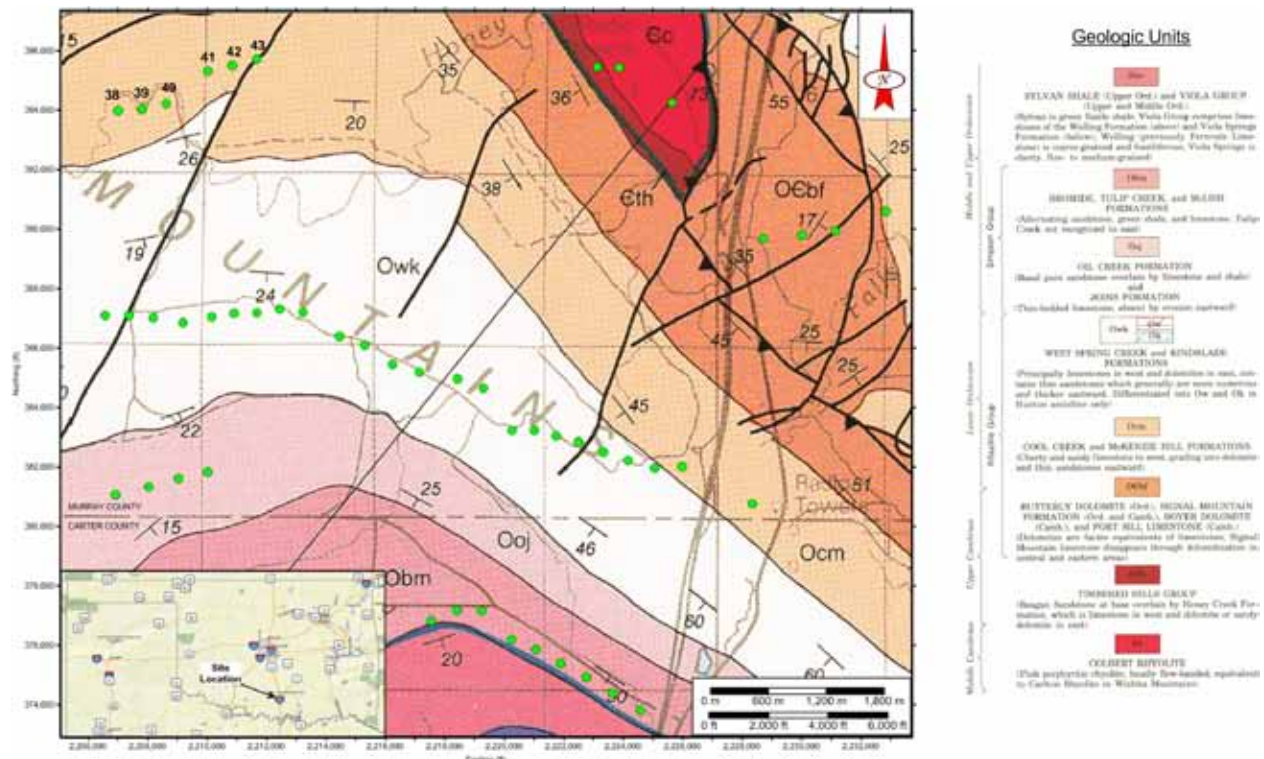


Figure 1. Geologic map of the western portion of the Arbuckle Mountains showing the locations of proposed wind turbine towers (green dots) to the Arbuckle Mountain Wind Farm (Johnson, 1990).

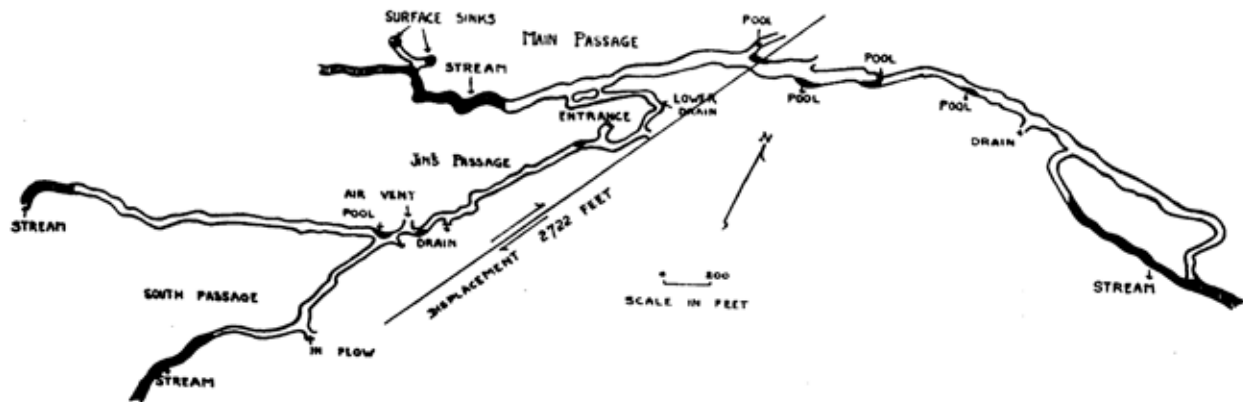


Figure 2. Subsurface plan map of Wild Woman Cave, Arbuckle Mountains (Harrel, 1959).

West Spring and Cool Creek Formations and cherty and sandy limestone is found throughout the Cool Creek and McKenzie Hill Formations.

The Simpson Group contains 5 Formations, the Joins, Oil Creek, McLish, Tulip Creek, and Bromide Formations. These units have a maximum thickness of 700 m in the Arbuckle Mountain region and are mainly comprised of limestone and dolomites with basal sandstones and minor amounts of shale (Ham, 1973).

During the formation of dolomite the net rock volume of limestone decreases leaving voids and vugs that can induce further dissolution. Klimchouk (2007; 2014) documents hypogene speleogenesis, or vertically upward migration of groundwater during the course of depositional history, as a mechanism for the creation of karst topography. Eschberger (2012) and Eschberger et al. (2014) noted hydrothermal intrusion during the Cambrian. Remanent magnetization of ferro-magnesium minerals during Pennsylvanian–Permian deformation has been attributed to the percolation of orogenic fluids through the carbonate units (Nick and Elmore, 1990). Sykes (1997) documented active basinal fluids during the Arbuckle and Laramide orogenies. Vertically upward flushing has continued to the present (for example, see Puckett, 2009; and Christensen et al., 2011). Blackwood (2017) and Blackwood et al. (2015) argued successfully that hypogenic flow created or initiated the dissolution processes, or speleogenesis, within the Arbuckle Mountains.

Theory and Methods

Electrical resistance is based upon Ohm's Law:

$$R = V/I$$

Where, resistance, R (Ohms), is equal to the ratio of potential, V (volts), to current flow, I (amperes). Resistivity, then, is a measure of the resistance (ρ) along a linear distance (L) of a material with a known cross-sectional area (A).

$$R = \rho L / A;$$

where

$$\rho = \frac{V \cdot A}{I \cdot L}$$

Consequently, resistivity is measured in Ohm-meters and the data can be presented as a geo-electrical profile of modeled apparent resistivity versus depth.

Electrical currents propagate as a function of three material properties: (1) ohmic conductivity, (2) electrolytic conductivity, and (3) dielectric conductivity. Ohmic conductivity is a property exhibited by metals (Kaufman, 1992). Electrolytic conductivity is a function of the concentration of total dissolved solids and salts in the groundwater that exists in the pore spaces of a material (Reynolds, 1997). Dielectric conductivity is a function of the permittivity of the matrix of the material (von Hippel, 1954). Therefore, the matrix of most soil and bedrock is highly resistive. Of these three properties, electrolytic conductivity is the dominant material characteristic that influences the apparent resistivity values collected by this method (Milsom, 1989).

In general, resistivity values decrease in water-bearing rocks and soil with increasing: fractional volume of the rock occupied by groundwater; total dissolved solid and chloride content of the groundwater; permeability of the pore spaces; and, temperature.

Materials with minimal primary pore space (i.e., limestone, granite) or lack groundwater in the pore

spaces will exhibit high resistivity values (Mooney, 1984). Highly porous, moist or saturated soil, such as fat clays, will exhibit very low resistivity values.

In homogeneous ground, the apparent resistivity is the true ground resistivity; however, in heterogeneous ground, the apparent resistivity represents a weighted average of all formations through which the current passes (Mooney, 1984). Many electrode placements (arrays) have been proposed (for examples, see Reynolds, 1997), including the most commonly deployed Wenner, Schlumberger, and dipole-dipole array. Two survey arrays, dipole-dipole and Schlumberger, were collected for each tomograph.

The Schlumberger array has proven to be an effective configuration for imaging the subsurface:

$$Ri = \pi a^2/b[1 - b^2/4 a^2] R; a = 5b$$

Where, resistivity (R_i) is related the separation distance between the current source and current sink (b), and the pole spacing, (a).

The dipole-dipole array collects a denser, deeper portion of the subsurface, and combined with the Schlumberger array, provides data for the construction of a detailed geo-electric profile. Dipole-dipole configuration is:

$$R = \pi a n(n + 1)(n + 2)$$

A forward modeling subroutine was used to calculate the apparent resistivity values for dipole-dipole and Schlumberger data sets, after which the data sets were combined using the EarthImager program (AGI, 2002). This program is based on the smoothness-constrained least-squares method (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). The smoothness-constrained least-squares method is based upon the following equation:

$$J^T g = (J^T J + \mu F) d$$

Where, F is a function of the horizontal and vertical flatness filter (J) is the matrix of partial derivatives, μ is the damping factor, d is the model perturbation vector and g is the discrepancy vector.

The EarthImager program divides the subsurface 2-D space into a number of rectangular blocks. Resistivities

of each block are then calculated to produce an apparent resistivity pseudosection. The pseudosection is compared to the actual measurements for consistency. A measure of the difference is given by the root-mean-squared (rms) error.

Discussion

Since air (i.e., voids) and carbonate rock have very high apparent resistivity values it is difficult to distinguish between the two. Fortunately, most of the voids at the site, or at least those we could identify, contained clay and/or water; both of which have very low apparent resistivity values. For this site then, low apparent resistivity values and inversions (i.e., resistive material overlying conductive material) are considered to be indicators of weak rock conditions at depth with the possibility of the presence of vuggy subsurface conditions or voids.

Initially, paired electrical imaging profiles were collected at all 50 tower sites, which included (at the client's request) the three sites located on the Colbert Rhyolite (Figure 1). The possibility of a void in the Colbert, however, is remote and no subsurface anomalies were detected. The survey consisted of a pair of 69 m long lines set at right angles to each other. Each profile was centered at the staked locations of the proposed tower and imaged the subsurface geo-electric stratigraphy to a depth of approximately 18 m below grade.

Eighteen sites were determined to have potential subsurface anomalies (Table 1). All were relocated away from the subsurface anomalies and the new locations drilled to insure stable subsurface conditions. However, during this work, it was noted that the Main Access Road to Towers 38 through 43 crossed Wild Woman Cave Complex (Figure 3). This report documents the additional work that was performed to relocate the Main Access, East Access, and West Access Roads (Figures 4, 5, 6, and 7).

During the course of imaging the foundations at towers 38 through 43, several subsurface anomalies were noted (Table 1). Further, this area was considered to be a potential hazard for the crane. Profile 1 and 1A through 1F; Profiles 2A and 2B; and Profiles 3A and 3B were collected to assess the potential hazard to the heavy crane along the East and West Access Roads (Figures 4, 5, and 6, respectively).

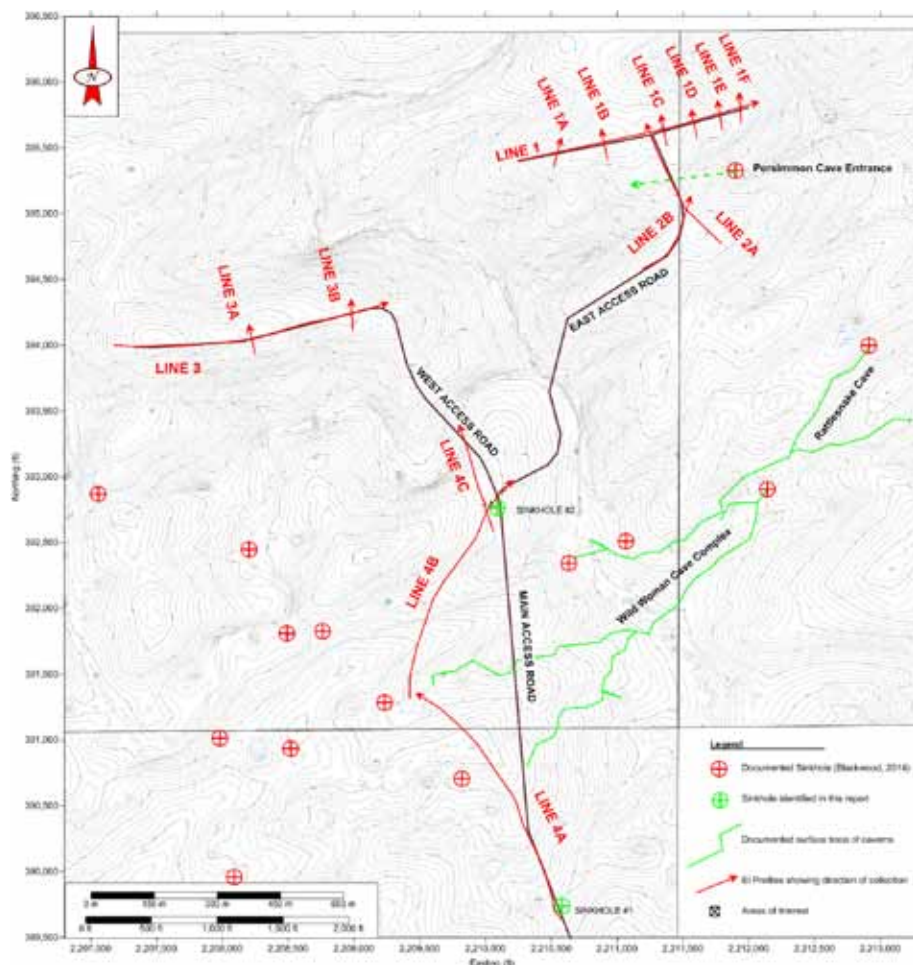
Turbine	Formation
16	West Spring and Kindblade
17	
22	
26	
27	
28	
29	
30	
31	
33	
40	Cool Creek and McKenzie Hill
41	
42	
43	
50	
47	Butterly, Signal Mountain, Royer & Fort Sill
48	
49	

Table 1. Table of towers with EI identified anomalies.

From the previous study, subsurface anomalies were noted at Towers 41, 42, and 43 (Table 1). Profile 1 and cross lines 1A through 1F show the presence of numerous subsurface anomalies along the proposed crane path (Figure 4). Due to the potential risk to the towers and crane, Towers 41, 42, and 43 and the portion of the East Access Road between the towers were relocated approximately 20 m to the south (Figure 8).

The southern portion of the East Access Road was inferred to cross Persimmon Cave. Two profiles; Profile 2A and 2B, were collected in the area to determine if any subsurface anomalies existed (Figure 5). Persimmon Cave is inferred to exist at depth at position 460 ft (140 m) on Profile 2A. There is approximately 8 m of interpreted hard rock overlying the inferred cave (Figure 5). Due to the interpreted size and depth of the cave, the proposed location of the East Access Road that crossed over the inferred location of Persimmon Cave was not interpreted to be a hazard to the crane and the road was not relocated (Figure 8).

Figure 3. Topographic map (contour interval 2 feet; 0.6 m) showing the originally proposed roads and the electrical imaging profile locations. The location of the Wild Woman Complex is from Curtis (1959) and the sinkhole locations are from Blackwood (2014). Location of Persimmon Cave is approximated and is not based upon real information. Map scale is set to Oklahoma State plane coordinate system, NAD 1983, in feet.



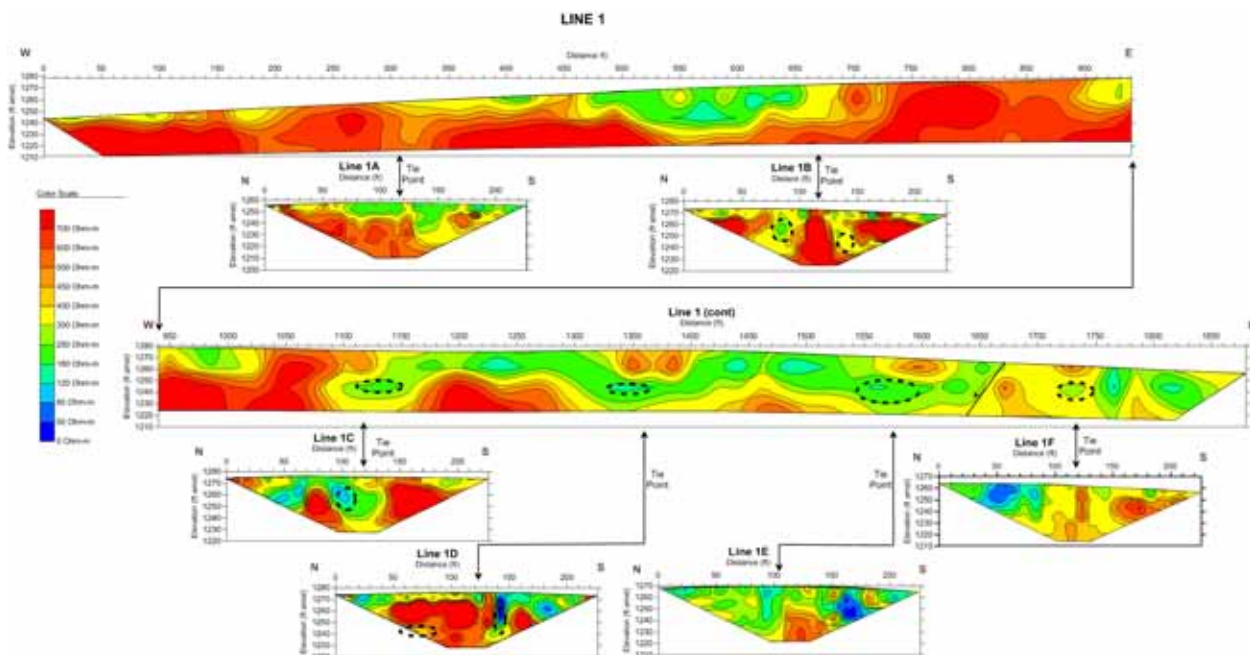


Figure 4. Profile Line 1 and cross Profile Lines 1A through 1F. Color scale shown is used on all figures but only reproduced here. Profiles have no vertical exaggeration. Subsurface anomalies are noted with dashed black ovals.

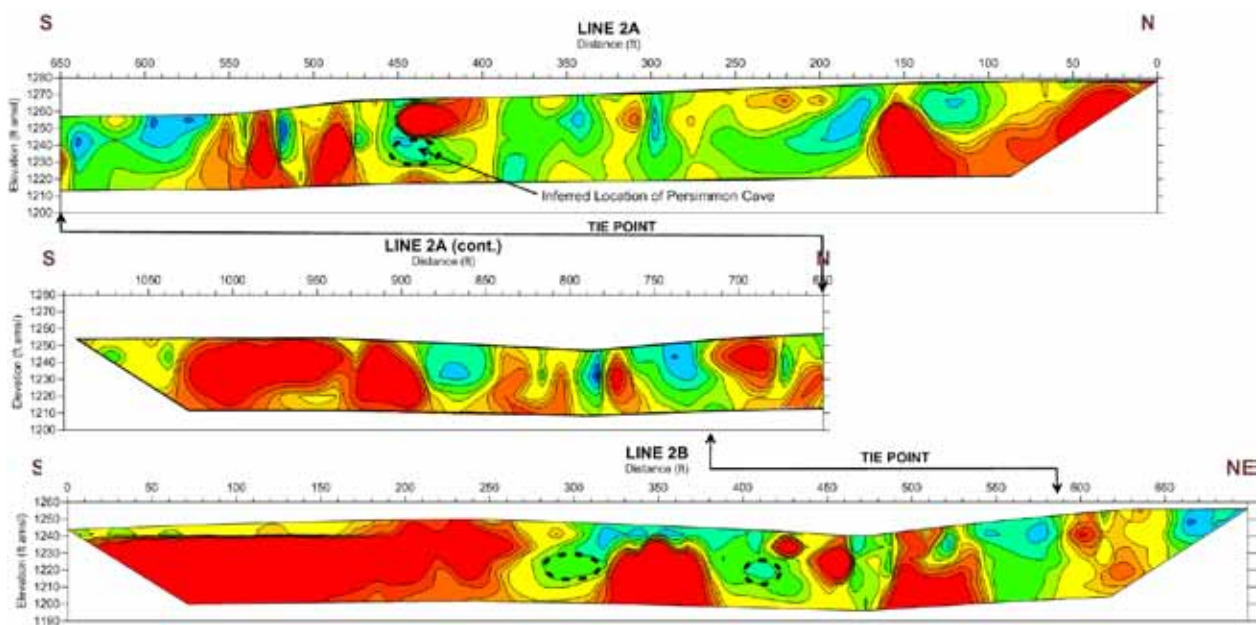


Figure 5. Profile Line 2A and 2B. Color scale from Figure 4. Profiles have no vertical exaggeration. Subsurface anomalies are noted with dashed circular black lines.

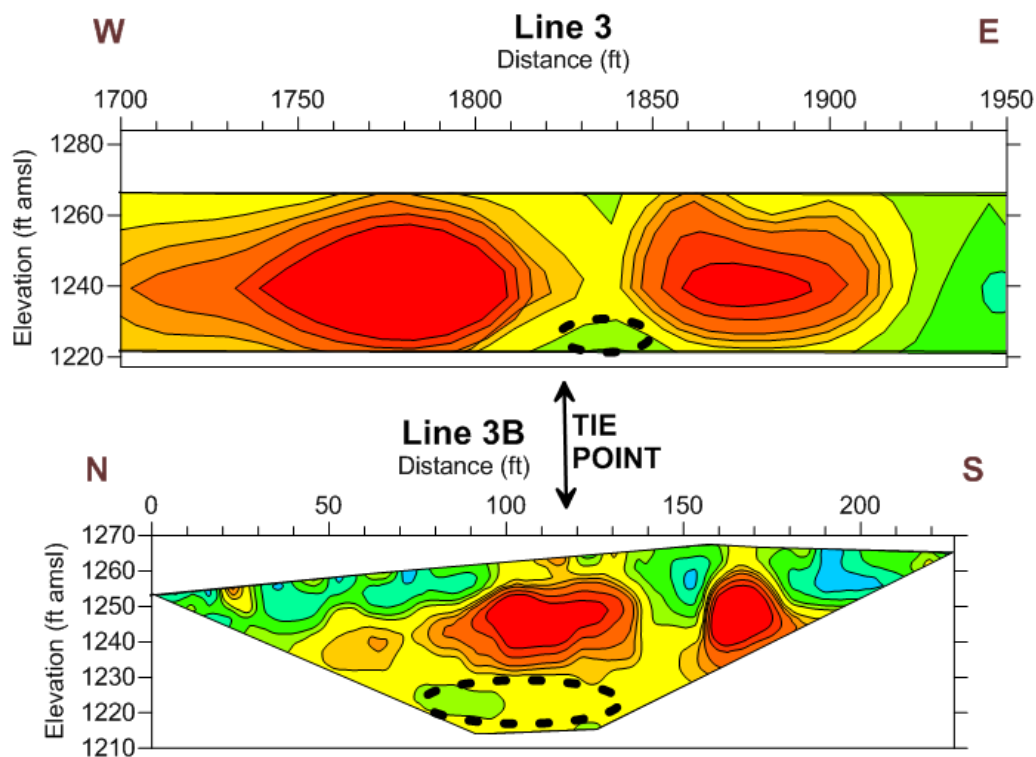


Figure 6. A portion of Profile Line 3 and all of Profile Line 3B. Color scale from Figure 4. Profiles have no vertical exaggeration. Subsurface anomalies are noted with dashed circular black lines.

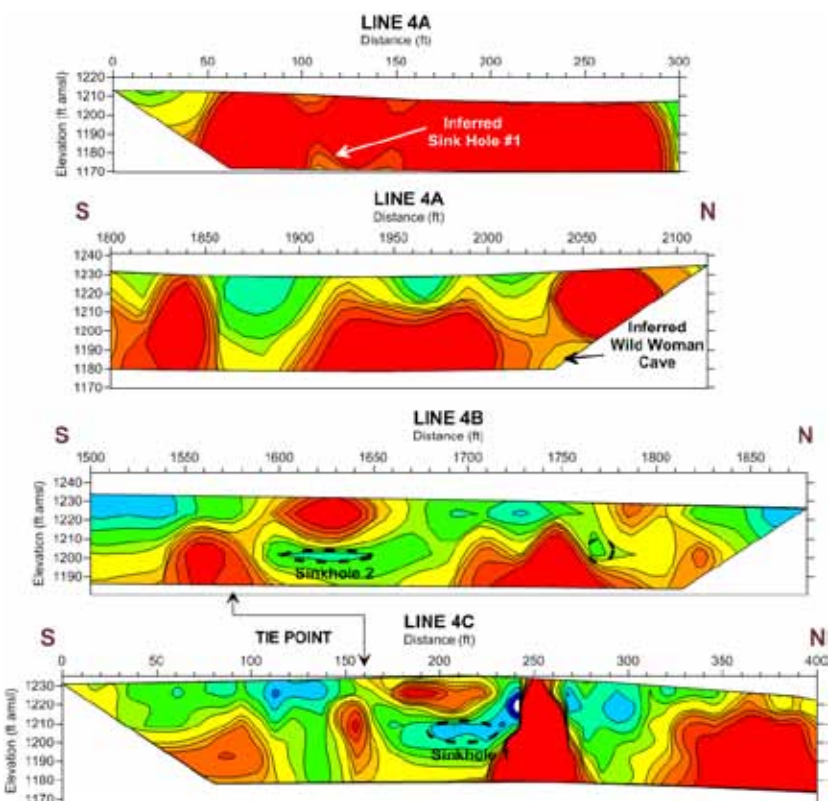


Figure 7. Portion of Profile Line 4A, 4B, and 4C. Color scale from Figure 4. Profiles have no vertical exaggeration. Subsurface anomalies are noted with dashed circular black lines.

Further south along the East Access Road to Towers 41 through 43, two subsurface anomalies were determined to be enough of a hazard to warrant relocation of the crane path (Figures 5 and 8). The crane path was moved 6 to 10 m southeast of the proposed path to avoid any subsurface issues (Figure 8).

The West Access Road to Towers 38 through 40 showed only one subsurface anomaly at a depth of 10 m below

grade (Figure 6). Due to its interpreted size and depth, this anomaly was not considered to be a hazard to the crane. It should be noted that Tower 40 was moved 10 m to the west to avoid a subsurface anomaly.

The Main Access Road to the six towers crossed portions of Wild Woman Cave Complex, that necessitated the relocation of the road (Figure 3). At the southern end of the road, Sinkhole #1 was discovered along the proposed

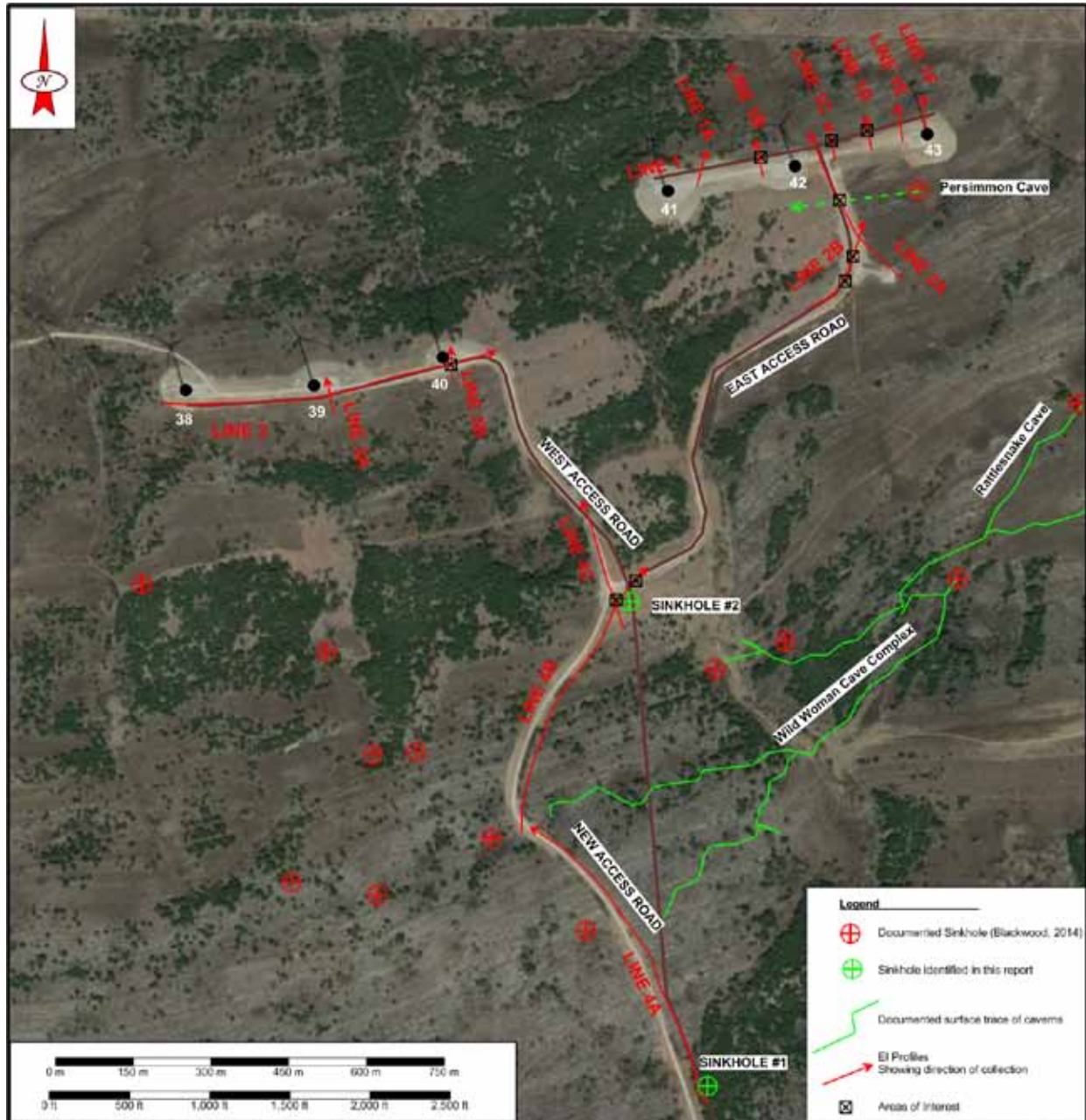


Figure 8. Aerial map of Anadarko Mountain Wind Farm showing tower locations (black dots) and as-built access roads (Google Earth, 2017).

road. Profile 4A at position 115 ft (35 m) shows an anomaly inferred to be this sinkhole (Figure 7). Profile 4A may have imaged Wild Woman Cave (position 2,050 ft; 630 m) at a depth of approximately 14 m below grade. Further, Profile 4B and 4C imaged Sinkhole #2 at a depth of approximately 8 m below grade. A small anomaly interpreted to be a cavern is located on Profile 4B at position 1,770 ft (540 m).

Wild Woman Cave was not considered to be a hazard to the crane as the cave was interpreted to be located at a depth too deep to impact the crane. The Main Access Road, now termed the New Access Road, was rerouted around Sinkhole #2. Further, the interpreted anomaly at the end of Profile 4B was interpreted to pose a hazard to the crane and the beginning of the East Access Road was moved north approximately 10 m to avoid the void.

The wind farm was installed successfully without any delays or problems. Consequently, electrical imaging methods are an effective method of identifying subsurface anomalies that pose a risk to engineered facilities.

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SINKHOLES AS TRANSPORTATION AND INFRASTRUCTURE GEOHAZARDS IN MIXED EVAPORITE-SILICICLASTIC BEDROCK, SOUTHEASTERN NEW MEXICO

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Abstract

Personnel with the National Cave and Karst Research Institute and the New Mexico Bureau of Geology and Mineral Resources conducted an assessment of karst geohazards southeast of Carlsbad, New Mexico, USA. The US Highway 285 corridor in this area is subject to high levels of oilfield traffic, and is particularly prone to sinkholes because of the presence of gypsum bedrock of the Rustler Formation at or near the surface throughout much of the study area. These features pose a geohazard for the transportation and pipeline network in this part of the state. The geotechnical properties of the Rustler Formation are influenced by soluble gypsum strata interbedded with mechanically weak mudstone and siltstone and more rigid dolomite beds. Surface geologic mapping and near-surface electrical resistivity (ER) surveys indicate that most sinkholes formed in the Rustler are relatively shallow (<3 m), without deep roots, probably due to the mixed lithology of soluble and insoluble bedrock. However, longer-array ER surveys have identified additional cavities at greater depths that do not breach the surface.

Background

On October 9, 2015 the New Mexico Department of Transportation (NMDOT) reported that a sinkhole had opened on the east shoulder of US Highway 285 south of the village of Malaga, New Mexico, about 16 km north of the Texas/New Mexico state line (Figure 1). This sinkhole is approximately two meters in diameter and 1.5 meters deep, and is less than six meters from the edge of the roadway, within the highway right-of-way. Because of nearby oil and gas activity, there is a substantial amount of traffic along this portion of US 285, including large trucks.

The sinkhole thus poses a hazard to the travelling public. Surface geologic maps indicate that bedrock of the upper Permian Rustler Formation is present at or near the surface beneath US 285 from Malaga south to the state line, and crops out within six meters of the new sinkhole. The Rustler is composed in part of highly soluble gypsum, thus making it prone to sinkhole formation. Sinkholes are widespread in outcrops of the Rustler Formation and associated upper Permian evaporites in the lower Pecos Valley (e.g., Kelley, 1971). Because of the poor condition of the existing roadbed, NMDOT has proposed construction of a highway realignment ~20 meters west of the existing highway, extending about 35 km from the state line to the community of Loving, New Mexico (Figure 1).

During an eight-month period from November 2016 through June 2017, personnel with the National Cave and Karst Research Institute (NCKRI) and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) conducted surface reconnaissance, geologic mapping, and near-surface geophysical surveys of the US 285 right-of-way (NCKRI and NMBGMR, 2016). The initial phase of the investigation involved walking the entire route from the Texas state line to the outskirts of Loving (Figure 1). Sinkholes and other karst features were recorded and the geology mapped. In November 2016 two electrical resistivity (ER) surveys were conducted adjacent to the sinkhole 16 km north of the state line that had generated the initial interest in this investigation. In March through June 2017 NCKRI and NMBGMR personnel conducted additional ER surveys of selected sinkholes and other karst geohazards that had been identified as potentially high-risk features during the previous year's surface reconnaissance mapping.

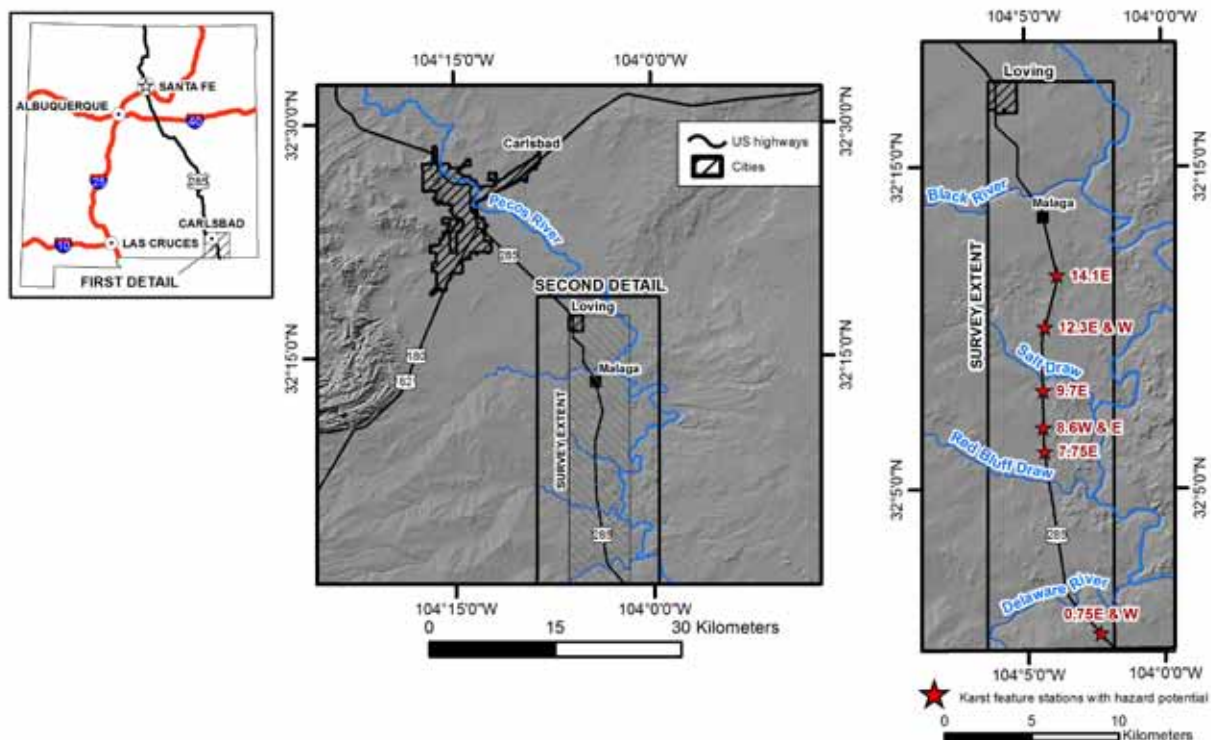


Figure 1. Location of study area and sites with estimated karst hazard potential. The sinkhole that initiated interest in this investigation is located at Station 9.7E.

Geologic Setting

The study area lies in the Pecos River Valley of southeastern New Mexico, on the northern flank of the Delaware Basin. Bedrock in the area consists of upper Permian evaporitic rocks of the Ochoan series, including the Castile, Salado, and Rustler Formations; and non-marine sands and mudstones of the Tertiary Gatuña Formation (Figure 2; Kelley, 1971). Only the lowest two members of the Rustler Formation, the Los Medaños and the Culebra Dolomite, crop out along US 285 in the study area. The lower of these, the Los Medaños, consists of up to 36 m of mudstones grading upsection to interbedded mudstones, anhydrite and/or gypsum, and halite (Bachman, 1980; Powers, 1997). The overlying Culebra Dolomite consists of 8 to 10 m of thinly bedded ledge-forming dolomite (Bachman, 1980). Where occurring at the surface, the Culebra commonly caps low knolls surrounded by swales underlain by gypsiferous Los Medaños outcrops. Locally, the Culebra forms low structural domes tens to hundreds of meters in diameter, where the dolomite beds dip radially outward from a central point. Very locally, outcrops of the Culebra are internally brecciated. Bachman (1980) interpreted both the structural domes and local breccia as products of dissolution of salts from underlying strata

causing localized subsidence or collapse of the Culebra into underlying karst features.

The Gatuña Formation consists of lenticular sandstones, mudstones, and thin beds of crystalline gypsum that accumulated in alluvial settings. It contains ~13 and 0.6 Ma volcanic ashes (Powers and Holt, 1993) and is typically capped by calcretes which range in age from several million years to ~0.5 Ma (Hawley, 1993). Cather (2011; 2016, personal communication) recognizes two main lithofacies: an axial fluvial facies and intercalated alluvial deposits of local transverse drainages containing eolian sandsheet beds. The Gatuña outcrops within the study site fall within this latter “piedmont” facies, comprised of reddish-brown mudstones with lesser lenticular sandstone beds. These are poorly exposed and crop out irregularly in road cuts along US 285, commonly capped by Quaternary alluvial gravels. Bedding measurements in most exposures have moderate dips (15 to 50°) and dip directions are inconsistent, locally directed toward the east, southeast, west, and north. Similarly inconsistent moderate dips in the Gatuña in the region have been interpreted as evidence for karst-related subsidence by Kelley (1971) and Powers and Holt (1993). Thickness of the Gatuña in the study area

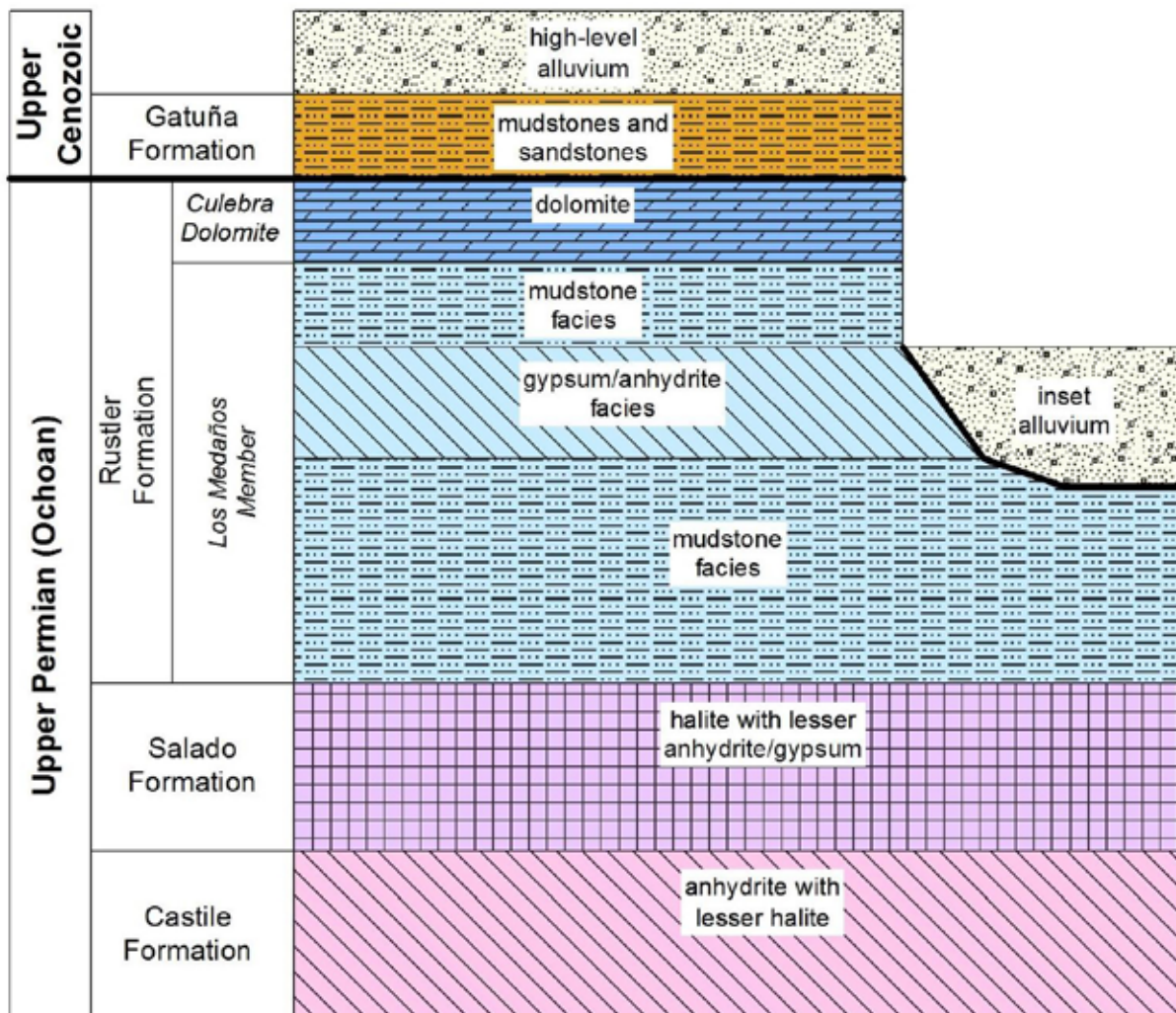


Figure 2. Upper Permian (Ochoan) stratigraphy of study area.

is highly variable, ranging up to ~90 m. Powers and Holt (1993) report that measurable outcrops are commonly 9 to 30 m thick, although a basal contact is not present at many exposures.

Several ages of Quaternary alluvium either cap or are inset into the Rustler and Gatuña Formations. The oldest alluvial deposits underlie the broad high-level plains found between major streams and are composed chiefly of gravels. Younger terrace deposits occur along the flanks of major streams inset against the high-level plains, and are composed mainly of sands and muds with lesser gravels. Alluvial deposits are zero to at least eight m thick in the study area.

The regional structure is dominantly a low-gradient, eastward-dipping homocline (Bachman, 1987). Several broad east-northeast-trending synclines and anticlines

can be inferred to affect the Rustler Formation based on structure contours compiled by Hiss (1976). These folds may be solution-subsidence troughs caused by subsidence into linear bands of preferential dissolution in the underlying Salado Formation (NCKRI and NMBGMR, 2017). Additionally, the erratic dip directions of Gatuña Formation beds may be the product of local dissolution-related subsidence. Sinkholes mapped during this study may be concentrated along at least one of these solution-subsidence troughs (NCKRI and NMBGMR, 2017). No mapped faults cross the study area, and no evidence of faulting was observed during this study.

The most important water-bearing unit within the Rustler Formation is the Culebra dolomite (Hendrickson and Jones, 1952), within which water is present in perched aquifers above low-permeability gypsum and mudstone lithologies of the Los Medaños Member, and underlying

halite and anhydrite beds of the Salado and Castile Formations (Figure 2). A well-defined and continuous shallow water table is not present in the survey area.

Methods

Surface Reconnaissance

Exploration for sinkholes, caves, and other karst features was conducted with teams of two to four people walking no more than ~15 m apart and generally parallel to the highway. This reconnaissance work was guided and supplemented by air photo imagery provided by the contractor. Most karst features within an area can be discovered with this spacing, although some small features (less than ~10 cm diameter and/or <5 cm deep) with little surface expression may still be missed. Discovered features were marked with small, engraved aluminum tags and long strips of red and white survey tape, with their identification numbers marked on the tape in waterproof ink. The locations of newly discovered karst features were measured with Universal Transverse Mercator (UTM) coordinates captured with hand-held global positioning system (GPS) receivers. Geologic contacts and outcrops were also similarly identified and located during this survey, with all of the data later processed by geographic information system (GIS) software for display and spatial analysis. Field evaluations included depth and lateral dimensions of sinkholes, lithology, measurement of fractures, and observations of flow features, sediment, water flow, and air flow. This information was recorded on forms designed for such surveys, and with a scaled sketch of each feature, including a plan view and profile.

Data from the forms were placed into an Excel spreadsheet designed to quantitatively predict which karst features pose the greatest potential risk of collapse or subsidence. The general method was discussed and successfully applied by Veni (1999). Per that method, the spreadsheet was adjusted to the local geology after weighing factors such as limestone vs. gypsum bedrock, predominant mode of cave development and morphology, preferential fracture orientations along which large and potentially unstable caves are more likely to develop, and related factors that may further suggest structural stability or instability of karstic cavities. The characteristics of each karst feature were tallied with point values commensurate with the significance of each characteristic in demonstrating its potential for collapse or subsidence. All non-karst features were classified

as artificial. The sum of the assigned point values is multiplied by a point value assigned to the feature type. Based on experience and comparison with related karst features in this and other areas, the significance of a feature is ranked as no potential risk for 0 points, low potential risk for 1–150 points, moderate potential risk for 151–250 points, and high potential risk for >250 points. These ranks were color coded and the features plotted on a geologic map that was created from the field survey, allowing prioritized selection of areas for geophysical investigation.

Geophysical Surveys

Electrical resistivity surveys are a common and effective geophysical method for detection of subsurface voids (e.g., Land and Veni, 2012; Land, 2013; Land and Asanidze, 2015). The basic operating principal for an ER survey involves generating a direct current between two metal electrodes implanted in the ground, while measuring the ground voltage between two other implanted electrodes. Given the current flow and voltage drop between the electrodes, differences in subsurface electrical resistivity can be determined and mapped. Modern resistivity surveys employ an array of multiple electrodes connected with electrical cable. Over the course of a survey, pairs of electrodes are activated by means of a switchbox and resistivity meter. The depth of investigation for a typical ER survey is approximately one-fifth the length of the array of electrodes.

Resistivity profiles illustrate vertical and lateral variations in subsurface resistivity. The presence of water or water-saturated soil or bedrock will strongly affect the results of a resistivity survey. Air-filled caves or air-filled pore space in the vadose zone are easy to detect using the ER method, because air has near-infinite resistivity, in contrast with 10 to 15 orders of magnitude more conductive surrounding bedrock.

A SuperSting R8/IP electrical resistivity system provided by Advanced Geosciences, Inc. (AGI) was used to collect resistivity data, employing a dipole-dipole array configuration. All of the ER surveys conducted in March, April, and May 2017 used a 42 electrode array at one meter electrode spacing, for a target depth of investigation of ~10 meters. Rollalong methods were used at some sites to extend the length of the survey lines. After data were collected using the initial array of electrodes, the lower half of the array was shifted forward

to the far end for a 50% overlap. In some survey areas, multiple rolls were employed. Although this method does not increase the depth of investigation, it permits a seamless ER profile much longer than the length of the main array. Additional ER surveys of bridges and bridge abutments, conducted in June 2017, employed 56 electrode arrays at three meter electrode spacing for a target exploration depth of ~33 meters.

While resistivity data were collected, a Topcon GR3 GPS instrument package was used to collect survey-grade GPS coordinates for each electrode in the arrays. Elevation data collected during these surveys were used to correct the resistivity data for variations in topography at each survey site. ER data were processed using EarthImager-2D™ software. The EarthImager software chooses a resistivity scale designed to highlight natural conditions in the subsurface, thus resistivity profiles from different survey areas may not have the same resistivity scale. AGI technical staff report that, in general, it is not advisable to force the software to adhere to a specific scale, and attempts to do so may yield misleading results.

High resistivity anomalies may represent either void space in the subsurface (caves or potential sinkholes), or brecciated/leached zones in gypsum bedrock with air-filled pore space. Laterally continuous layers of high or low resistivity may reflect near-surface stratigraphy, such as gypsum or dolomite beds (generally higher resistivity), or mudstone/shale layers (lower resistivity) in the Los Medaños; or interbedded finer- and coarser-grained sediments in alluvial deposits. Very near-surface high resistivity layers often result from air-filled porosity in soil or weathered bedrock. Areas of medium resistivity may reflect sediment-filled voids.

Results

Six specific areas were identified with a high estimated hazard potential based on surface geologic mapping, quantitative evaluation of karst features, and electrical resistivity surveys (Figure 3). The southernmost area is located about 1.2 km from the Texas state line. The remaining five potential hazard areas are located between 12 and 23 km north of the state line. All of these sites are located in areas where the gypsiferous Los Medaños member of the Rustler Formation crops out or is present within one meter of the surface, consistent with the soluble nature of that lithology. Three of these sites are discussed below.

Where surface karst features are present within five meters of the survey line, their positions are projected onto the resistivity profiles and indicated by black bars. Individual resistivity surveys discussed below are labelled according to their proximity to specific karst features identified during the surface reconnaissance.

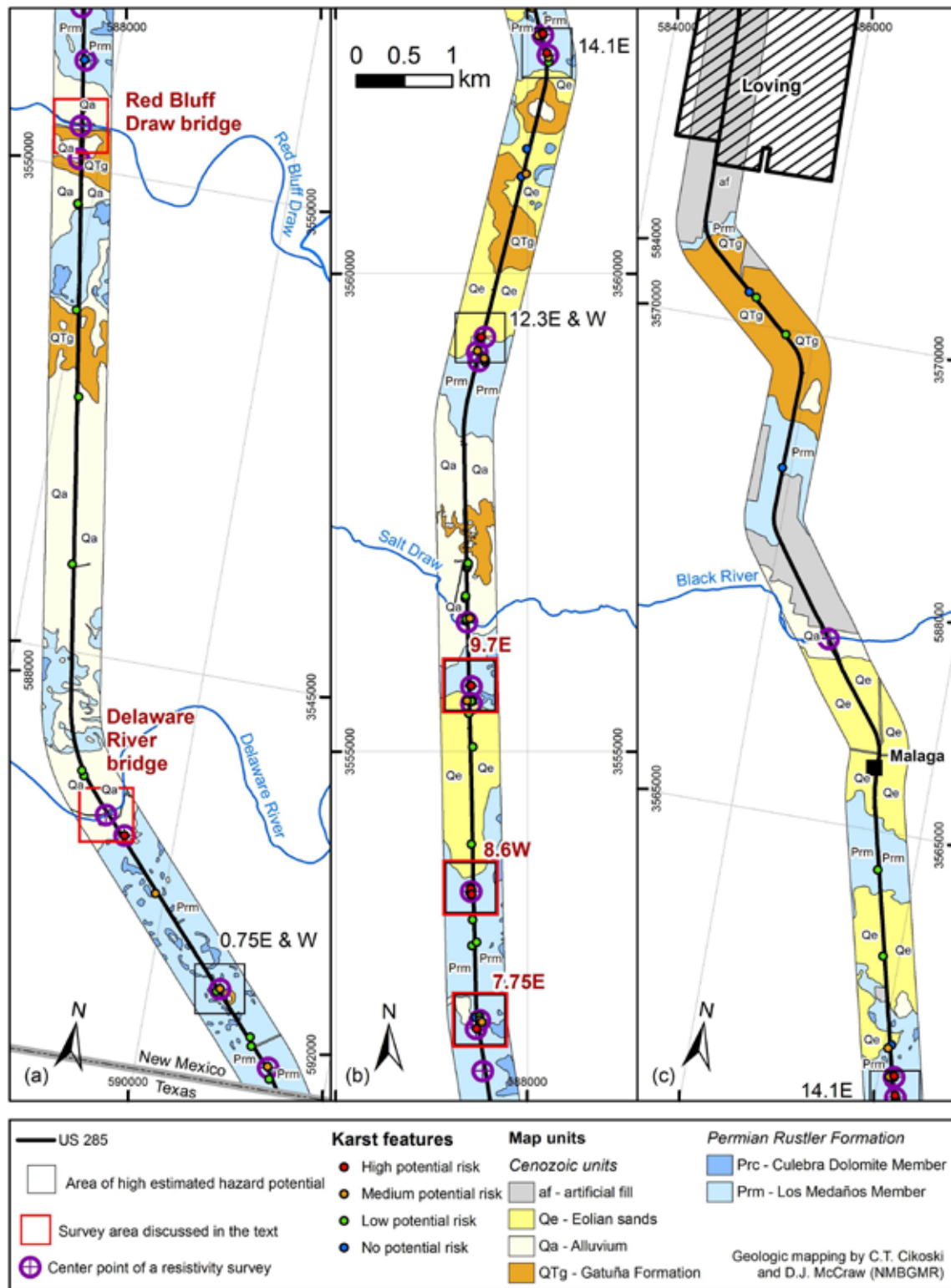
Station 7.75E

Three large sinkholes (>3 m diameter, 1.5 m deep) were identified at this site, formed in Quaternary sediment underlain by gypsum bedrock, which is exposed at the bottom of the sinkholes. These features occur in a broad swale on both sides of the right-of-way fence. An ER survey was conducted west of two of the sinkholes, and skirted one large sinkhole on the west side of the fence. The latter feature shows up clearly as a high resistivity anomaly between ~50 to 55 meters on the profile (Figure 4). An elongate depression on the east side of the fence with a deep sinkhole at the south end roughly coincides with a zone of moderate to high resistivity between 25 to 35 meters on the ER profile. A borehole drilled by the contracting agent, projected onto the survey line at 30 meters, encountered a possible cavity at 2.3 meters below ground level (bgl). Given the size of the sinkholes at this site, it is interesting to note that none of the high resistivity anomalies extend more than 5 meters bgl.

Station 8.6W

This site has a very high concentration of sinkholes over a distance of about 76 meters, some of which may be cave entrances (Figure 5), formed in soil and gypsum bedrock on the eastern edge of a broad, shallow (<1 meter deep) subsidence depression.

An ER survey was conducted at Station 8.6W with the array of cable deployed between and immediately adjacent to most of the sinkholes. The ER profile shows some high resistivity anomalies that coincide with the surface features (Figure 6). However, none of the anomalies extend more than three meters beneath the surface, possibly due to a layer of insoluble mudstone underlying the gypsum beds, indicated by a layer of more conductive material (blue shading) on the profile. The north end of the survey line passes directly over two sinkholes, as can be seen on the topographic profile, yet those features are not indicated in the ER survey data. Thus, in spite of the abundance of surface features, these sinkholes do not appear to have deep roots.



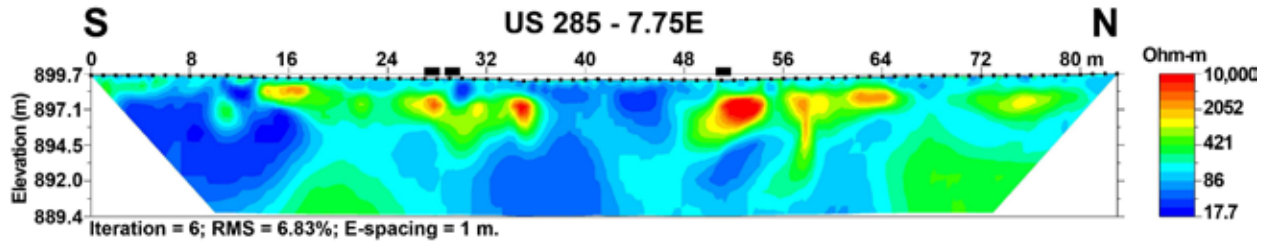


Figure 4. ER profile at station 7.75E. Sinkhole locations are projected onto the survey line and shown by black bars.



Figure 5. Sinkhole with possible cave entrance, station 8.6W. First author's legs for scale.

Station 9.7E

This station includes the sinkhole originally identified by NMDOT in 2015 (Figure 7), plus two additional sinkholes formed in gypsum bedrock that crops out within six meters of the original sinkhole. One of the sinkholes may be the entrance to a small cave but is not enterable by humans. Additional sinkholes are present ~6 meters east of the survey line on the east side of the right-of-way fence.

Two resistivity surveys were conducted at this site. The first survey used a 42 electrode array extended with one 28 electrode roll, for a total of 70 electrodes at one meter spacing, and a target exploration depth of 11 meters (Figure 8A). The ER survey line passes two meters east of the possible cave entrance formed in gypsum bedrock at 35 meters on the profile. That feature is represented

by a shallow (one to three meters deep) zone of high resistivity that extends laterally from ~20 to 38 meters. The high ER anomaly connects to a deeper zone of high resistivity at the south end of the profile, ~6 meters bgl, indicating the presence of either a subsurface cavity or brecciated zone within Rustler gypsum. In contrast to most of the other sites surveyed, the surface karst features identified at station 9.7E appear to extend deeper into the subsurface.

The second survey used 112 electrodes at six meter spacing, and achieved an exploration depth of 125 meters (Figure 8B). The array for this survey is centered on the shorter array, which is shown in Figure 8B by a red bar. The shallow karst features imaged on the 70 electrode survey are still visible as near-surface high resistivity anomalies. This survey also shows a pod of moderately high resistivity (~2000–5000 ohm-m) near the center of the profile ~50 meters bgl, which may indicate the presence of a filled cavity or brecciated zone at greater depth.

Bridge Surveys

Two long-array ER surveys were conducted on both sides of the Delaware River bridge, perpendicular to the stream valley, using 56 electrode arrays at three meter spacing, and achieving a depth of investigation of ~40 meters, seven meters greater than the original estimated exploration depth of 33 meters (Figure 9). The survey on the northeast side of the bridge was shortened by 33 meters because of a dense stand of mesquite

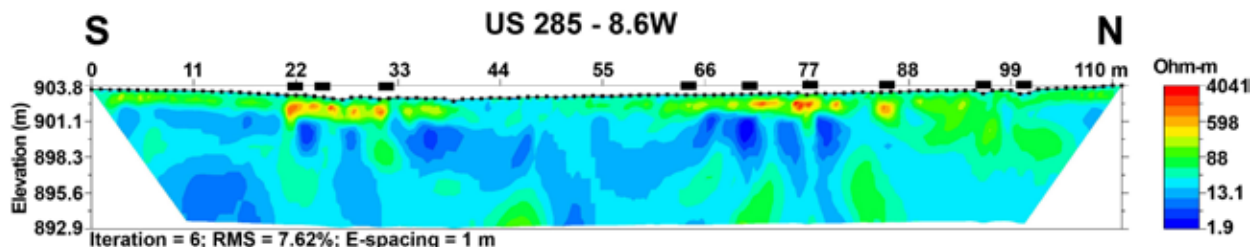


Figure 6. ER profile at station 8.6W. Sinkhole locations are projected onto the survey line and shown by black bars.



Figure 7. Sinkhole at station 9.7E. Beer bottle for scale.

blocking the survey line. The ER profiles for the most part show moderate to low resistivity material (<3000 ohm-m), with no evidence of deeper-seated cavities or other karst geohazards. However, an interesting feature of both profiles is an indication of more generally resistive material on the northwest side of the river valley. This phenomenon may reflect differences in the bedrock weathering profile of the Los Medaños gypsum. Surface geologic mapping (Figure 3) indicates that a more extensive alluvial cover as well as older alluvial deposits are present northwest of the Delaware River than is observed to the southeast. This distribution of alluvial material suggests that the Delaware

River may have previously flowed along a trend farther to the northwest of its current location. At that time, leakage from the river could have preferentially weathered the gypsum bedrock, resulting in a lower-density lithology and thus higher electrical resistivity. Although speculative, this model would explain some of the variations in bedrock resistivity observed during this investigation.

Buried anthropogenic material provided ground truth for some of the bridge surveys along the Highway 285 corridor. ER surveys conducted at the base of the north and south bridge abutments at Red Bluff Draw show broad zones of very conductive material (<3 ohm-m) beneath the bridge ~6 meters bgl extending beneath the entire bridge (Figure 10). Engineering drawings indicate that a buried concrete apron is present at the base of the north and south bridge abutments. The low resistivity zones on the ER profiles probably result from electrically conductive iron reinforcing rods embedded in the concrete apron.

Long-array ER surveys were also conducted on both sides of Red Bluff Draw bridge, perpendicular to the stream valley, achieving a depth of investigation of ~38 meters. These surveys extended parallel to each side of the bridge across the entire valley of Red Bluff Draw.

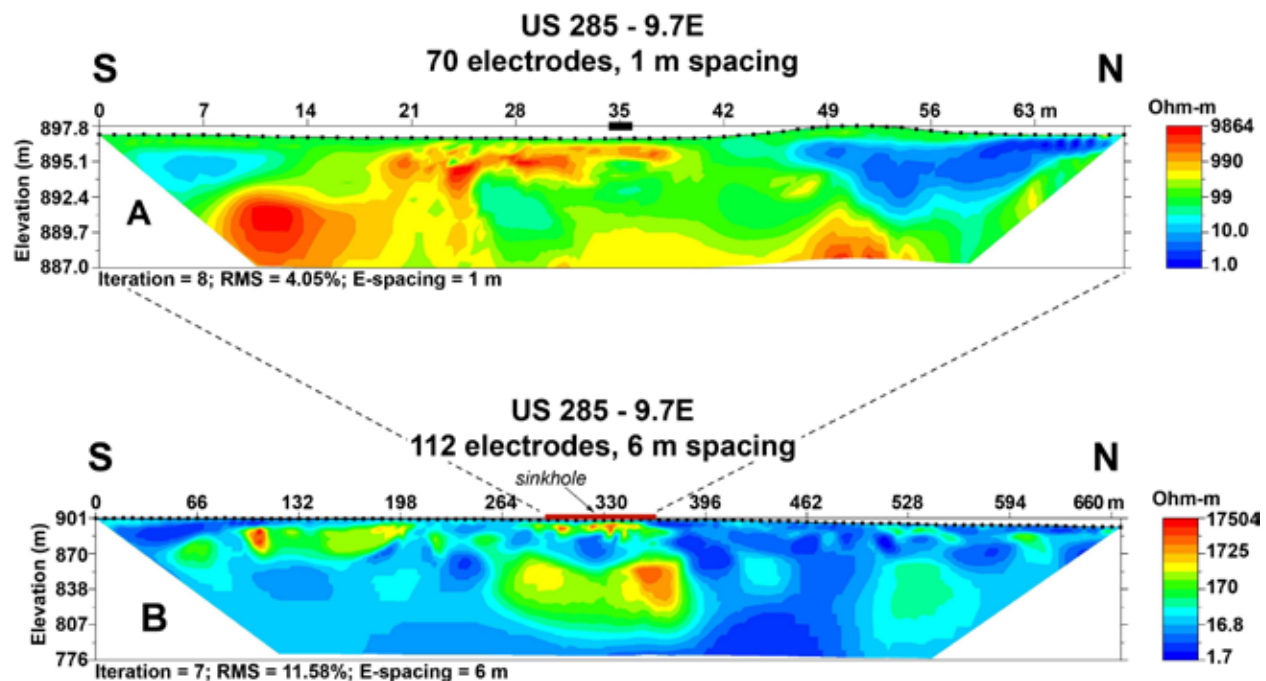


Figure 8. A. ER profile at station 9.7E, 70 electrodes; electrode spacing = 1 meter. Sinkhole location projected onto survey line and shown by black bar. B. ER profile at station 9.7E, 112 electrodes, electrode spacing = 6 meters. Position of the 70 electrode profile with respect to the 112 electrode profile is shown by a red bar in B.

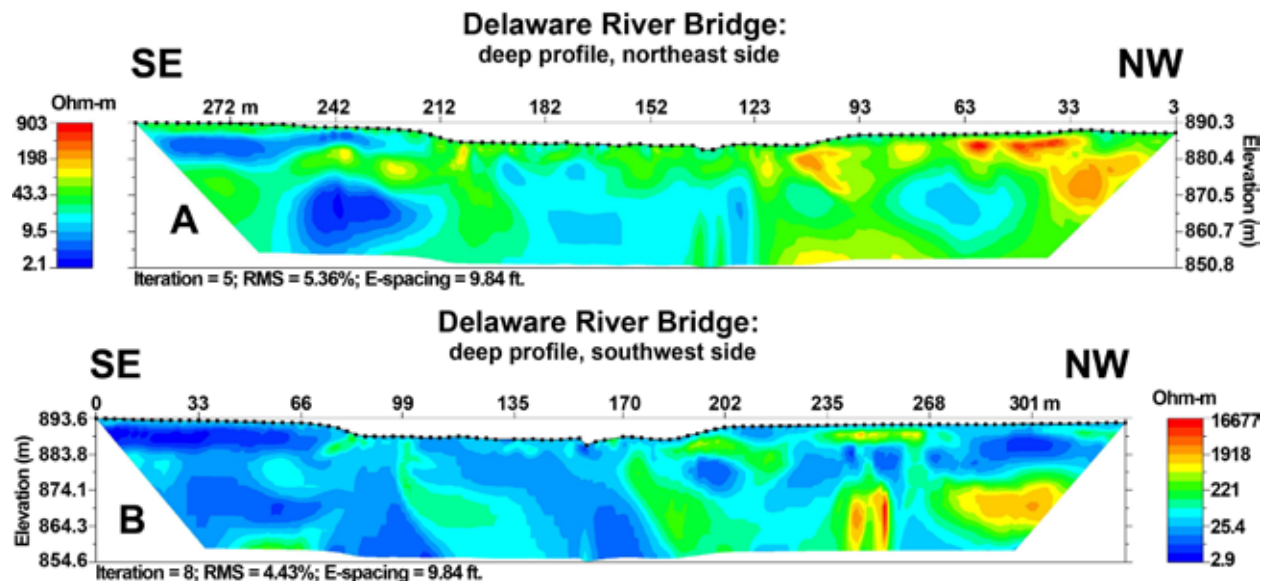


Figure 9. A. Deep profile, northeast side of Delaware River bridge. B. Deep profile, southwest side of Delaware River bridge.

The east side profile of Red Bluff Draw bridge shows a distinct zone of higher resistivity ($>70,000$ ohm-m) beneath the south abutment, ~25 meters bgl (Figure 11). The west side profile shows a resistivity anomaly of similar size beneath the south abutment at about the same depth (Figure 12). A second ER anomaly is present on the west side profile at ~18 meters bgl beneath the stream bed, centered at

95 m. These features probably indicate subsurface cavities formed in gypsum bedrock that do not breach the surface.

Summary

Six specific areas have been identified in the study area with a high estimated sinkhole hazard potential based on surface geologic mapping and electrical resistivity

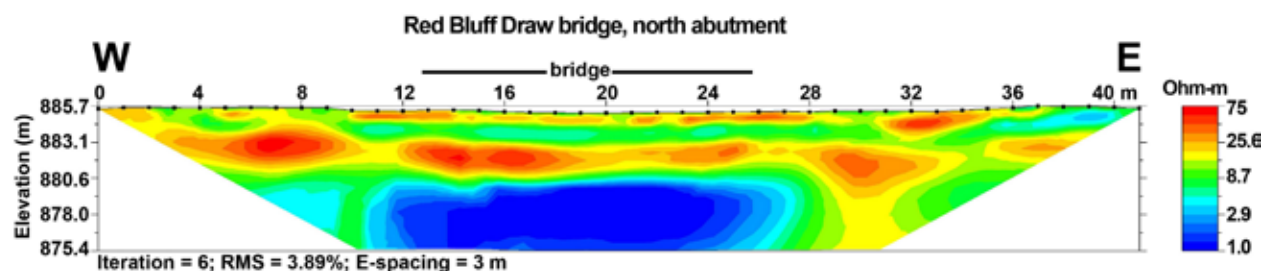


Figure 10. ER survey conducted below Red Bluff Draw bridge, base of north abutment. Position of bridge shown by black bar. Broad zone of electrically conductive material (blue shading) reflects the presence of a buried concrete apron containing iron reinforcing rods at the base of the abutment.

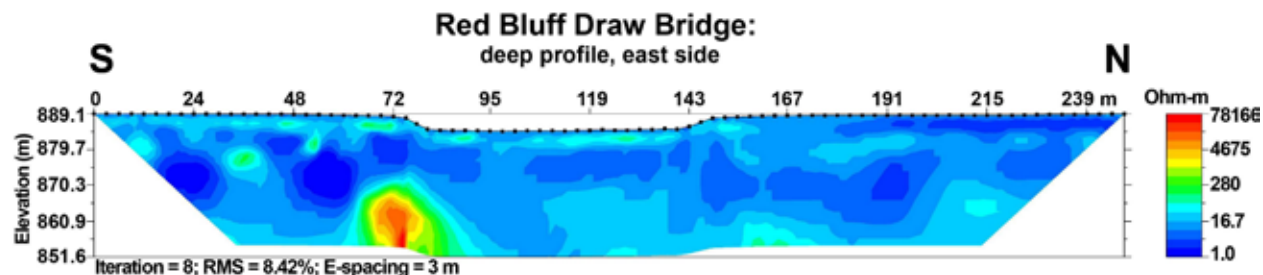


Figure 11. Deep profile, east side of Red Bluff Draw bridge.

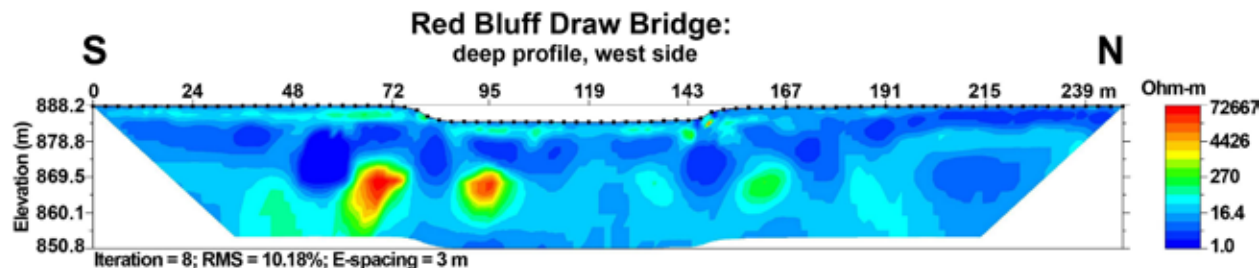


Figure 12. Deep profile, west side of Red Bluff Draw bridge.

surveys. The results of these surveys will guide NMDOT engineering decisions during the planning and construction phase of the highway realignment and possible bridge replacements.

All of these sites are located in areas where the gypsiferous Los Medaños Member of the Rustler Formation crops out or is present within one meter of the surface. This distribution of karst features is consistent with the soluble character of gypsum bedrock in the survey area, and suggests that additional karst features can be anticipated where the Los Medaños crops out beyond the mapped area of this study.

Most of the sinkholes in the study area are relatively shallow (<3 m). Resistivity surveys conducted adjacent to the sinkholes indicate that in most cases they do not have deep roots, rarely extending more than five meters below ground level. Given their widespread distribution in the study area, the shallow extent of most of the sinkholes detected during surface reconnaissance was surprising and unexpected. The limited vertical extent of these features probably results from the mixed lithology of soluble and insoluble bedrock (interbedded gypsum, mudstone and dolomite) in the Rustler Formation.

At some stations, longer-array electrical resistivity surveys identified high resistivity anomalies at greater depths. These features may represent void space, brecciated zones, or filled cavities in the underlying gypsum bedrock that do not breach the surface. Variations in specific values of bedrock electrical resistivity were observed over the course of this investigation, particularly on the long array surveys with greater exploration depth (e.g., the Delaware River bridge surveys). This phenomenon may reflect lateral variations in bedrock weathering properties of the Los Medaños gypsum, resulting in variations in bedrock resistivity.

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REMEDIATION OF THE CENTENARY COLLEGE PRESIDENT'S HOUSE

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Abstract

A week after the New Year 2015, a fire started in the over 125-year-old President's House at Centenary College, Hackettstown, New Jersey. Large quantities of water were used to put out the fire on that freezing night. As a result, a roughly 22-foot diameter sinkhole opened near the back door, causing a fireman to fall into the collapse. Subsequently, approximately 1½ to 2 cubic yards of pumpable, flowable fill was placed into the sinkhole throat. The house was a loss and demolished in the late spring of 2016, leaving the foundation in place. During long delays resulting from local zoning laws being somewhat different than they were in 1910 (when the house was moved to its present location), another sinkhole opened below the rear foundation wall and basement floor slab.

Approval was granted to build a similar structure within the existing footprint of the historic home and the old foundation was removed in April 2016. To support the new structure in an area known for sinkhole formation, an exploratory grouting program was employed. 45 probe holes were drilled and grouted with 88.4 cubic yards of site-mixed, fluid grout. The subsurface conditions were erratic and difficult to model as the voids encountered were not large in size, nor very linear, but appeared to extend for distances beyond the house footprint. The new structure was completed in 2016.

Introduction

The President's House was originally built as the Bright Stowe house in the "Millionaires Row" section of Morristown, NJ in 1890. It was dismantled and moved by rail to Hackettstown, NJ, to a lot across the street from the College. It was reconstructed in 1910 and subsequently purchased by the college in 1945. Under the college's ownership, it housed five college presidents, but has been used for meetings, gatherings and housing guests more recently. It was gutted by fire in January 2015.

The authors have been involved in a number of sinkhole- and karst related projects for Centenary College (now Centenary University) in the past. Therefore, it was no surprise when we were called to inspect a sinkhole that formed adjacent to the President's house as a result of the large quantities of water used in an attempt to extinguish a raging fire. A firefighter reportedly fell into the collapse as it formed.

We were asked to inspect and remediate the sinkhole so that demolition work could safely begin on the house. During our inspection, we also noted two depressions in the rear yard that may have been sinkhole precursors. The valley in which the college is situated is a geologically complex portion of the Valley and Ridge physiographic province of northern NJ. There are a variety of sedimentary formations, many carbonate, with a glacially altered landscape. As in most Appalachian Karst landscapes, the bedrock has been highly tectonized, leaving the bedrock faulted, fractured and folded with varying bedding and fracture angles. Solutioning in this hard rock environment is usually slow and additional solutioning is likely not of concern during the economic lifetime of most structures. Therefore, karst remediation efforts are generally directed toward the existing conditions.

The college campus is a little larger than a square mile in area and is mantled by residual and glacially derived soils atop at least three carbonate bedrock formations. In our previous experience at the campus and in the region, bedrock solutioning takes place along a complex set of bedding and fracture channels that, collectively, can account for significant overburden volume or grout losses. Often times, the channel system includes cavities of significant size, but their extent is extremely difficult to determine because of their usually complex shape.

The President's House is on the northwest side of the campus and is mapped as being underlain by Flanders Till

atop Leithsville Formation dolomites. The Leithsville has exhibited sinkhole formation at other locations in the region. There was no specific drilling data or nearby outcrops of the bedrock in the area, so specifics such as bedding and fracture angles were unknown.

The Middle to Lower Cambrian Leithsville Formation is described as light- to dark-gray and light olive-gray, fine- to medium-grained, thin- to medium-bedded dolomite. Grades downward through medium-gray, grayish-yellow, or pinkish-gray dolomite and dolomitic sandstone, siltstone and shale to medium-gray, medium-grained, medium-bedded dolomite containing quartz sand grains as stringers and lenses near the base. Lower contact gradational. Thickness ranges from 0 to 56 m (0-185 feet) due to erosion.” (Volkert et., al, 2001).

Sinkhole Remediation

The sinkhole that formed was some 22 feet in diameter and 10 feet deep (see Figure 1). Debris was removed from the sinkhole and water was introduced in order to develop the throat, which trended in a direction parallel with the side of the house. No water returned. Another suspected throat trending toward the center of the house did not accept the introduced water. An old, likely abandoned dry well was adjacent to the sinkhole and roof drainage appeared to go underground, but did not lead to a receiving source.

The following day, transit-mix, pumpable flowable fill (a high-cement content flowable fill available from certain suppliers) was placed in the sinkhole and its throat using a standard concrete pump (Putzmeister TK-15). Some 1½ to 2 cubic yards of the pumpable flowable fill was observed to enter the throat and the balance of the load was used to fill the resulting depression.

Because the home had been in place since 1910 without distress, sinkhole formation in this residential area seemed to be limited and our previous drilling and sinkhole remediation experience in the region, we suspected the bedrock below the site to have relatively small cavities as well as solutioning along an extensive and complex set of bedding and fracture partings.

Municipal Approvals

The foundation was left in place after the building was razed under the assumption that the foundation would be used for the new structure. The foundation had no footings, just a cement block wall bearing directly on the residual soils, and the floor slab was thin and incomplete. Only the fireplace foundation had proper support. However, as a result of the current code

requiring greater setbacks from the property line, the hope was to use the existing foundation to reconstruct the house as it was. Otherwise, a much smaller house footprint would be required by code.

Shortly after the building was razed and the debris removed, a roughly eight-foot diameter sinkhole formed in the basement, compromising the rear foundation wall and an interior foundation wall (see Figure 2).

As the lack of footings and the loss of support resulting from the second sinkhole (Figures 2 and 3) precluded the use of the existing foundation, the college approached the town with a plan to construct a completely new structure within the existing house’s footprint.

An extended series of meetings between school representatives, municipal officials, State and Federal archeological/historical personnel, engineering



Figure 1. The sinkhole created by water used to fight the fire.



Figure 2. Sinkhole that compromised existing foundation.

Not to scale

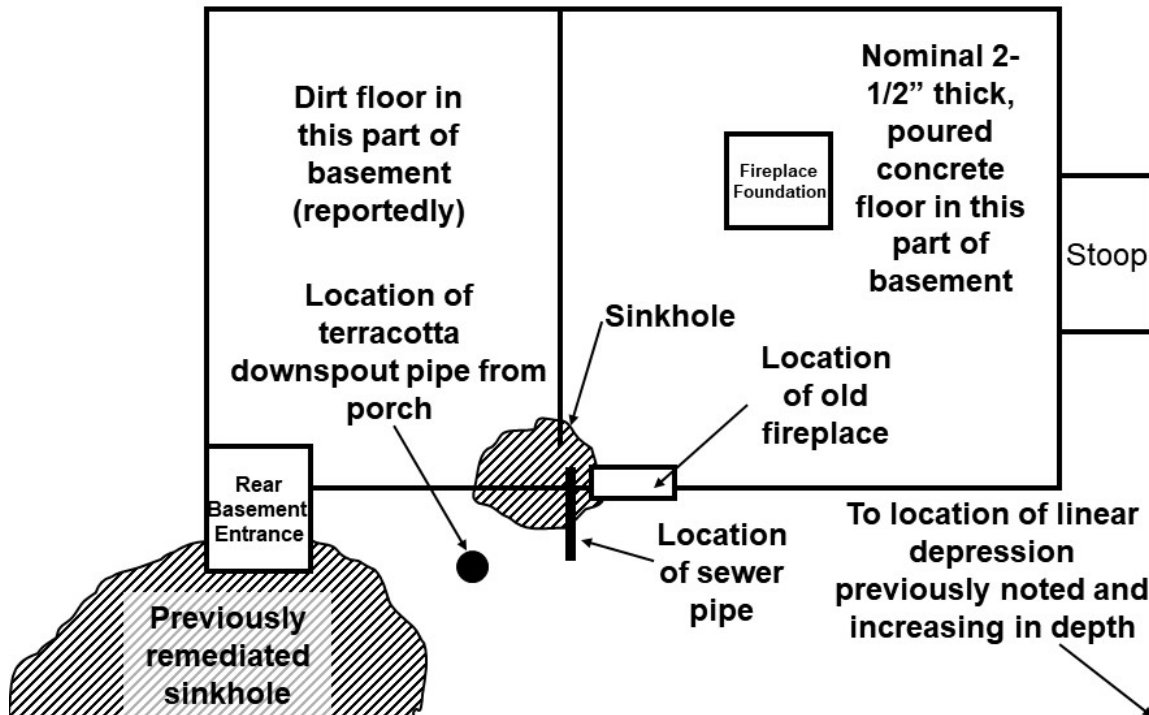


Figure 3. Sketch plan of site conditions prior to foundation removal.

professionals, the architect and geotechnical consultants continued through the political battles and the design process. The plans were changed throughout the process as these various groups interacted.

Approval was finally received to build a similar structure within the existing footprint more than a year after the fire. The only addition to the structure was a large ramp for handicap access and an elevator. The old foundation was removed and Geoscience Services (GS) and Compaction Grouting Services, Inc. (CGS) were hired to remediate the subsurface soils and maintain a proper subgrade for the new foundation and buildings.

Remedial Grouting Program

A remedial grouting program below the proposed footings, handicap ramp foundations and the elevator shaft were proposed, accepted and executed. An exploration/grouting program utilizing high-mobility, site-mixed grout was selected upon the basis of our expectation that there was a complex network of solutioned channels

leading to cavities of relatively limited size. Finding the target cavities would be difficult and the complex solution channel network could, collectively, account for a significant void area. The flexibility of site mixing allowed changes in the grout mix to address changing or unexpected subsurface conditions.

CGS provided the equipment and personnel to drill probe/grout holes and place site-mixed high-mobility grout under the technical direction of GS. Probe/grout holes were drilled using air-track drilling equipment (TEI MME) mounted on a mini-excavator for accessibility reasons. The drilling equipment utilizes a top-hammer with a carbide tipped cross-cut bit to pulverize the rock and air to remove the drill cuttings from the hole. After the 3½-inch holes were drilled, 2⅝-inch steel casing was installed and a fluid grout consisting of Type I Portland cement, water, bentonite, and a foaming agent (to increase the grout volume) was pumped under gravity to light pressures. When pressure built to the threshold of about 50 psi, the grout pipe was removed in stages as grout injection continued. A hole was considered

grouted when grout reached the surface from the annulus between the pipe and drilled hole, thus ensuring that the entire length of the probe hole had been grouted.

In our experience, the grout mix used at this site is capable of travelling through openings in the subsurface laterally some 10 feet with little pressure. Grout holes were placed with 10-foot or less spacing around the foundation perimeter to treat below the planned footing and elevator locations. Additional areas outside the planned foundation were drilled and grouted for a porch and a handicapped ramp. Secondary grout holes were also drilled both within and outside the building footprint to check the efficacy of the grouting operations and to follow suspect trends revealed by previous drilling.

The penetration rates and the materials “blown” to the surface by air during grout hole drilling were used to log the holes. However, air was often lost and penetration rates were all that was available for logging. The probes indicated a thin (less than 8 foot) layer of silt/clay tills atop varying depths of clayey residual soils over a variably weathered bedrock surface. Layers of soft soils and weathered to sound bedrock were inconsistently encountered at many depths and drilling indicated some narrow, near-vertical, open seams.

In general, the holes were terminated after encountering at least 2 feet (depending upon encountered depth) of hard bedrock. The bedrock surface was initially encountered at depths ranging from 1 to 12 feet below foundation grade. Grout hole final depths ranged from 16 to 54 feet below foundation grade.

Some 2,330 cubic feet (86.3 cubic yards) of grout was placed in the 45 grout holes for remediation below the foundation of the house as well as the planned deck and entrance ramp. Three more probe-grout holes, drilled to depths between 29 and 46 feet below grade, were drilled in the two previously mentioned suspect areas near the northeasterly property line and fence. Similar drilling conditions with soft soils were encountered in these areas, although no significant cavities were noted. These three grout holes took 57.75 cubic feet (2.1 cubic yards) of grout to fill.

The grout holes that took 50 to 100 times the theoretical hole volume were 3, 15, 16, 20, 22 and 48. The grout holes taking more than 100 times the theoretical hole volume were 1, 2, 17 and 39. The largest single grout-take was in Probe 2 at almost 11 cubic yards. The exploration/grouting program took 3½ weeks to complete in the spring of 2016 (Figure 4).

Grout Composition and Delivery Techniques

There are three crucial components for any high mobility grouting program to be considered successful at filling solution channels and mitigating future sinkhole development. The grout must be capable of travelling far distances under low pressure while maintaining it's designed consistency, it must be stronger and less-permeable than the soil substrate it is injected into, and it must be economical when compared to other remedial techniques. These components are all primarily controlled by the mix design and the mixing and pumping procedures.

Developing an appropriate mix design was the first step to producing a grout that would meet all three crucial components. For the subject grouting program, we used a grout consisting of Type I Portland cement, water, bentonite, and 50% (by volume) of a foaming agent for a theoretical unit weight of about 60± pcf and a compressive strength of about 500± psi. A synthetic foaming agent (Aerlite-iX) was used for its increased bubble structure stability to ensure that the grout/foam volume was maintained during grout injection. The bentonite and foaming agent were added as bulk filler and will impact the compressive strength of the grout mix significantly. However, the benefits of increased mobility, mix stabilizer (cement particle suspension), and material (cement) cost savings far outweighed

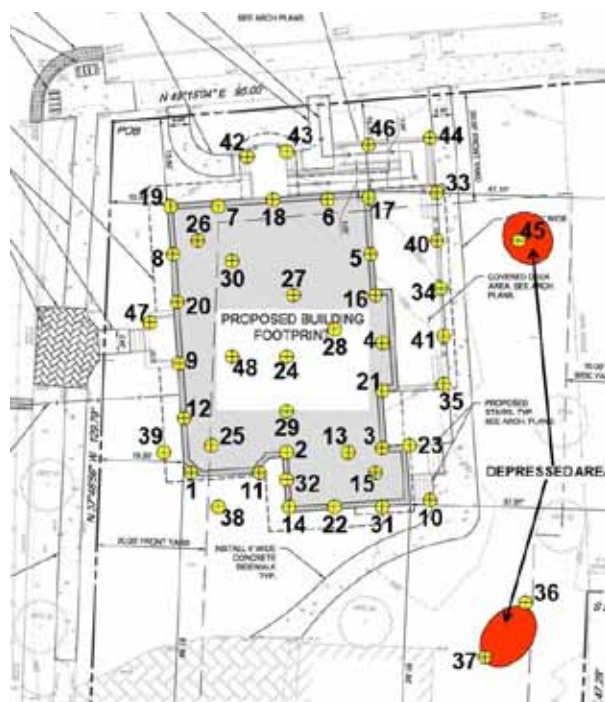


Figure 4. Grout hole plan.

the reduction in compressive strength. Even with the addition of bentonite and the foaming agent, the grout theoretically remains stronger and less permeable (non-permeable) than the surrounding soil substrate, thus reducing the potential for existing and/or new solution channels forming and/or further develop leading to continued soil piping and raveling. It should be understood that the volume of grout injected to fill voids and/or solution channels is more critical to a successful high mobility grouting program than the compressive strength of the grout as long as it is stronger than the weakest substrate (soil).

To ensure proper production of the designed grout mix, an on-site batch plant consisting of a high shear colloid mixer (ChemGrout CG600) was used. A high shear mixer is crucial to proper hydration and full suspension of the cement particles. The water, bentonite, and cement were mixed in the mixing tank and then transferred to a holding tank where the foaming agent is added. Typically, the foaming agent is added in the holding tank where only an agitation paddle is used for blending so that the foam's "structure" is not compromised.

As part of the ChemGrout CG600 grout batch plant, the grout pump used for injection consisted of a high pressure dual piston pump capable of reaching pumping pressures of 1,000 psi. Although this high of a pressure was not required at the point of injection, a high-pressure pump is necessary considering potential head pressure (pumping to a higher elevation) and overcoming friction loss in longer grout hose runs. This high-pressure pump also ensures a continuous supply of grout during the injection process.

Considering the high-pressure capabilities of the grout pump and the potential for hydrofracturing the subsoils and/or bedrock, full time monitoring and control of injection pressure were employed. A low pressure (0 to 500 psi in 10 psi increments) gage was affixed inline to a T-head at the point of injection. The gage was used to monitor the injection pressure and if the pressure threshold of 50 psi was reached, the return line was opened at the T-head to allow grout circulation. Upon determining that no further production injection at or below 50 psi was possible (which included slowing the injection rate to match takes), the stage was terminated and the grout casing raised.

Grout injection quantities per stage were determined from grout level drop in the holding tank, a count of the pump strokes (which had been calibrated) and verified by the number of cement bags used for batching.

Recommendations

Our report provided what we consider general recommendations for any construction atop remediated karst. The recommendations below do not include specifics such as lateral earth pressures which are site specific.

Surface runoff water permitted to enter the subsurface in areas with voids in the underlying rock due to changes in existing grades or open excavation for foundations and underground utility installation is the primary cause of sinkhole formation during construction operations. The following recommendations for site work and construction are intended to minimize the penetration of water into the subgrade:

- Minimize the extent of surface soil cutting, where possible, to maintain the present thickness of the compact overburden soils that have likely limited surface water penetration into the subgrade in the past.
- Grade and maintain exposed subgrade so as to move water away from excavations and prevent the ponding of water.
- Maintain positive drainage away from all existing and planned structures to prevent the ponding of surface water.
- Where foundation excavations or utility trenches are left open overnight, surface grading along trenches or other excavations should eliminate surface water flow into trenches. In lieu of surface grading at trenches, pumping of the trenches to prevent ponding of water should be maintained until the trenches are evaluated by qualified engineering personnel and backfilled.
- Roof drainage should be piped away from structures, preferably into a storm water collection system.
- Clean crushed stone or other highly permeable materials should not be placed below grade to prevent the potential for water ponding in the subgrade. Where fill must be placed to maintain grades in excavations, well-compacted on-site materials or Quarry Processed Aggregate choked with fines to reduce permeability (such as NJDOT I-5) should be placed and compacted to 95% of the maximum dry density obtained using ASTM Test Procedure D 1557. Compaction of each lift should be monitored to verify that the required dry density is obtained.
- PVC sanitary waste lines normally specify a clean crushed stone bedding below and surrounding the pipe within the trenches. We recommend the use of a low-permeability alternative bedding material such as NJDOT I-5.
- To preclude the infiltration of surface water into

below grade trenches, the upper two (2) feet of the excavation should be filled with low-permeability materials compacted to at least 90% of the maximum dry density obtained using ASTM Test Procedure D 1557 in non-structural areas and to at least 95% in structural areas.

- Materials selected for other utility piping systems that may be installed below grade or building slabs should be designed to have adequate strength, flexibility and corrosion resistance to prevent leakage during service.

Conclusions

The results of the probe hole drilling and grouting program indicated the solutioned openings in the bedrock were discontinuous, but did trend in a northeasterly/southwesterly direction; roughly parallel to the local geologic “grain” or orientation. It appeared that the vertical extent of these “thin” cavities was greater than their lateral extent as very few of the secondary and tertiary grout holes encountered previously placed grout.

Considering the small footprint of the area remediated, and the drilling conditions encountered, the large grout takes seem to result more from a complex network of solutioned channels formed along bedding and fracture partings than to any large cavities.

Our report concluded “In our opinion, the remediation performed for the sinkholes and support of the planned structure sufficiently filled the subsurface voids and cavities created by the overburden soils eroding into cavities in the underlying, solutioned bedrock. We urge continued monitoring of the general area for any possible future subsidence.”

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CASE HISTORIES: KARST SUCCESSES AND FAILURES IN THE EASTERN UNITED STATES

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Abstract

A basic understanding of karst development and sinkhole formation is that water drives everything in karst. Design efforts need to consider this basic karst principle before undertaking any meaningful design. Another aspect of karst often overlooked by engineers is that sinkholes are direct input points where surface water can access the karst aquifer and impact water quality and hibernacula of caving dwelling species. Site characterization activities in karst typically only involve test borings and geophysical methods. These methods provide a valuable snap-shot in time of subsurface conditions, which is important, but they provide no insight into groundwater fluctuations. Case histories involving roadway, pipeline and building projects demonstrate the successes and failures of geotechnical engineering over karst. Several case histories indicate the detrimental impact of altering subsurface water conditions which can result in increased subsurface erosion and new sinkhole development. Case histories also underscore the importance of controlling surface water and when not properly considered the result can be sudden and catastrophic sinkhole development. Experience gained from new and forensic karst projects located along the eastern United States with aggregate construction costs approaching \$1 billion all had a common theme; understand and control surface and subsurface water.

Introduction

Karst is the German form of the Slavic word “kras”, which means a “bleak waterless place” and dates back to the 19th century where it referred to an approximate 500 meter high limestone plateau situated in Slovenia. Similar terrain has since been termed karst, which is defined as a type of topography formed over limestone, dolomite or gypsum by dissolving or solution, and that is characterized by closed depressions or sinkholes, caves and underground drainage (Field, 2002).

Karst is a unique and challenging environment that can offer powerful and sudden surface expressions in the form of sinkholes. Karst features such as sinking streams, swallets, karst windows, and blind valleys are among some of the many engineering challenges when considering site development. Karst owes its origins to water; water drives everything in karst. Failure to understand surface and subsurface water conditions

will likely lead to exacerbating site conditions with the consequence of continued sinkhole development.

Karst Origins and the Role of Water

Limestone, a sedimentary rock consisting of at least 50 percent calcium carbonate (CaCO_3), is perhaps the most commonly associated bedrock with karst (Field, 2002). In general, the origin of limestone begins from the precipitation of bicarbonates that generally occur in a sea water environment. Bicarbonate precipitation occurs from direct chemical precipitation as well as from sedimentation of the skeletal remains of marine organisms. Consolidation of carbonate sediments along with other mineral impurities (e.g., clays, silts, sands, et cetera) result in a reduction of porosity and void ratio. Environmental changes may also result in the re-solution and re-precipitation of the carbonates that remove most of the identity of the original particles. The varied sedimentation and post-sedimentation history of limestone make it one of the most varied of all sedimentary rocks (Sowers, 1996).

The development of karst is a natural process driven by water. Water that percolates downward through soil and unconsolidated sediment overlying limestone tends to become more acidic as it absorbs CO_2 . In simple terms, CO_2 dissolved in water partially disassociates and forms H_2CO_3 , a weak carbonic acid. The weak acid reacts with the calcite to form soluble $\text{Ca}(\text{HCO}_3)_2$. Dissolution rates generally occur at a rate of a few millimeters per 100 years in the eastern United States and the rate can increase dramatically in tropical climates (Sowers, 1996; Waltham and Fookes, 2005). The dissolution process can be exacerbated or terminated by seemingly subtle changes in temperature, pH, and dissolved ion concentrations. For example, limestone dissolution rates in a tropical environment may reach 20 mm per 100 years whereas limestone placed in distilled water is less soluble than silica (Sowers, 1996). Interested readers are encouraged to refer to White (1988) for detailed discussion regarding the chemistry of carbonate dissolution.

As groundwater drains downward and pools along the limestone surface, lateral water flow will inevitably reach a fracture, bedding, or joint feature. These features allow



Figure 1. *Solution grooving in limestone*

the continued downward water migration to an erosional base level that creates preferential pathways through a self-accelerating process. Figure 1 presents a typical example of solution grooving associated with limestone dissolution. This grooving, although exposed at the surface, could result in the development of preferential drainage pathways over geologic time through a similar process in the subsurface.

Subsurface water under differential head conditions can transport soluble components while insoluble components remain (i.e., gravels, sands, silts and clays deposited with the carbonate of the original rock). This process results in a residual soil strength profile that is typically inverted compared to that of deposited soils as the residual soil in karst becomes softer with increasing depth, usually most pronounced within 2 to 4 meters above the limestone (Sowers, 1996). Residual soil in karst is also reverse of typical soil deposits as the oldest soil in karst is at the top of the residual layer and the youngest is at the bottom of the residual layer; an important concept often misunderstood when evaluating site conditions.

Over geologic time, a complex and highly developed network of solution conduits, voids, and irregular bedrock surface develops, which is collectively known as “epikarst”. Significant water storage and flow can occur here and this is where most of engineering challenges exist. Williams (2008) notes that epikarst can exhibit secondary porosity between 10% to 30% compared to less than 2% for the main body of unweathered limestone. Figure 2 provides a typical example of exposed epikarst. Epikarst thickness is typically 3 to 10 meters deep, although the characteristics can vary considerably and zones of several 100 meters deep have been noted (Williams, 2008). However, since soil is the

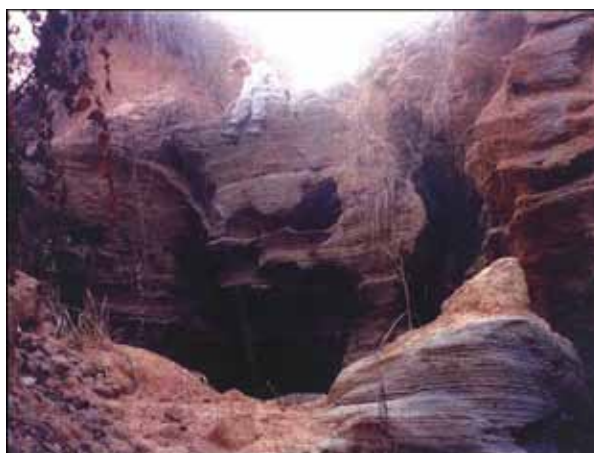


Figure 2. *Exposed epikarst*

main source of CO₂ production, the greatest expenditure of chemical energy occurs near the bedrock surface and this will tend to limit epikarst depth as the water becomes saturated with dissolved minerals at depth. Fords and Williams (2007) note that about 70% of solutional denudation is typically accomplished within the top 10 meters and corrosion attack gradually diminishes with distance from the CO₂ supply.

Sinkhole Classifications

Sinkholes result from two different processes, either the erosion and transport of surficial materials along solution pathways or the collapse of roofs over cavities. Sinkholes are generally classified into five types, namely (Culshaw and Waltham, 1987; Beck 1991; Waltham and Fookes 2005):

- 1) Solution sinkhole;
- 2) Cave collapse sinkhole;
- 3) Buried sinkhole;
- 4) Cover-Subsidence sinkhole; and
- 5) Cover-Collapse sinkhole.

Each of the five sinkhole types has its own discrete mechanism of formation, but they are all ultimately the result of water (Beck, 1991; Lowe and Waltham, 2002). The first two sinkhole types (i.e., solution and cave collapse) occur in rock and are essentially stable features except that open solution conduits or caves must exist beneath them (Waltham and Fookes, 2005). The natural event of rock collapse is rare (Newton, 1987). Sowers (1996) indicates that of the hundreds of investigated sinkholes, perhaps only 2 or 3 were rock collapse and they were located in the Caribbean Islands. Beck (1991) also notes that of the 1,700 sinkholes that developed in Florida in approximately a 25-year period, none were bedrock collapse. Karst bedrock collapse features may

be more common in seismically active regions with occasional strong ground motions, such as the Caribbean.

The greater hazard in karst is associated with sinkholes that develop in the overburden created as a direct result of subsurface erosion of sediment into the underlying solution conduits. An important concept is that sinkholes do not occur randomly; they occur where geologic conditions have created solution pathways in the underlying soluble rock, and they involve the last three sinkhole types noted above (i.e., buried, cover-subsidence and cover-collapse sinkholes). Although the karst hydrogeologic regime is extremely complex, sinkhole formation is relatively straightforward and is driven by water. Solution conduits from karstification provide a channel for water to move and to erode cover sediment into deeper dissolved voids.

Basic Karst Principle

Personal experience and published literature readily indicate that conditions which increase the downward movement of water through the soil overburden can initiate or increase sinkhole activity in karst regions. Three factors are leading contributors to sinkhole development in areas underlain by karst (Newton, 1987; Sowers, 1996; Hubbard 2001; Waltham and Fookes, 2005):

- 1) Increasing the infiltration of water at the ground surface,
- 2) Depressing the piezometric level in the rock significantly below the soil-rock interface to provide high exit gradients for downward draining water, and
- 3) Repeated fluctuation of the groundwater from well above to well below the soil-rock interface.

These leading contributors to sinkhole development need to be considered when engineering over karst and they form the basic karst principle: understand and control surface and subsurface water. Failure to neglect this basic karst principle will inevitably result in continued and perhaps accelerated sinkhole occurrence.

The literature has ample documentation on the mechanics of sinkhole formation and interested readers are encouraged to read Beck (1991) or Waltham and Fookes (2005) for further details.

Karst Case Histories

The development of karst is a natural process driven by water over geologic time (i.e., millions of years). However, it is the downward movement of water through the overburden and epikarst that can cause subsurface erosion of the overlying soil mantle and sinkhole development within project life cycles. Therefore

sinkholes do not occur randomly, they occur where geologic conditions have created solution pathways in the epikarst that allow water to cause subsurface erosion.

Sinkholes noted herein are generally of the cover-collapse type as these tend to be the most catastrophic. Waltham and Fookes (2005) and Newton (1987) note that many sinkholes are created as a direct result of human activities, particularly those that affect surface drainage or groundwater flow. Newton (1987) also notes that the formation of new sinkholes under natural conditions is relatively rare during the course of human lifetime, while sinkholes induced by engineering works are abundant. The abundance of these sinkholes is due to a lack of understanding of the basic karst principle noted herein as will be demonstrated by the following case studies.

Understand Subsurface Water Conditions

Understanding subsurface drainage conditions is vital to developing appropriate karst remediation methods as exemplified by a grout program that was as part of a rail improvement project located in Maryland. Review of structural geology data for this project indicated that the grout program essentially created a subsurface cut-off wall parallel to the synclinal axis (or perpendicular to the bedding dip). Upon completion of grouting, a monitoring well near the rail recorded a water elevation increase of 12.2 meters over a three-month period as subsurface water drained down-gradient along the bedding dip and became dammed by the grout wall. This was the largest head increase noted in the monitoring well during the five-year monitoring period. Unfortunately, a power failure in the instrument was not repaired until four months later when the water was back to its normal level. It is the author's opinion the large head drop occurred because of an apparent occluded conduit that softened under the head increase and allowed rapid subsurface water drainage causing subsurface erosion. Soil raveling likely occurred and shortly thereafter, a cover-collapse sinkhole developed that measured 34 meters by 15 meters and was 11 meters deep. Refer to Figure 3 for a picture of the sinkhole. This sinkhole developed over an approximate five month period. The sinkhole was backfilled with large stone and an emergency grouting contractor began repairs. However, during the grouting operation, another sinkhole developed directly underneath the grouting equipment. The additional collapse would claim a small front-end loader, toolbox and site supplies before final remediation; site personal were not injured (Kutschke, et al. 2005).

The sinkhole noted in Figure 3 developed as a result human activities that changed subsurface drainage

conditions. Engineers seem to readily approach karst with various forms of grout programs and neglect to consider its impact on subsurface water. By occluding or otherwise altering subsurface drainage, one has to consider where subsurface water will go now that the pre-existing subsurface drainage path has been altered. Assuming that no other conditions have changed which would otherwise alter subsurface water recharge (which is often the case with grout programs), saturation of the peripheral area will increase subsurface drainage to adjacent epikarst drains and / or softening of occluded conduits with the consequence of new sinkhole development (Hubbard, 2001).

The importance of subsurface water and its ability to cause subsurface erosion is demonstrated by monitoring wells at large resort in Florida. Handfelt and Attwooll (1988) explain that this site is situated over 20 to 30 meters of mature karst (Waltham and Fookes, 2005) and that monitoring wells switch water pumping where a local water table decline is detected in an attempt to actively manage the water table elevation. The intent of this program is to minimize differential head conditions that would cause water movement with the potential impact of subsurface erosion.

Conversely, dewatering activities such as those conducted by quarries, significantly alter subsurface water conditions with the consequence of new sinkhole development. This action depresses the piezometric level significantly below the soil-rock interface to provide high exit gradients for downward draining water. This condition is favorable for new sinkhole formation as Kutschke et al (2005) notes an aggressive sinkhole occurrence interval of eight sinkholes per year in an area surrounding a rock quarry. The literature has many other examples of dewatering that leads to new sinkhole formation and subsequent legal action to define the zone of influence (Quinlan, 1986; Gary, 1999).

So where does the subsurface water go? As Hubbard (2001) notes, using grout to seal a solution throat has the potential to restrict or occlude the under draining conduit, which can lead to back-flooding, quick soil conditions and new sinkhole formation. Restricting the subsurface flow into the existing subsurface drains by grouting merely diverts the subsurface flow elsewhere. Without an understanding of the process driven sinkhole hazards, site development and associated design activities will continue to exacerbate sinkhole development. Mellet and Maccarillo (1989) underscore this basic karst concept in which they conclude that grouting some areas will only divert subsurface flow elsewhere into unknown

areas with the likely consequence of new sinkholes development.

To help visualize this concept of subsurface water flow, Figure 4 presents a typical construction site with active grading over karst. Excavation has removed significant portions of the overburden to expose the top of rock. Figure 5 presents an oblique view of the idealized top of rock based on extensive geophysical investigation where the “dots” represent known sinkhole locations. Although the projects noted in Figure 4 and Figure 5 are not related to each other, they display the same basic characteristics of karst, that being an irregular rock surface. One could easily imagine that with no change made to subsurface drainage or subsurface recharge that occluding the sinkhole throat with a grout program would result in peripheral pooling. As the peripheral pool(s) rise and saturate new areas, karst features that were otherwise



Figure 3. Cover-collapse sinkhole due to changed subsurface drainage conditions. Note proximity of railway to sinkhole



Figure 4. Typical excavation in karst

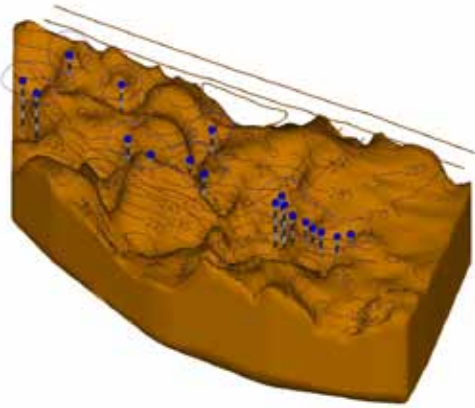


Figure 5. Idealized top-of-rock surface in karst based on geophysical test methods

abandoned or occluded would become saturated and could provide new preferential pathways for subsurface erosion, as evidenced by Figure 3.

Sinkholes mark epikarst drains and they also serve to mark preferential subsurface drainage pathways. Sinkholes develop where solutional pathways exist in the underlying rock. Efforts should be made to understand sinkhole formation, the hydraulic conditions that cause the erosion, and only then can logic based approaches be developed to remediate karst.

Understand Surface Water Conditions. Human activities, particularly those that affect surface drainage are documented to have a direct and significant effect on triggering sinkhole collapse (Newton, 1987; Sowers, 1996; Waltham and Fookes, 2005; and Kutschke, et al. 2005). Figure 6 provides a typical example that underscores the basic karst principle of what happens when surface water is not properly controlled. The literature also provides several examples that demonstrate how large downward water gradients lead to sinkhole development.

- Sowers (1996) provides one of the most catastrophic examples of the effects of increasing surface water drainage resulting in new sinkhole development. Flooding resulted when a tropical storm generated flood water depths as high as 6.5 meters near Albany, Georgia in July 1994. This flooding resulted in more than 300 new sinkholes with the majority of them occurring in a 14 sq km area. The largest measured 44 by 21 meters.



Figure 6. Sinkhole development as a result of concentrated surface water

- Jammal, et al (2010) provide a case history of multiple sinkhole developments in a ten hectare single cell storm water retention basin located in Florida. They note that compaction grouting was used to stabilize known sinkholes. However, two dozen “spontaneous sinkholes” developed after several rain events and a heavy storm that filled 40% of the design storage volume. Repairs consisted of a sand infill due to concerns with environmental degradation of the karst aquifer (i.e., sand provides some filtration). Subsequently, after a heavy rain event that filled 60% of the design capacity, thirty sinkholes developed. Jammal, et al (2010) notes that the pond bottom was expected to be approximately 3 to 6 meters above the limestone surface and about 8 meters above the piezometric level within the limestone; the site allowed for high exit gradients at the soil-rock interface.

- Bonaparte and Berg (1987) note sinkhole development along a portion of roadway in Pennsylvania, which first documented karst features in the early 1960’s and which developed into a perennial problem by the 1970’s. One cover-collapse sinkhole that directly impacted the roadway had initial dimensions of 30 meters by 60 meters. Bonaparte and Berg (1987) indicate that development of the area resulted in increased surface water infiltration, rerouting of a surface stream and a 60 to 100 meter drop in the water table caused by ground-water pumping for an underground zinc mine.

- Heung and Gobin (2010) note that roadway construction induced sinkholes that were the result of altered pathways of groundwater recharge at the soil-rock interface (i.e., epikarst) for the construction of a new roadway in Florida. They also note that after project completion, new sinkholes “occurred only in retention ponds and swales during rainy seasons.”

Newton (1987) and Waltham and Fookes (2005) provide many other examples of how civil engineering works changed surface water conditions with the consequence of new sinkhole development.

The case histories demonstrate the important concept of understanding surface water. All of the projects had either large concentrations or altered drainage patterns of surface flow. The real deterrent to sinkhole formation is the control of surface water and the prudent application of sinkhole repair methods. If an area is not undergoing active sinkhole development, efforts must be made to maintain the existing surface and subsurface groundwater conditions. If groundwater conditions are altered, new flow paths will likely develop with the result of new sinkhole development as the karst system erodes a new “equilibrium.”

Environmental Impacts

Circulation of groundwater through karst is significantly different from water circulation through non-karst settings. Recharge of karst aquifers can be direct input into epikarst drains and by percolation of rainwater through a network of joints. Stephenson and Beck (1995) present an extensive review of the stormwater discharge from highway runoff in karst areas. Soil thickness is an important variable as a thin or nonexistent soil cover offer little to no immobilization for many runoff pollutants and result in direct input into the karst aquifer. Karst groundwater systems can transport sediment and contaminants virtually unimpeded into an aquifer, cave, or spring system due to the rapid recharge rate and lack of filtering. Figure 7 was obtained from a down-the-hole camera in a completed test boring that encountered a water filled void. Careful examination of the image will reveal a crustacean “speleologist” that apparently found his way into a solution conduit from a nearby stream.

New construction in karst must consider environmental impacts. For example, directing highway runoff into known karst features can degrade water quality. Conversely, redirecting run-off from karst features can



Figure 7. *Crustacean in Karst Conduit*

have a negative impact on aquatic species within the karst system by decreasing the quantity of water entering the system. As noted, if a karst site is not undergoing active sinkhole development or environmental degradation, then one should try to minimize changes to surface and subsurface water conditions. That being said and with proper site knowledge and environmental controls, innovative solutions can be applied to protect baseline karst system integrity.

Stephenson, et al. (1997) present a case study in which highway storm water runoff was directed into a sinkhole as part of the storm water management program in Tennessee. The initial flush of storm water went through a filter system consisting of peat, sand, and limestone to remove contaminants by sedimentation, filtration and adsorption. The tested sorption/filtration systems achieved contaminant removal efficiencies in the range of 90 to 99%. A similar program was going to be conducted in Maryland on a project that the author had direct involvement with, but the program was canceled at the last minute due to lack of funding. Duffy (2008) also made use of existing sinkholes for stormwater management for a new hospital in Indiana. Special measures included oil-water separators to minimize petroleum hydrocarbon contaminants from reaching the subsurface water.

Engineering Over Karst

The variability of karst makes characterization and identification of features extremely difficult. Characterization for geotechnical engineering efforts in karst must include methods that provide understanding of surface and subsurface water as well as site activity regarding sinkhole occurrence intervals; this knowledge must be developed before assessing any karst project.

Test borings and geophysical methods are tools that will help characterize localized areas, but one must be extremely careful in relying on this data alone.



Figure 8. *Difficulties of Site Characterization in Karst*

Construction within karst will encounter unexpected challenges no matter how much time and money is invested (or wasted) in an effort to fully characterize all karst features; karst will never fully reveal itself. For example, consider a typical roadway project involving several kilometers of roadway in Indiana with multiple test borings developed along cross sections. Refer to Figure 8 and consider the odds of encountering this feature with a test boring program (which this project did not encounter). This is not an idealized or isolated case when dealing with karst as the author could provide multiple examples of unexpected karst features. However, to properly address these types of challenges in the field, one must have an understanding of the basic karst principles noted herein. Proper site characterization must not only involve our traditional geotechnical tools, but it must involve methods to assess subsurface water conditions. Water level monitoring of both elevation as well as temperature and correlating that data to precipitation are powerful tools to begin understanding karst. Fluctuations in subsurface water begin to provide an understanding of potential risk for subsurface erosion. Variations in temperature provide insight into subsurface water recharge and water movement. Relative risk of sinkhole collapse can also be calculated with a high degree of certainty with a proper site characterization program (Zhou, et al. 2003; Kutschke, et al. 2005).

Sinkhole remediation from a geotechnical engineering perspective is generally undertaken to alleviate subsidence hazards. It is important to note that most cover-collapse sinkholes are associated with epikarst drains where water movement has eroded sediments. Common methods to remediate these sinkholes involve creating an obstruction in the sinkhole throat, which consists of an inverse aggregate graded filter or a grout plug (Sowers, 1996; Hubbard, 2001; Duffy, 2008;

Kutschke, et al. 2014). Prudent use of these treatments requires consideration of surface water and subsurface water conditions. Although a grout plug is thought to be the most effective means to repair a sinkhole, it is not the most effective means to deter future sinkhole development. Sinkholes develop because of subsurface water movement causes erosion; remediation should consider allowing the water to flow along its known preferential path but not let the water cause erosion. Plugging the preferential pathway merely diverts the water to surrounding areas with unknown consequences. The use of inverse-graded filters to seal a sinkhole throat and allow the continued movement of water should be given serious consideration. However, solutions may require grout due to site constraints, although this does not alleviate understanding the ramifications. Consideration should also be given to the use of geomembrane lined drainage ditches and geomembrane lined storm water retention basins with pump stations to control surface water.

Summary

Every karst site is unique. However, lessons learned from review of case histories all have a commonality, that being water. Site characterization must focus efforts to understand the cause of sinkhole occurrence along with surface and subsurface water over seasonal conditions. Given the many site characterization tools available today, simple methods that provide a snap-shot in time are not sufficient. Water is the driving force in karst and sinkhole formation, and one must not become blind to the process operating in the subsurface over time. Occluding known epikarst drains, altering surface drainage, and lowering groundwater are among the many contributors that could lead to sudden and catastrophic karst expressions. Understand the water, and you will begin to appreciate the challenges of karst.

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LINKING GEOLOGY AND GEOTECHNICAL ENGINEERING IN KARST: THE QATAR GEOLOGIC MAPPING PROJECT

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Abstract

During a time of expanding population and aging urban infrastructure, it is critical to have accurate geotechnical and geological information to enable adequate design and make appropriate provisions for construction. This is especially important in karst terrains that are prone to sinkhole hazards and groundwater quantity and quality issues. The State of Qatar in the Middle East, a country underlain by carbonate and evaporite rocks and having abundant karst features, has recognized the significance of reliable and accurate geological and geotechnical information and has undertaken a project to develop a robust geotechnical relational database and prepare geologic and thematic digital maps. These products will support planning, design, and decision-making processes related to urban infrastructure development in the rapidly growing State and be particularly useful in the early stages of geotechnical investigations. The U.S. Geological Survey (USGS), Gannett Fleming, Inc., and the Qatar Ministry of Municipality and Environment (MME) have partnered to design a geologic mapping project that will merge geological and geotechnical information to develop a framework to model the geology, karst, and resources important to support growth in the State. The Qatar Geologic Mapping Project (QGMP) has a mission to integrate sound geoscience data for the State of Qatar to address societal, environmental and educational needs that include water and mineral resources management and natural hazards reduction.

Introduction

Currently, the State of Qatar does not have adequate geologic maps at regional and local scales with detailed descriptions, proper base maps, GIS, and digital geodatabases to adequately support future development. To better understand the region's geological and geotechnical conditions influencing long term sustainability of future development, the Infrastructure Planning Department (IPD) of the Ministry of Municipality and Environment (MME) of the State of Qatar has commenced the Qatar Geologic Mapping Project (QGMP). This project will develop high-quality geologic maps, geotechnical data, and thematic maps important in meeting this objective, which includes understanding the State's karst environment and characteristics through development of a geologic framework.

Qatar, located in the Middle East, is a peninsula surrounded on three sides by the Arabian Gulf (Figure 1). Although it has an arid climate with average annual precipitation of 7.5cm, its karst topography is well developed with more than 9700 depressions identified in a country of 11,586 km² (U.S. Central Intelligence Agency, 2017). Large open throat and collapse sinkholes, and caves are found in rural and urban areas. Although Qatar is a desert environment, karst that formed during a wetter climate in the Pleistocene impacts the State today as developers often encounter cavities in the subsurface

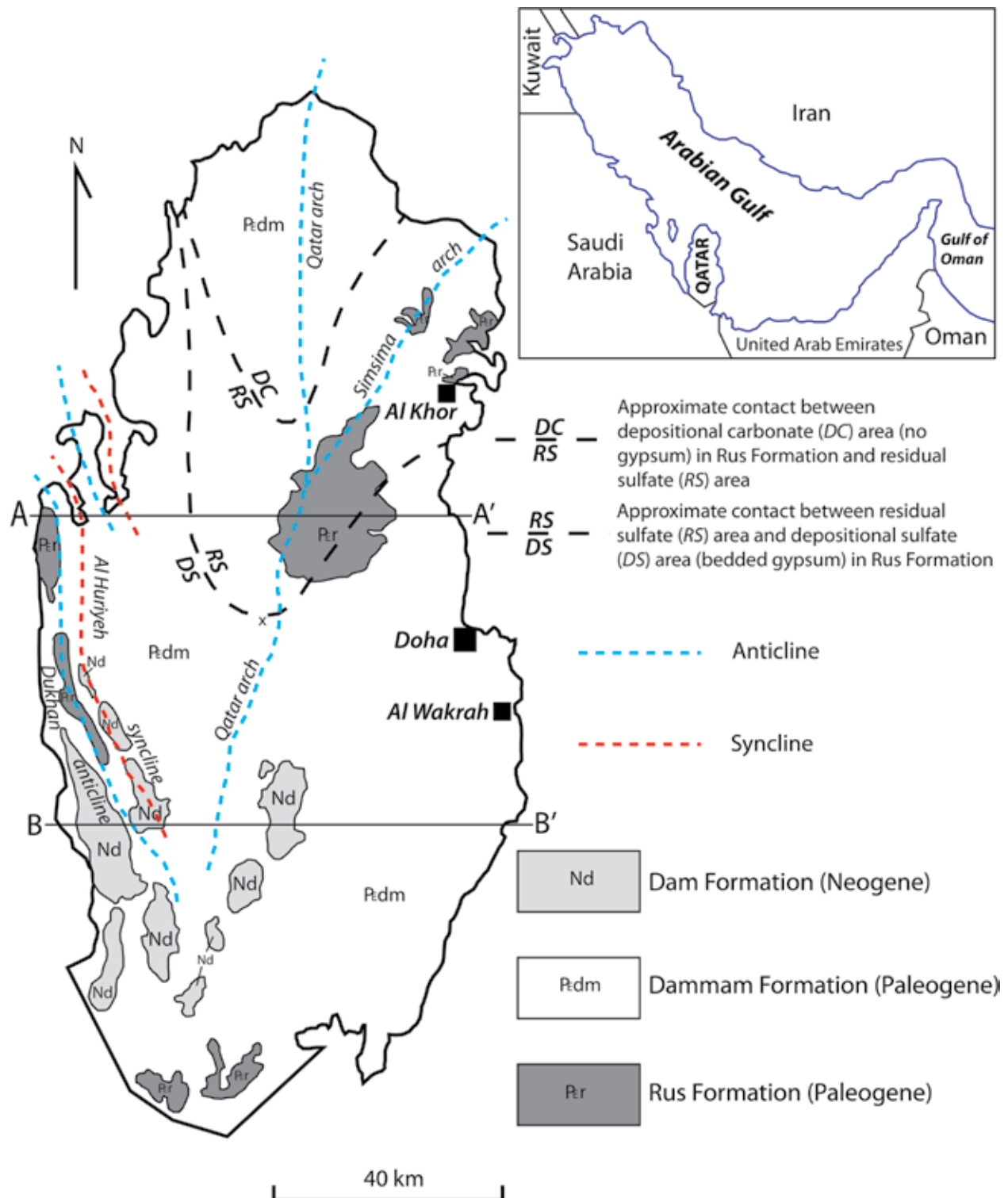


Figure 1. Simplified geologic map of Qatar showing facies types of the Rus Formation and differences in karst development (modified from Eccleston et al., 1981). Schematic sections A-A' and B-B' are shown on figure 2.

during construction activities. One of the essential objectives of the QGMP is to analyze the geologic controls on karst development, particularly in terms of lithology, groundwater, regional structures, and fractures by utilizing geologic field mapping, subsurface information, and remote sensing data. Development of high-quality geologic and thematic maps coupled with a robust geotechnical relational database will provide planners, developers and designers the scientific basis to make informed decisions with respect to the potential physical and financial risks associated with future land use and development.

Geologic Setting

The low relief of the Qatar peninsula is coincident with a broad, north-trending fold called the Qatar arch with the axis of the arch being nearly equidistant from east and west coastlines (Figures 1 and 2). Along the western margin of the peninsula is the Dukhan anticline, a structure that defines Qatar's largest onshore oil field (Figures 1 and 2). Approximately 80 percent of the land surface exposes chalky dolostone and limestone of the Eocene Dammam Formation (Figure 1). In southern Qatar, the Dammam is disconformably overlain by 40-80 m of limestone, dolostone, and evaporite rocks of the Miocene Dam Formation. The Dam Formation commonly occurs as erosional remnants that cap the higher elevations.

Qatar has been part of a stable platform from the Permian through part of the Tertiary as recognized by the cycles of shallow water carbonate rocks with some anhydrite, gypsum and clay deposits (Perotti et al., 2011).

The surface and near subsurface stratigraphy includes as much as 600 m of Tertiary carbonate and evaporite rocks with some interbedded clastic units (Figure 3). Within the limestone and dolostone exposures of the Eocene Dammam Formation, the Umm Bab Member is an important unit to structural engineers based on its common use as a load-bearing stratum, however it also exhibits a proclivity to air- and water-filled cavities, and thus, is the focus of considerable geotechnical investigation. The base of the Dammam consists of clay or shaley to clayey dolomitic limestone called the Midra Member. In southern and central Qatar, this member can be considered an aquitard where it is sufficiently thick and mostly clay; it is absent in the northern part of Qatar. The underlying Eocene Rus Formation also demonstrates lithologic changes between the northern and southern parts of the State (Figure 1). Thick sequences of gypsum in the lower part of the Rus Formation are present in the south, but not in the north where both depositional conditions and secondary dissolution may explain its absence (Eccleston et al., 1981). The Paleocene and lower Eocene Umm er Radhuma Formation is a complex, poorly understood unit that only occurs in the subsurface of Qatar. Due to its secondary and tertiary porosity, the Umm er Radhuma Formation is an important unit for injection of treated sewage effluent and waste fluid disposal in oil and gas production areas. Also, the unit is under evaluation for use in regional aquifer storage and recovery programs.

Robust Geologic Map Products

The wide variety of uses of geologic maps is so broad that they are one of the most requested scientific products whose return on investment have been calculated at more than 25 times their cost to produce (Bhagwat and

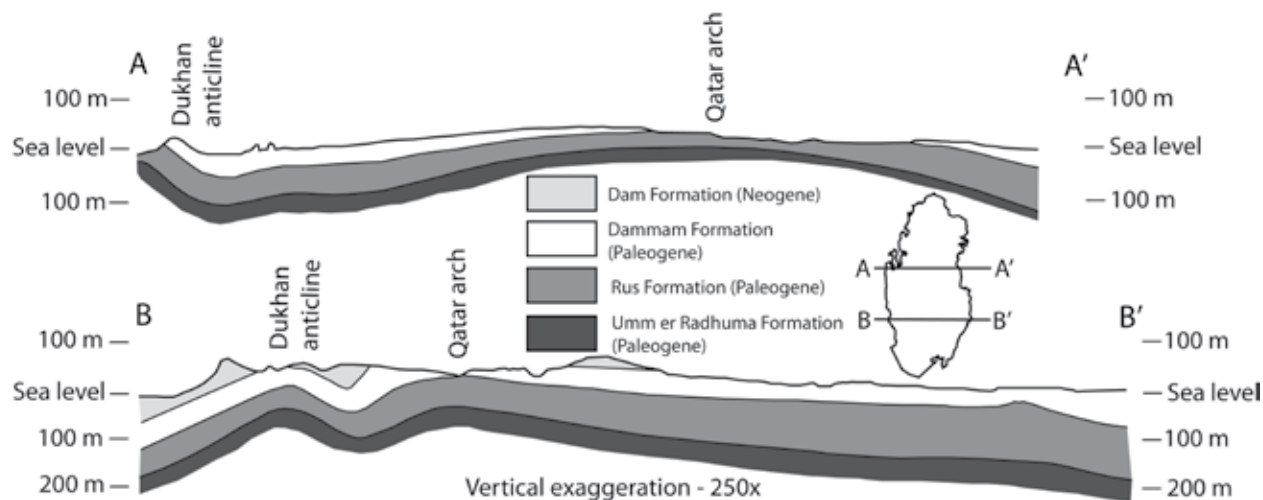


Figure 2. Schematic geologic cross sections of Qatar (modified from Seltrust Engineering Ltd., 1980). Lines shown on figure 1.

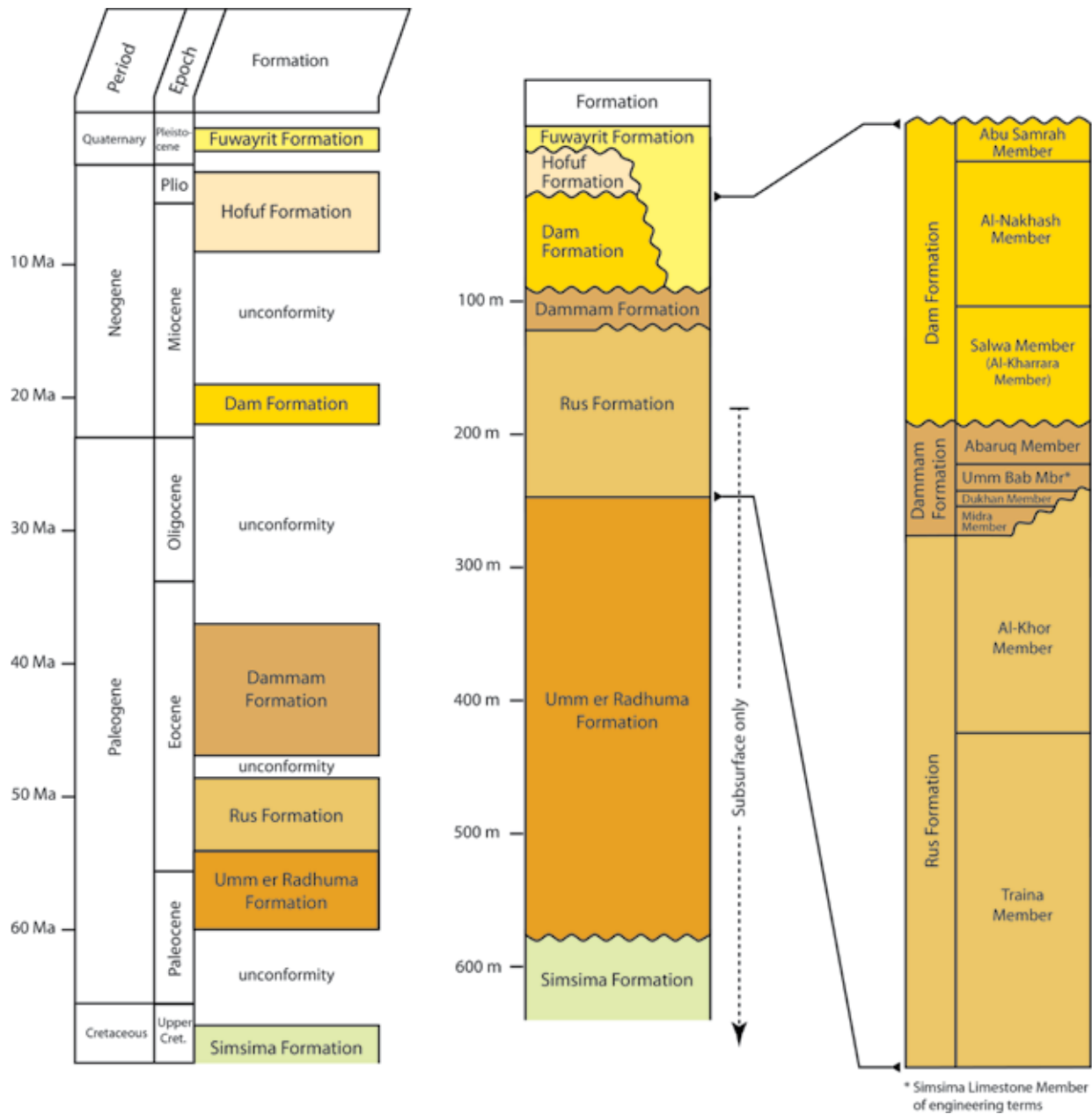


Figure 3. Stratigraphic column for the Qatar Geologic Mapping Project including age and thickness of uppermost Cretaceous and Cenozoic units in Qatar. Sources include Al-Husseini (2008), Al-Saad and Ibrahim (2002), Al-Saad (2005), Dill et al. (2003), Dill et al. (2005), Dill and Henjes-Kunst (2007), Haq and Al-Qahtani (2005), Kok and LeBlanc (2012), LeBlanc (2008), Sharland et al. (2004), Williams and Walkden (2002).

Ipe, 2000a; Bhagwat and Ipe, 2000b). The benefits of a geologic map include increased credibility of projects and time saved in completing projects. The robustness of a geologic map is found in its multiple uses. For example, a geologic map produced to address mineral and energy resources of a region can be used by other investigators to evaluate groundwater resources. Therefore, geologic maps tailored to geotechnical and

other development issues will continue to provide useful information to address future needs.

The MME has undertaken the development of a geotechnical relational database to compile and preserve existing subsurface information, and to provide a structure for future updates. This investment in engineering and science is now actively used to assess

conditions in and around on-going infrastructure and development projects. In addition, the database serves as a substantial information source for producing geologic maps and 3D frameworks, structure contour maps, and isopach maps. The geotechnical attributes contained in the database provide detail for the many engineering investigations being completed in Qatar, and they add geotechnical information to descriptions of map units that are important to the geologic mapping effort. Ultimately, the desired GIS-based digital geologic map for the State of Qatar will be a data schema backed by a geodatabase that can support development of a diverse and utilitarian suite of thematic maps.

Evaluation of karst characteristics and impacts on development in Qatar requires detailed geologic products:

- Geologic map of the entire State of Qatar at 1:100,000 scale
- Regional and local geologic maps at 1:50,000 and 1:20,000 scales
- Thematic maps related to specific geological properties and geotechnical characteristics
- A Geotechnical Cavity Collapse Model based on detailed analysis of geological, hydrogeological, and geotechnical factors influencing failure/stability of subsurface cavities
- A 3D geological model for the Doha Metropolitan Area

Karst Characterization

With carbonate and evaporite rocks at and near the surface, Qatar exhibits widespread karst features characterized by sinkholes, shallow closed depressions, and caves. Active karst regions are usually associated with humid climate regimes where precipitation and organics in soils create carbonic acid that over time dissolves carbonate and evaporite rocks at and below the surface. By contrast, Qatar currently lacks both abundant precipitation and a well-developed soil profile containing organic material, strongly suggesting that karst initiation occurred in the geologic past. Previous investigators concluded that karst in Qatar developed in the past during a time of a wet climate 560,000 to 325,000 yrs ago (Sadiq and Nasir, 2002). Several prominent karst features, including large sinkholes and caves (Figure 4), are natural laboratories to understand past conditions.

Embabi and Ali (1990) report more than 9,700 depressions in Qatar that range from a hundred meters to about 3 km in width and between a few centimeters to 25 m in depth. They identified the following types of depressions:

- Sinkholes developed by collapse or subsidence, generally circular
- Shallow depressions with a single center
- Compound depressions, which are an amalgamation of depressions with overall closed drainage (Sadiq and Nasir, 2002)



Figure 4. Misfir sinkhole and cave in central Qatar.

Duggan (2014) demonstrated that the number and size of depressions or closed drainages is sensitive to the mapping method. His study developed GIS work flows to identify depressions with large drainage basins that were most likely to be associated with collapse. The size and depth of depressions correlated directly with the presence or absence of gypsum layers in the Rus Formation (Figure 1). Larger depressions were found in areas where gypsum in the Rus Formation was likely to have dissolved.

The relationship of various geologic and hydrologic parameters to the spatial distribution of karst features aid in determining controls on the various morphologies and density of features (Orndorff et al., 2000; Weary and Orndorff, 2002). These include stratigraphic, lithologic, structural, topographic, and hydrogeologic controls. Previous remote sensing techniques used to identify depressions and sinkholes in Qatar used Landsat satellite imagery or air photo analysis. More recently, the use of high resolution digital elevation models generated from LiDAR has greatly improved identification of controls on karst processes by producing a more comprehensive spatial distribution and database of karst.

For the current study in Qatar, LiDAR data collected in 2017, new topographic maps, and sub-half meter satellite imagery provide multiple geospatial data sets to assess geomorphic features associated with karst and their potential relationship to geologic structures. This data will be processed utilizing appropriate GIS-based algorithms of Doctor and Young (2013) and Duggan, (2014) to delineate closed depression and then evaluated to determine if they are of karst origin.

Through detailed geologic mapping and high resolution digital elevation models from LiDAR, future karst studies will build onto Duggan's (2014) work. For example, high resolution terrain models may lead to an increase in mapped sinkholes. With accurate delineation of karst features such as sinkholes and caves, an understanding of geologic (i.e., structure and stratigraphy) and hydrologic (e.g. relationship to wadis and depth to water table) controls can be determined. Since the Rus Formation plays a major stratigraphic role in both past and current karst processes, mainly in the south, data from outcrops and the subsurface will be built into a southward migrating anhydrite dissolution model following the work of Eccleston et al. (1981). More information on karst related to deeper systems can be gleaned from studying facies changes in the Umm er Radhuma and Dammam Formations in concert with facies models for the Rus Formation. The Dammam Formation is of interest for geotechnical engineering, and the Umm er Radhuma has

critical karst zones that continue offshore and are used for waste disposal (Zampetti et al., 2014). Mapping facies changes of the Umm er Radhuma can help determine if its varying lithologies can serve mixed use of waste disposal and aquifer storage.

Karst Hazards

Karst features pose a potential hazard that need to be considered for land-use planning, construction, and groundwater resource management. Sinkholes, collapses, and caves/cavities present a hazard for construction, potentially impacting the load-bearing capacity of the rock. Deep-seated sinkholes with connections to deep conduits provide a point source for surface and near-surface contamination that can impact aquifers. By adding karst features to a GIS-based geospatial project, this information can be used with geologic maps to better define geologic controls associated with, (1) karst-related potential sources of groundwater contamination, (2) collapse features that affect transportation infrastructure, and (3) karst features that may potentially impact future development in urban areas.

In addition to the geotechnical rock mass characteristics of subsurface materials, particularly with respect to building foundation design and buried infrastructure, owners, engineers, developers, and planners are also very interested in understanding the behavior of karst features and the potential geological hazards they may cause. With carbonate and evaporite rocks at and near the surface, cavity collapse and settlement associated with the presence of shallow solution cavities cause significant geotechnical and other engineering problems across the entire State of Qatar. The Rus and Dammam Formations, which are composed of interlayered limestone, dolostone, mudstone, siltstone, and gypsum, underlie the majority of the State including the developing urban corridor between Al Khor and Al Wakrah (Figure 1). The geologic framework is used to define and understand the following:

- Types of karst features present
- Density of karst features
- Catchment areas of depressions
- Geologic controls on karst formation (structure and stratigraphy)

Although Qatar is a mature karst terrain with more than 9,700 large and small depressions (Sadiq and Nasir, 2002), few published karst studies exist. Duggan (2014) delimited three geographical areas of depressions with differing characteristics - a northern, central, and southern area, which individually are associated with Eccleston et al.'s (1981) model of deposition and gypsum dissolution in the Rus Formation (DC, RS and

DS on Figure 1). The northern area (DC) is associated with depositional carbonate (no gypsum) with shallow, low-lying irregular-shaped depressions (Figure 1). The central area (RS) is associated with residual sulfate (residual gypsum) with elongate depressions, and a southern depositional sulfate area (DS) (bedded gypsum) with deep circular depressions. The southern area is associated with bedded gypsum and appears to cause collapse sinkholes as intrastratal karst. Many known caves are located along or near the crest of the Qatar arch suggesting structural control on karst development (Sadiq and Nasir, 2002). Sadiq and Nasir (2002) noted that most karst features are oriented northeast-southwest and northwest-southeast. These orientations are similar to the trends of regional fracture traces, providing strong evidence of fracture or structural control on karst. Since the modern arid environment is generally not conducive to major karst development, it is suspected that much of the carbonate dissolution occurred in the past. Sadiq and Nasir (2002) reported that the middle Pleistocene was one of these humid periods. Current collapse potential is believed to be tied to dissolution of gypsum in the Rus Formation in central and southern Qatar (Eccleston et al., 1981).

Of concern to the MME is the impact of karst on existing infrastructure and development projects. The following have been observed:

- Settling of foundations due to intrastratal dissolution
- Subsurface erosion of soil into fractures and conduits by flowing groundwater
- Collapse of the land surface
- Rapid inundation of groundwater into construction sites

In urban areas, the shallow aquifers are highly affected by the dewatering associated with the enormous construction projects. This leads to changes to the water table that may lead to the development of karst features. In February 2015, a tunnel boring machine (TBM) working near a light-rail station as part of the Qatar Rail Doha Project was damaged when an unexpected incursion of saline water flooded into and inundated the underground excavation of one of the twin Red Line tunnels during pilot boring advancement (MME, personal communication). No human injuries were suffered in this incident but the 7-meter diameter TBM was heavily damaged requiring extensive repair. Geotechnical investigations preceding the TBM work, which included numerous shallow bore holes, did not detect the ground conditions indicative of conduit flow of saline water. However, north of this location, the Dahl Al Hamam sinkhole was

reported to have a tidal interconnection and is approximately 4.5 km from the coastline (Howari et al., 2016).

Rising groundwater levels have been noticed in various urban areas in Qatar due to infiltrations from public water supply lines, reticulated wastewater collection systems, septic tanks, drainage networks, and irrigation water. However, state-wide, the limited natural renewable groundwater resource is proving to be insufficient to supply the increasingly high rates of water consumption with population growth. The State of Qatar is heavily investing in groundwater management studies to develop strategies for water security and in infrastructure to build resiliency.

Future Karst Studies

By tailoring geologic maps of karst areas with geotechnical rock properties and collaborating with the professionals who use the maps, a more comprehensive, robust geologic map can be produced to aid in planning infrastructure projects. Production of digital geologic maps at detailed scales will support the QGMP mission of integrating sound geoscience data for the State of Qatar to societal and environmental needs, which include water and mineral resources management and natural hazards reduction.

There are many potential karst studies that can be undertaken for the State of Qatar. However, to address the current needs related to the QGMP, the following actions and deliverables are envisioned as part of this project.

- Map and study sinkhole caves to determine controls on cave and conduit development
- Digitally map closed depressions utilizing appropriate geospatial tools and algorithms on LiDAR-derived digital elevation model
- Build upon Duggan (2014) work on mapping and predicting sinkholes
- Classify depressions based on geologic, topographic, and hydrologic controls
- Determine geologic and hydrogeologic controls on karst development
- Attempt to date cave formation (i.e., OSL and paleomagnetism)
- Compare cave passage orientations, sinkhole distribution, and other karst features with fracture, lineament, and discontinuity trends, structural geology, stratigraphy, and potentiometric surfaces to determine controls on karst development
- Include karst features on geologic maps, and in GIS and geodatabase

- Produce lithofacies maps of Rus Formation and compare to karst zones
- Develop gypsum karst model of the Rus Formation using previous and new data on the stratigraphy, and the presence and absence of gypsum from north to south (no gypsum, residual gypsum, bedded gypsum zones)
- Develop a country-wide hydrogeological model to better understand the rapid changes in groundwater and its impact on forming new cavities

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SITE SELECTION OF THE WORLD'S LARGEST RADIO TELESCOPE WITHIN THE DAWODANG KARST DEPRESSION

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Abstract

The world's largest single-aperture radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST), was constructed within an extremely large karst depression, Dawodang, in Pingtang, Guizhou, China. The FAST system will improve the sensitivity and extent of astronomical investigations in the near future. In June 1994, astronomers decided to construct the next generation and largest radio telescope. Many types of topographical depressions such as mine pits, volcanic craters, meteor craters, karst depressions, and extremely large sinkholes were considered during the site selection process. Considering the size, spherical shape, bearing capacities, and ease of drainage of karst depressions, extremely large karst depressions were targeted areas for the FAST system. After careful investigation and site characterizations of more than 1000 large karst depressions, the Dawodang karst depression was determined to be the ideal and unique site for the FAST observatory. Construction of the FAST started on March 25, 2011 and completed on September 25, 2016.

Introduction

In April 1994, many astronomers decided to actively participate in the international large radio telescope project. Many types of topographical depressions such as mine pits, volcanic craters, meteor craters, karst depressions, and extremely large sinkholes were considered during the site selection process. By the end of 1995, a Kilometer-square Area Radio Synthesis Telescope (KARST) project was determined to be the next generation large arrays of radio telescope. The KARST project was presented during August 26-30

1996, at the 179th Symposium of the International Astronomical Union (IAU) held in Baltimore, USA (Peng and Nan, 1997).

The proposed KARST project was well received at the 179th IAU symposium and attracted great attention in the IAU community. In 1998, Chinese astronomers proposed a Five-hundred-meter Aperture Spherical radio Telescope (FAST) as a predecessor of the KARST project. Considering the size, spherical shape, bearing capacities, and ease of drainage of karst depressions, extremely large karst depressions were targeted areas for the FAST system. After careful investigation and characterization of more than 1000 large karst depressions, the Dawodang karst depression in Pingtang, Guizhou was selected to be the ideal and unique site for the FAST observatory.

Study Area and Site Characterization

The Dawodang karst depression is located in fengcong karst areas of Pingtang, Guizhou province of southwestern China. Fengcong karst is a major type of karst landscape, which is loosely correlated to cone karst (Waltham, 2008) or cockpit karst (Huang et al., 2014). Mature fengcong karst is dominated by U shaped depressions bounded by rolling hills.

Within a 6.2 by 4.6 km area, there are 64 karst depressions and the mean density is approximately 2.2 depression per km² (Figure 1). Characteristics of the Dawodang depression include 1) It is a U shaped depression so that the surrounding hills would block external electromagnetic signals (Figure 2 & 3); 2) Excavation

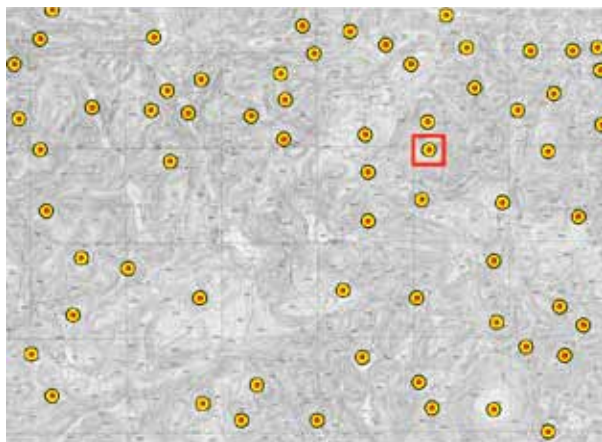


Figure 1. The Distribution of karst depressions in the 6.2 by 4.6 km Liushui area. Dawodang depression is highlighted by the red box.

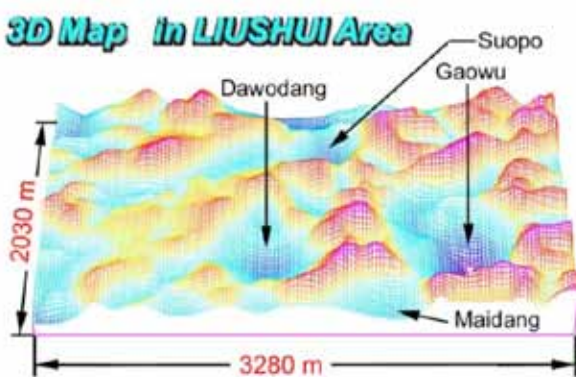


Figure 2. Topographical contour of the Dawodang and the surrounding Liushui area.



Figure 3. Photo of Dawodang depression before FAST construction (May 25, 2009).

of the site is minimal for a 500-meter diameter radio telescope; 3) The site is located in a remotely rural area without urban development which would ideally result in low background electromagnetic radiation; 4) No major natural disasters such as earthquakes, landslides, floods existed in the site and issues of unstable rocks and internal floods can be resolved through engineering design and practice; 5) Dawodang is about 7.5 km from the Guizhou highway S312 and 185 km from Guiyang, the capital city of Guizhou with an international airport and high-speed rail way stations; and 6) The Guizhou government and local residents are very supportive of the FAST project. Construction of the FAST started on March 25, 2011 and was completed on September 25, 2016 (Figure 4 & 5).

Conclusions

The selection process for the FAST Observatory lasted 12 years and ended up in an ideal and unique location, the Dawodang depression. Dawodang is a typical U shaped



Figure 4. Aerial view of the Dawodang depression during the construction of FAST, image was taken by a DJI drone (Mar 31, 2012).

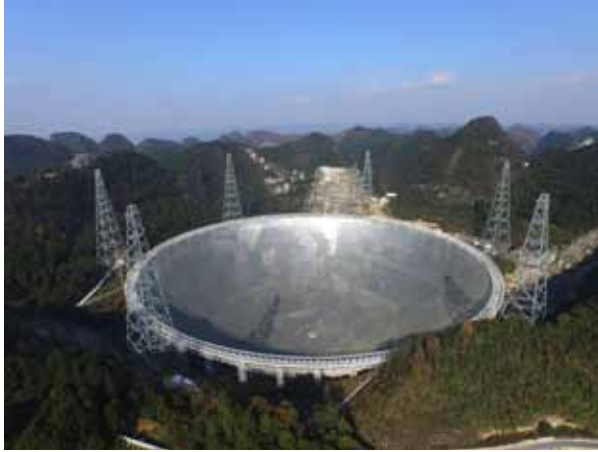


Figure 5. Bird's eye view of FAST (December 31, 2016).

karst depression. The FAST Observatory was a great example of utilizing a large fengcong karst depression for a main scientific observatory.

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DEVELOPMENT OF A SINKHOLE RAVELING CHART BASED ON CONE PENETRATION TEST (CPT) DATA

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Abstract

Naturally occurring sinkholes in Florida are formed when the soluble limestone bedrock weathers and creates cavities at its interface with the overburden finer-grained soils. The overburden soil then erodes into the limestone fissures, thus weakening the strength and holding capacity of the soil above. This initial stage of a sinkhole is referred to as soil raveling and is considered to be the most effective time to perform soil improvements measures, such as grouting, to mitigate further expansion of the subterranean void. Geotechnical engineers and scientists use subsurface exploration techniques such as Cone Penetration Testing (CPT) to stratify soils and estimate soil properties. This paper presents a CPT-based raveling chart, to be used in identifying raveled soils in Central Florida during initial subsurface exploration. The raveling-chart was developed by collecting a large sample of CPT data (i.e. cone tip resistance, q_c , and sleeve frictional resistance, f_s) from multiple sites within the same geological formation. CPT data was grouped within three categories: collapsed sinkholes, suspected raveling, and non-raveled, and plotted using a scatter of data points with coordinates (f_s , Q_{tn}); that is sleeve friction resistance, and normalized tip resistance. A simple statistical analysis was applied for the resulting data group to create envelopes, or threshold lines, which bound the data to create certain categories. The resulting chart provides quantifiable measure of sinkhole raveling due to soil erosion.

Introduction

Sinkhole risk assessment is not a simple task, and effective prediction of such events would require an extensive amount of knowledge and research in multi-disciplinary subjects. Sinkholes in Central Florida are caused by soil instability, geological formation and degradation, and hydrological extreme events. Studies have shown sinkholes are more frequent in the rainy

months following a severe drought (Tihansky, 1999), but can also occur sporadically due to human-induced influences such as over-pumping of the Floridan aquifer for extended periods of time. Other human-induced *sinkhole-phenomenon* found in Central Florida cities, include poorly constructed storm water pipes which may leak or break and over time erode the soil underneath, causing collapse above. These “wash-out” cases of sinkhole involve a similar internal erosion mechanism.

Naturally occurring sinkholes are a function of soluble bedrock, groundwater flow characteristics, and soil type. Over geologic time, finer-grained soils dislodge at the bedrock interface, and erode into the cavities within limestone. In areas where there is a positive difference between the non-artesian groundwater level and the piezometric level of the Floridan aquifer, a hydraulic gradient can expedite the internal erosion in concentrated areas through seepage forces and subsequent piping (Sinclair, 1986). Figure 1 presents the conceptual progression and profiles of the most typical type of naturally occurring sinkhole in central Florida: the cover collapse. This form of sinkhole only develops in certain types of geology where there exist some strata with relatively high cohesive properties overlain by sandy material. Internal erosion within this competent clay or silt layer, enables formation of a *void* as the finer-grained soil migrates into the cavities of the limestone. This zone of internally eroded soil is known as soil raveling.

From a civil engineering perspective, initial detection of this raveled soil zone is key to maximize effectiveness of any required sinkhole mitigation procedures (e.g. grouting), and to minimize the risk of construction-induced collapse (e.g. groundwater pumping, pile driving, or increase in stress from heavy machinery). However, detection practices of raveled soils are not well defined and are far from being standardized. The objective of this paper is to present a technique to detect

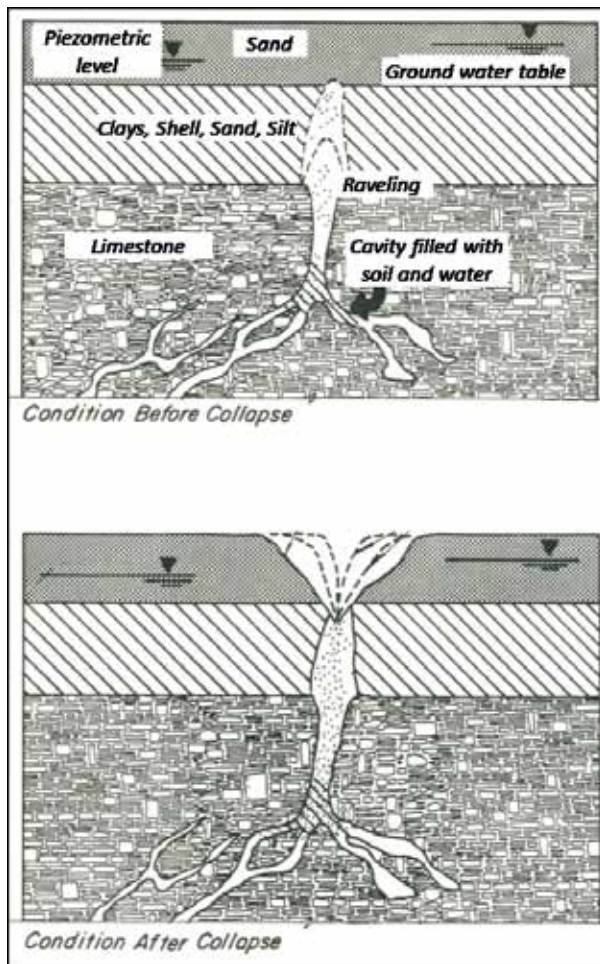


Figure 1. Conceptual Profile of Sinkhole formation and raveling phenomenon. (from Jammal, 1984)

these raveled zones using Cone Penetration Test (CPT), which is a common subsurface test during initial site investigation.

Cone Penetration Testing

The Cone Penetration Test (CPT) was developed from the need to quickly estimate the strength of subsurface soils without the use of large scale, intrusive drilling equipment. The test consists of a hydraulic ram (commonly mounted on an off-road vehicle) which pushes a probe and subsequent series of hardened steel rods into the ground at a constant rate (2 cm/s). The probe (shown in Figure 2) has a conical point with apex angle of 60° . Electric transducers within the probe measure the reaction forces behind the cone tip and along a 14cm long section of the outer pipe diameter, resulting in measurements of cone tip resistance (q_c) and sleeve frictional resistance (f_s), respectively. Recently produced probes also allow for the measurement of pore-water pressure with depth, through piezo-

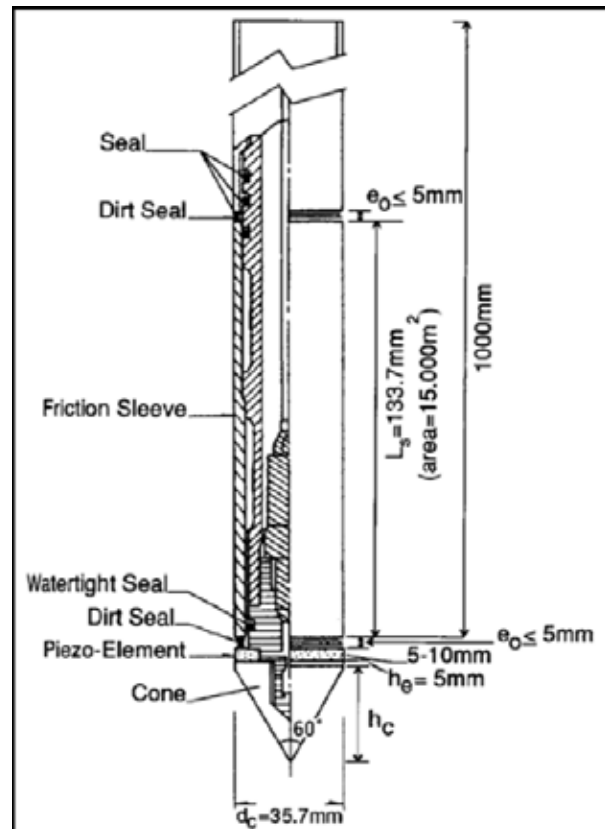


Figure 2. Schematic section through a CPT probe (from ASTM D 5778-95)

element transducers. The major benefit of CPTs over the conventional Standard Penetration Test (SPT) is its ability to detect discrete changes in soil density, and to provide a continuous profile of stiffness data during penetration. This benefit makes the CPT ideal for detecting and analyzing anomalous soils which may be indicative of geohazards such as sinkholes or landslide slip-planes. Unfortunately, the CPT does not provide any *insitu* soil samples like the SPT, therefore subsurface characterization using strictly CPTs is not advised without a good understanding of expected soil types at a project site. The CPT data analyzed in this study was obtained from test sites with available SPT and soil classification data used for verification.

Methodology

CPT provides engineers and geologists an immense amount of data regarding the soil stiffness profiles with depth. The conventional CPT provides a data set consisting of tip resistance, q_c , and sleeve friction f_s , every 2 cm of penetration. Development of correlations to estimate soil classification, soil strength parameters, and soil capacity limits, is a well-established research area (Meyerhof, 1956; Schmertmann, 1978; Robertson,

1990). However, very little in-depth research has been performed to link CPT results with sinkhole-prone soils. Data collection, filtering, and analyzing was held in high regards in this study to ensure an accurate raveling criteria useful for Central Florida practitioners. With hopes to understand and identify trends in how CPTs record measurements in raveled soils, subsurface data was collected from several known sinkhole active sites in central Florida, exhibiting karst terrain. To account for any variation in soil type (even on a local scale), the data processed in this study was collected within the same geological formation in Central Florida and shared similar characteristics with encountered stratigraphy.

Data collection and preparation

CPT data was provided for this study by Florida Department of Transportation (FDOT) District 5. Their available database of Cone Penetration testing performed at active sinkhole project sites consisted of a large amount of subsurface data performed to mitigate or repair natural-sinkholes occurring under or near central Florida's highway within the past 15 years. From this data pool, a total of 4 sites were chosen for this study, due to their similarities in encountered strata, elevations, and hydrogeological conditions. All four sites also lay within the same geological formation, as shown in Figure 3. The Cypresshead Formation (Tc) is found only in the Florida peninsula and eastern parts of Georgia.

This formation originates from the upper Pliocene epoch (~5.3 to 2.5 million years before present) and consists of reddish brown unconsolidated to poorly consolidated, fine clean to clayey sands (FGS, 2001). At these central Florida test sites, the Cypress head formation is underlain by a relatively thin layer of Hawthorne groups of soils (Th and The) which are then underlain by the Ocala limestone bedrock (To). The Hawthorne Group consists primarily of marine deposited clayey to silty sands with trace phosphate mineral and shell. This layer generally acts as the confining unit in this area, separating the surficial aquifer and the upper Floridan aquifer.

The CPT data was first collected and categorized based on its original purpose of testing (i.e. Sinkhole Repair or sinkhole mitigation). Sinkhole repair sites include the US 27 Polk (2010), US 27 Lake (2008), and Deland 15A (2016), in which CPTs were performed to assess the expanse of raveling zone around the perimeter of a recently formed sinkhole.

The Wekiva Parkway (2014) data was the only site in which no actual sinkhole collapse had occurred. Rather, CPTs were performed at this site to assess mitigation techniques in response to extremely loose material encountered above the limestone interface. Twenty-two SPTs were also performed at the Wekiva Parkway site. These tests not only show strong correlation in

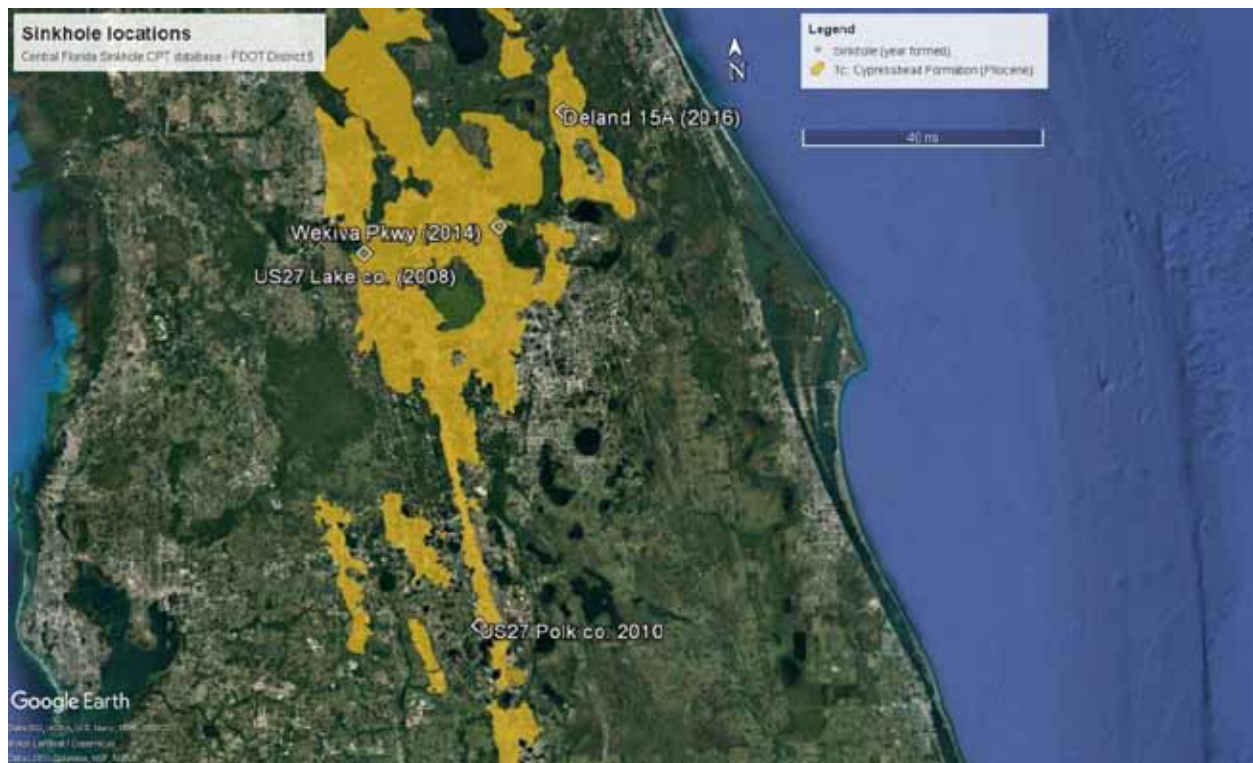


Figure 3. Location of Central Florida CPT data sites, located within the Cypresshead Formation (Tc).

encountered soil strata by comparing tip resistance trends in the CPTs, and blow count values from the SPT, but they also aid in the detection practice of raveled soils. Soil exhibiting extremely low tip resistant values may not always be a result of internal erosion. Research in soil classification using CPTs, shows that some naturally formed clays, highly organic silts, and colloidal fine-grained soils, may exhibit an abnormally low tip resistance value of less than 10 kg/cm² (Robertson, 1990). By retrieving soil samples from these layers of low tip resistance (possible with SPTs), it is much easier to determine whether the encountered soil is consistent with the expected soil strata in suspicion to be experiencing raveling. Figure 4 shows results from a CPT and an SPT, performed within close proximity to each other, at the Wekiva Parkway site. From the comparison, we see a strong correlation between the SPT blow count data (N60) and the Normalized tip resistance curve (Q_{tn}). However, also apparent is the lack of resolution within the N60 curve due to the smaller sampling rate with depth from the SPT. Because of this limitation, SPTs were only used in this study to verify the type of soil encountered in the CPTs.

A total of 125 CPTs from the database sites were deemed significant for use in this study. The CPTs were categorized into three categories based on the encountered soils: Verified Raveled, Suspected Raveled, and non-raveled. The verified raveled CPTs were all taken from the three sinkhole collapse sites. Since there has recently been a collapse of a sinkhole within a few meters of the test, the loose material consistently encountered at depths above the limestone interface, were assumed to be associated with the nearby sinkhole collapse. The suspected raveled data set was obtained from CPTs at the Wekiva parkway project, where multiple SPTs and ground penetrating radar analysis suggests the possibility of internal erosion and sinkhole activity within the site property (PSI, 2014). However, also at the Wekiva parkway site, multiple CPTs did not encounter any anomalous soil. These CPTs were categorized as “non-raveled,” due to the lack of indication of significant zones of loose material.

Although the CPTs were all performed within the same geological formation, raveled soils were encountered at varying depths, even within the same project site. Therefore, a normalization procedure was performed prior to filtering and comparison of the complete dataset. The normalization equation used in this study manipulates the measured tip resistance (q_c) to produce a normalized, dimensionless, tip resistance (Q_{tn}), as shown in Equation 1, and outlined in further detail by Robertson and Wride (1998).

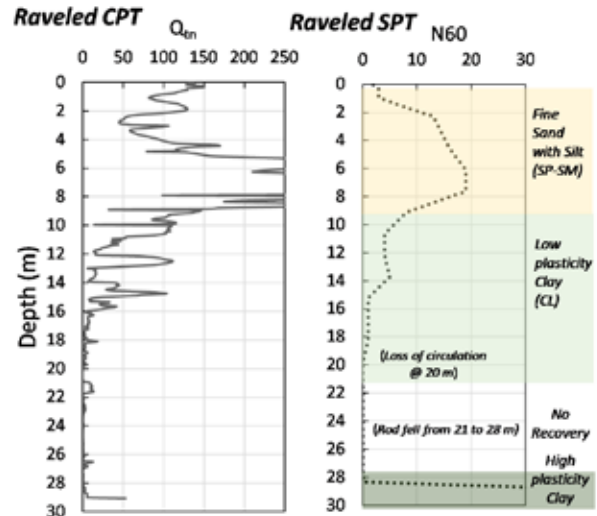


Figure 4. Comparison between a CPT tip resistance profile, and SPT blow count profile with stratified classification.

$$Q_{tn} = \frac{q_c - \sigma_{vo}}{P_a} * \left(\frac{P_a}{\sigma'_{vo}} \right)^n \quad \text{Eq. 1}$$

where, P_a is the atmospheric pressure; σ_{vo} and σ'_{vo} is the estimated total and effective *insitu* vertical stress, respectively; and n is the stress exponent, varying from 0.5 in sands, and 1.0 in clays (Olsen and Malone, 1988). An assumed value of 0.65 was used for the stress exponent in all cases. Likewise, the effective stresses were calculated based on an assumed soil unit weight of 17.3 kN/m³ for each test, with the groundwater table depths taken from SPT observations for each site. It should be noted that the measured sleeve friction value (f_s) was not normalized or corrected for overburden stresses. Normalization of f_s is a highly debated topic and is not well established in literature. The resulting data set, after normalization, consists of Q_{tn} values and the respective f_s values, at each measuring depth (every 2 cm). The average depth of CPT analyzed in this study was 33 meters, therefore the data set from all 125 tests was immense and needed to be filtered for proper analysis.

Data filtering

The following filtering procedure was performed on the Q_{tn} data from the CPTs in the verified and suspected raveling group. Each respective f_s was also then deleted from the data set. This was performed in two primary steps and an example of such is shown in Figure 5. The goal of this step is to create a new dataset with CPT parameters strictly from raveled soils.

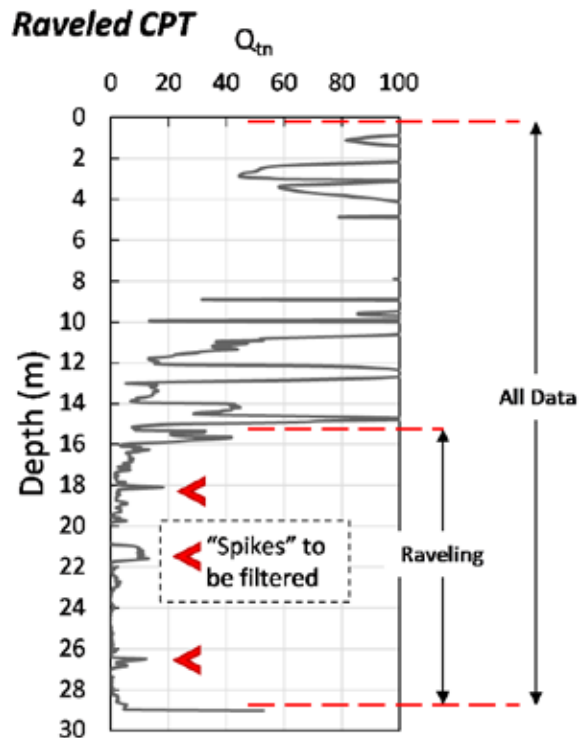


Figure 5. Example of filtering procedure to identify data within raveled zone only.

1). In the CPTs performed within proximity to SPT borings suggesting raveling conditions, an expected depth-of-raveled was established and only data within that window was kept. Figure 4 shows a prime example of how SPT results—such as weight of hammer/rod conditions, or loss of drilling circulation—can be used to estimate the depths at which raveling starts. Further details on this technique can be found in Gray and Bixler’s paper (1994) regarding detection practices of sinkholes in Central Florida using the SPT. For CPTs performed without any nearby SPT borings, the raveled soil zone was assumed to be the abnormally low q_c values directly above the refusal layer. Luckily, the only project site analyzed which did not have SPTs performed, was a site where a collapsed sinkhole had formed. Therefore, the assumption that the encountered loose soils is a sign of sinkhole activity, is validated by nearby collapsed sinkhole.

2) Once the data from the raveled soil zone was determined, further filtering was performed to account for the non-homogenous soil. Even in the raveled soil zones, the penetrating cone sensor may push into lenses of harder material, such as weathered limestone fragments, shell, or phosphates. Since the penetrating cone sensor is roughly 3.54 cm in diameter, the slightest

inconsistency in material density can skew the Q_{tn} curve, causing a drastic “spike”. Although these lenses of material most likely will affect the over-all severity of the raveled zone in regards to its possible collapse (Shamet 2017), the purpose of this study is to identify how CPTs record values of Q_{tn} and f_s data in the raveled material. Therefore, these “spikes” are excluded from the analyzed data set.

Data Analysis

The effects of filtering the data is apparent by simply viewing the data sets on a scatter plot, as shown in Figure 6. In both the collapse site data, and the suspected-raveled site data, we see a drastic decrease in large Q_{tn} values during the filtering process; however, the range of f_s seems to show less deviation.

Another observation from Figure 6 is the concentrated group of negative f_s values in the suspected raveling data set. This anomaly was measured at similar depths from several CPTs performed close to each other. Therefore, the negative sleeve friction is most likely a result of an isolated instance of either improper calibration. Regardless, this encountered negative sleeve friction requires further investigation and is beyond the scope of this paper, therefore is also excluded from the data set.

The filtered data from both the suspected and raveled sites show similar trends in mean, average, and upper limits for both Q_{tn} and f_s . Therefore, for the purpose of developing the raveling chart, both data sets will be included as one to increase in the sample size.

Raveling

The combined CPT-raveled data set now consists of a total of 7334 data points (i.e. Q_{tn} , f_s). When mapped on a scatter plot, there is an apparent confinement of the raveled data. Based strictly on visual observation, the majority of the data seems to fall within the values of 0 – 26 for Q_{tn} , and 0 – 1.0 kg/cm² for f_s . However, the relationship between minimum Q_{tn} and maximum f_s is not as easy to define. As shown in Figure 6, the CPT-raveled data cluster loses its density as f_s increases. In order to properly define this boundary of data containment, a moving histogram analysis was conducted for f_s in terms of its Q_{tn} bin. The values of Q_{tn} were ranked in numerical order, and separated into 19 bins of equal sample size. Since there is a total 7334 data points, each bin consisted of 386 data points (i.e. $7334/19 = 386$). The mean, quartiles, and inter-quartile ranges were then calculated for the f_s data in each respective Q_{tn} -bin. Figure 7 shows the results of such statistical analysis. The ‘+1.5*IQR’ data points were calculated by determining the interquartile range (IQR) for the f_s values in each Q_{tn} bin. By multiplying

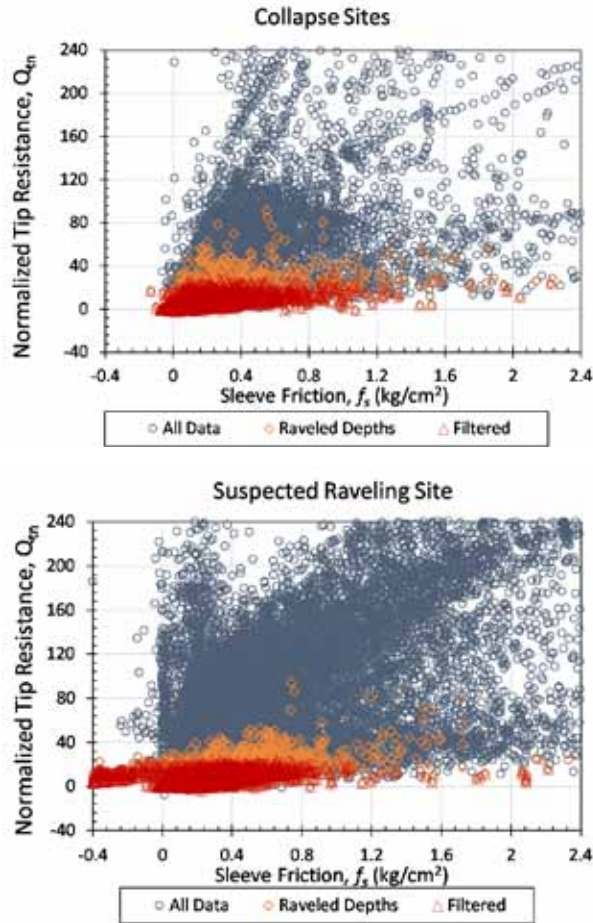


Figure 6. Comparison of data from suspected raveling and collapsed sites, at each stage of the filtering process.

the IQR by 1.5 and adding it to the third quartile value, we get a data point representing the upper “whisker” for that specific bin data.

The upper “whisker” data point represents the value of f_s which is greater than approximately 98% of the remaining f_s in that bin. Therefore, we can use this value as a conservative maximum, stating that any f_s encountered less than this value, for a specific range of Q_m , will be representative of raveled soils. When we perform this analysis for each bin of Q_m values, a clear trend is observed in the resulting means and upper interquartile range “whiskers” ($1.5 \times \text{IQR}$). The envelope drawn by power-law regression of the upper “whiskers” in f_s data, will be used as the upper envelope of f_s and lower envelope of Q_m within the CPT-raveled data set.

Non-Raveling

Similar data analysis was performed for the CPT database of non-raveled material—obtained from

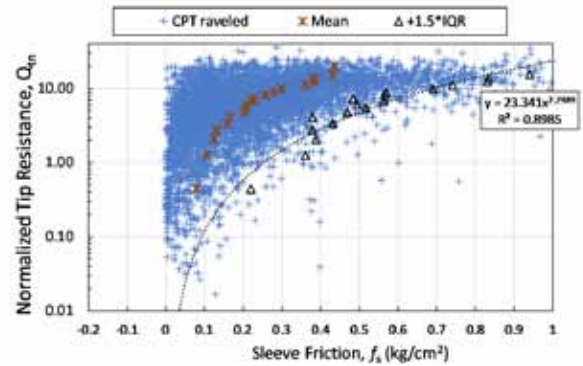


Figure 7. CPT-raveled data scatter with upper-bound f_s quartile envelope.

the Wekiva parkway site. However, no filtering was performed on this dataset since there was no clear trend in Q_m data profiles, suggesting raveling. Therefore, the resulting data ranges were much larger, as expected, than the Raveling Data set. The final non-raveled data group consisted of a total of 4244 data sets. Therefore, to keep consist with the Raveling analysis, a total of 12 Q_m bins were used to assess the f_s histogram plots (resulting in 362 data points in each bin).

Figure 8 presents the results of the same mean and upper “whisker” calculation, expect for the CPT-non raveled data set. However, there is a clear discrepancy in data’s mean values of f_s as the Q_m bins increase. This clear jump in data suggests the upper and lower ranges of Q_m (shown boxed in Figure 8) may be obtained from different data sets. Recall that this specific analyzed CPT-non-raveled data set did not have any filtering procedure applied to it. Even though the CPT profile curves of Q_m , within this data set, did not suggest raveled soil was encountered, smaller zones of loose material (low Q_m) were still encountered in many of the tests.

These relatively smaller zones of soft soils may still indicate soil internal erosion, but on a less severe scale as the ones in the raveled data set. Therefore, this “transition” of raveled-to-non-raveled soil data is still of significance and will be incorporated into the soil-raveling chart. Since the verified raveled soil range of Q_m appeared to have a maximum value of 26, the transitional range of raveled soil conservatively includes values of Q_m up to 50. The upper f_s envelope within this Q_m range was also calculated using the same technique as for the raveled data set. However, the upper “whiskers” of f_s in this specific range, follow more closely linear trend, rather than to a power law.

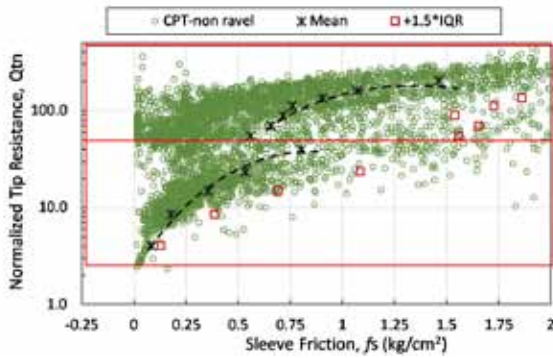


Figure 8. CPT-non-raveled data scatter with split in upper-bound mean envelopes.

CPT-Based Raveling Chart

The comparison of raveled and non-raveled CPT data sets, presented in the earlier sections, were used to develop a CPT-based raveled chart for central Florida sites existing within the Cypress head formation of residual soils. This chart, presented in Figure 9, was developed as a tool to identify potential raveled soils from Q_{tn} and f_s values obtained from CPTs. Practitioners can quickly plot the CPT parameters along this chart, to estimate the likely hood of sinkhole forming raveled soils, during initial site investigation. The five categories which make up the chart represent the most likely degree of raveling encountered within the soil. The boundary lines were created using the aforementioned analysis on both the raveled and non-raveled data sets and are summarized in Table 1. During initial site investigation, if a CPT performed results in a large amount of data falling within the “Raveled soil” category, then the data greatly coincides with CPT stiffness parameters measured from soil which has experienced internal erosion. The Raveled soil* category was included as a provisional or transitional stage. If data from a CPT falls within this zone, but not within the “raveled soil” category, then this soil is most likely undisturbed or at least has not experienced a great amount of raveling yet. The categories labeled “Out of Range” are such that conclusive results could not be drawn strictly from the lack of data within those ranges. However, due to the few isolated occurrences of $f_s < 0$, any data falling in this zone will most likely have a correlation to sinkhole activity, but further investigation should be performed to verify this conclusion.

Summary and Conclusion

The information presented in this study provides an extensive look at the results of Cone penetration testing performed at sites associated with sinkhole activity. A CPT database was developed from a total of 3 historical sinkhole collapse sites located in Central Florida. This

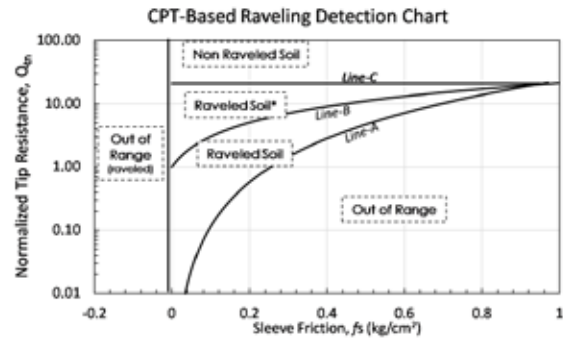


Figure 9. Proposed raveling chart using CPT data (Q_{tn} vs. f_s) for Central Florida

Line	Equation
A	$Q_{tn} = 23.241 (f_s)^{2.2989}$
B	$Q_{tn} = 25.5 * f_s + 1.0039$
C	$Q_{tn} = 26$

Table 1. Category envelope equations for CPT raveling Chart

database was compared to another database of CPT data from a site which had no sinkhole collapse in recent history, but showed strong suggestion that sinkhole activity may be occurring unseen. After comparing and deeming the two datasets statistically comparable, they were combined and analyzed to obtain the limiting values of Q_{tn} and f_s which indicate sinkhole raveling. Additionally, a third dataset was collected and formed of tests which showed no signs of sinkhole forming-soil raveling. This data group was also analyzed using the same technique, and value boundaries were also set. The resulting analysis between the two groups (raveled vs non-raveled) showed a clear distinction between the two's typical Q_{tn} and f_s data, but also showed a zone of data overlap. The resulting envelopes were used to create the proposed raveling chart shown in figure 9. This chart can be implemented to aid in the risk evaluation future sinkhole development during the initial site characterization through correlating any loose soils at a potential sinkhole site, with those obtained from a site with known sinkhole activity. If a large portion of CPT data lies within the “raveled soil” area on the chart, then engineers can conclude that the encountered soil has most likely been exposed to a type of internal erosion indicative of sinkhole formation. Caution should be used, however, when implementing this chart with CPTs data obtained from areas not lying within Cypress-head formation of soils; or at least within sediments of

similar geological deposition. Current studies are being performed to verify the proposed chart is consistent for other geological group soils associated with karst sinkhole formation in Florida. However, the authors believe this proposed chart will still aid engineers through “adding another tool to the toolbox” when discerning whether further subsurface investigation are necessary or to aid in selection of mitigation technique.

Acknowledgement

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PHYSICAL AND NUMERICAL ANALYSIS ON THE MECHANICAL BEHAVIOR OF COVER-COLLAPSE SINKHOLES IN CENTRAL FLORIDA

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Abstract

The behavior of cover-collapse sinkholes in Central Florida was investigated in this research by both physical and numerical methods. In the physical model, a head drop between the unconfined aquifer and the confined aquifer was applied, and the cavity propagation due to a fracture at the boundary between the two aquifers was visually monitored. The cavity grew upwards in an inverted triangle shape until ground surface collapse occurred. The same cavity shape was then incorporated into the numerical study. A stress-seepage coupled analysis was carried out using GeoStudio modules: SEEP/W and SIGMA/W, simultaneously. The stress conditions during sinkhole formation were assessed at different groundwater conditions and cavity sizes. Stress redistributions were observed around the cavity due to soil arching. The effective stress significantly increases at the corners of the cavity to compensate for a stress reduction above the center of the cavity. Highest recharge values and seepage forces occur around the cavity corners. The stress paths at the corners show that the stability decreases when the cavity height increases, even when the overburden thickness decreases. Additionally, the side angles of the cavity affect the stress conditions around it.

Introduction

Sinkholes are a common geohazard in karst terrain which threaten human life and infrastructure throughout the world approximately 20% of the United States has karst features where residual soils are underlain by soluble carbonate rocks. Cavities develop at the interface between the residual soils and bedrock by a soil

erosion process which ultimately leads to ground failure (Newton & Hyde, 1971; Newton, 1976, 1984; Williams & Vineyard, 1976). According to the USGS, the most damage from sinkholes tends to occur in Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania. Florida Geological Survey classifies sinkholes in Florida into three major types: cover-collapse, cover-subsidence, and dissolution. The most dramatic type is the cover-collapse due to its abrupt behavior. The collapse occurs when a subterranean cavity grows until the overburden thickness above the cavity becomes too thin for soil arching to be maintained.

In Florida, the groundwater flow triggers the growth of subterranean cavities by erosion and increases the instability of the system by seepage forces. Florida's aquifer system consists of an unconfined surficial aquifer (residual soil layer) overlying the confined Upper Floridan Aquifer (bedrock layer) which is the main source of groundwater withdrawn for usage purposes. The water level in the surficial aquifer is highly influenced by the rapid infiltration of rainwater due to the relatively high hydraulic conductivity of this soil layer. However, the hydraulic conductivity in the Upper Floridan Aquifer, which is mainly composed of limestone, is relatively low. Therefore, the head of water in the residual soil (surficial aquifer) is usually greater than that in the limestone (Upper Floridan Aquifer) which results in downward seepage (recharge). Wilson and Beck (1992) observed that 85% of new sinkholes in the Orlando area occurred within areas of high groundwater recharge. Whitman and his team (1999) examined the spatial interrelationships of head difference between

the surficial and Upper Floridan Aquifer and sinkhole occurrences in Central Florida, where head differences ranged between 5 m and 15 m.

Subterranean cavities were often modeled and simplified as circular voids, which has been commonly adopted in numerical modeling of sinkholes (Yang & Drumm, 2002; Drumm et al., 2009). However, experimental studies on cover-collapse sinkholes (Tao et al., 2015; Perez et al., 2017) show that a cavity tends to develop as an inverted triangle with a curve-shaped roof. Most investigations of sinkholes often emphasized on the dome stability as a stability/failure problem without considering the soil behavior during sinkhole formation from the stress distribution perspective. Additionally, the sinkhole stability problem has been mostly studied in dry conditions assuming the groundwater level was below the cavities (Yang and Drumm, 2002; Drumm et al., 2009).

The stress redistributions around an underground opening are often governed by the soil arching effect (Tien, 1996). Terzaghi (1943) defined the arching effect as: “the transfer of pressure from a yielding mass onto adjoining stationary parts”. Therefore, the stress redistributions around subterranean openings commonly lead to a stress reduction above the opening, and consequently a stress increase at its sides. This results in high shear stresses in the residual soil on the sides of the cavity which may cause plastic flow (yielding).

In this paper, cover-collapse sinkholes are investigated experimentally and numerically. The behavior of cavity growth and shape is determined from the laboratory study then a numerical model is implemented to assess the soil behavior around the cavity. The study included the effects of the downward seepage and water level variation on the stress distributions and the stress paths at different locations around the cavity. The coupled stress-seepage analysis is performed using two modules of the finite element software GeoStudio: SEEP/W and SIGMA/W

Physical Simulation

The schematic diagram of the sinkhole physical model testing setup is shown in Figure 1. The overall volume of the model is 60 inches x 40 inches x 7.5 inches. The designated volume for soil placement is 36” x 24” x 6”. The model comprises of an unconfined and a confined aquifer. The aquifers are connected by a ¼” wide and 5” long cut in the internal floor that supports the soil and simulates the fracture in the limestone. Valves are installed on both sides of the unconfined aquifer and one at the bottom of the confined aquifer as seen in Figure

1(a). The valves are connected to a constant head system as shown in Figure 1(b). A soil constructed from a 3:1 mixture of AASHTO rated A-3 and A-2-4 soils is used in the model. The soil has an optimum moisture content of 11% and a maximum dry unit weight of 16.8 kN/m³. After compacting the soil to a Standard Proctor relative density of approximately 93% and leveling off the soil surface, the overburden thickness was approximately 43 cm. The soil is then allowed to saturate for a minimum of 48 hours after slowly raising the water levels in both aquifers. To initiate sinkhole formation, downward seepage is produced by lowering the head in the confined aquifer, causing the overburden to erode through the cut in the internal floor.

Figure 2 displays the evolution of a cover-collapse sinkhole. Stage 1 shows the initial conditions before the simulation started. 16 seconds after opening the valve to lower the confined aquifer to apply a 3 cm drop in head, it was noticed that the soil started eroding through the cut. 6 minutes into the experiment a small void became visible (Stage 2). Stage 3 was the most critical stage where the void continued to grow larger due to the erosion process, forming an inverted triangular shaped cavity which enlarged (with the sides inclined around 50° from the horizontal) until collapse took place in Stage 4. During Stage 3, the upward cavity growth was mostly evolving from the corners where the erosion process was most obvious. However, no visible signs of surface settlement took place during Stage 3 until a couple of minutes before the surface collapse, which occurred after 33 minutes. As the near surface soils dried up, the 2nd failure occurred, thus the size of the sinkhole was now significant (Stage 5). In this last stage, an increase in the groundwater level occurred and a pond was subsequently formed; by this time the sinkhole was no longer active.

Numerical Simulation

The numerical model was executed to maintain a similar cavity shape to that observed in the physical study. The configuration of the model is shown in Figure 3. The height and width of the model are 30 m and 60 m, respectively. The cavity has a symmetric triangular shape, and its sides make an angle of 51° with the bottom horizontal boundary. Two different cavity heights were analyzed in this study: 4 m and 8 m. The residual soil layer is modeled as a single homogeneous layer. Zero vertical and horizontal displacements are assumed at the bottom boundary representing the relatively stiff bedrock. The soil is assigned the properties shown in Table 1. These properties are determined from correlations based on field testing data obtained from the Wekiwa area in Central Florida (Shamet et al., 2017).

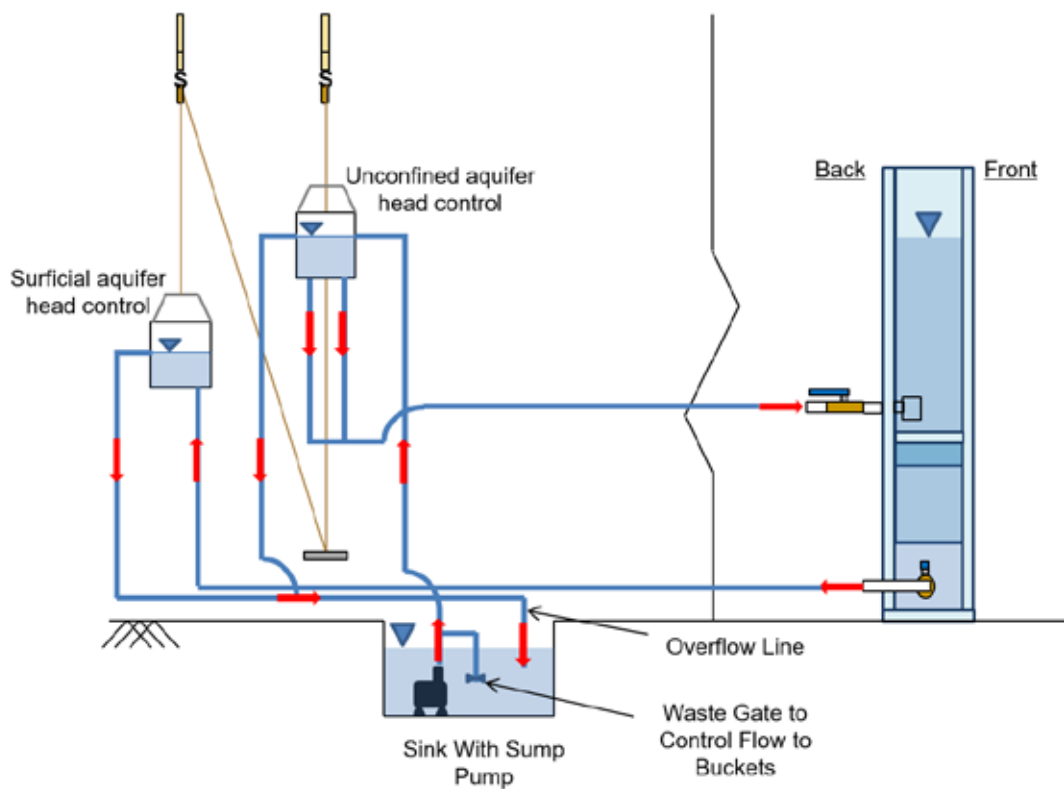
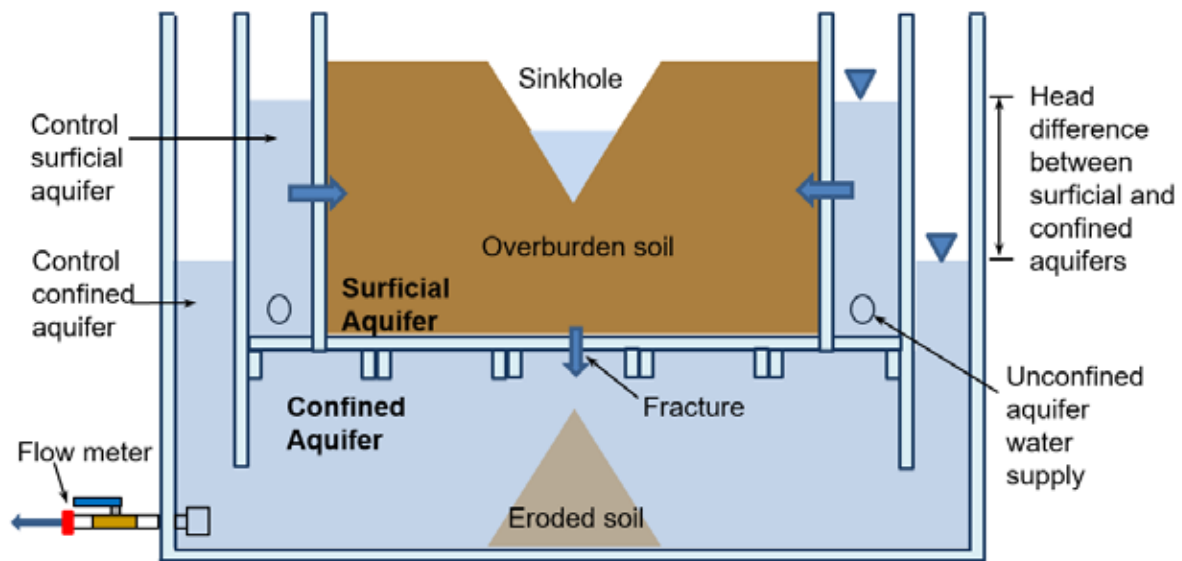


Figure 1. Setup of physical model. (a) Valves are installed on both sides of the unconfined aquifer and one at the bottom of the confined aquifer. (b) Valves are connected to a constant head system

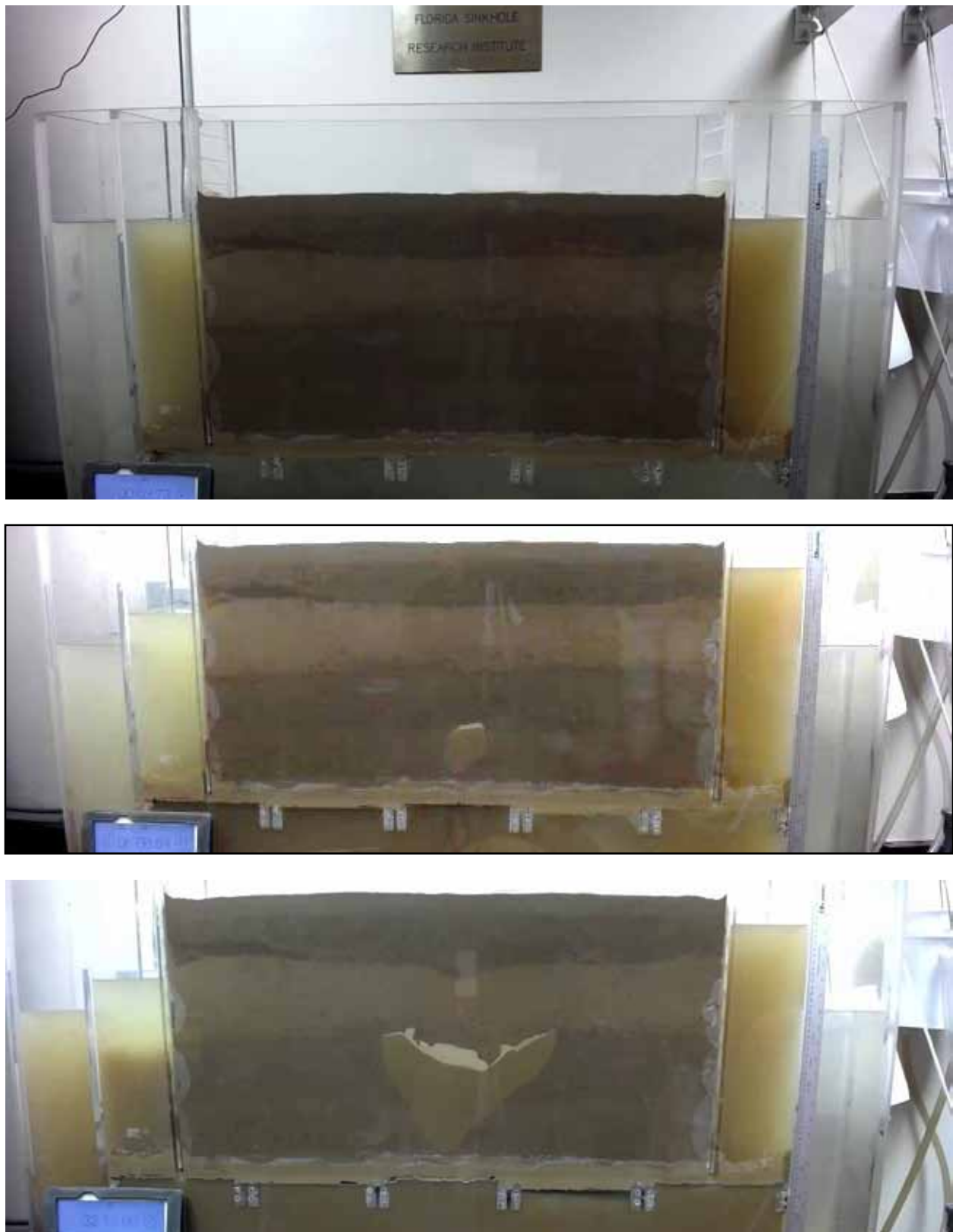


Figure 2. Physical simulation of a cover-collapse sinkhole (a) Stage 1: Test Setup (b) Stage 2: Cavity Initiates (c) Stage 3: Cavity Grows Toward the Surface (Continued on next page)

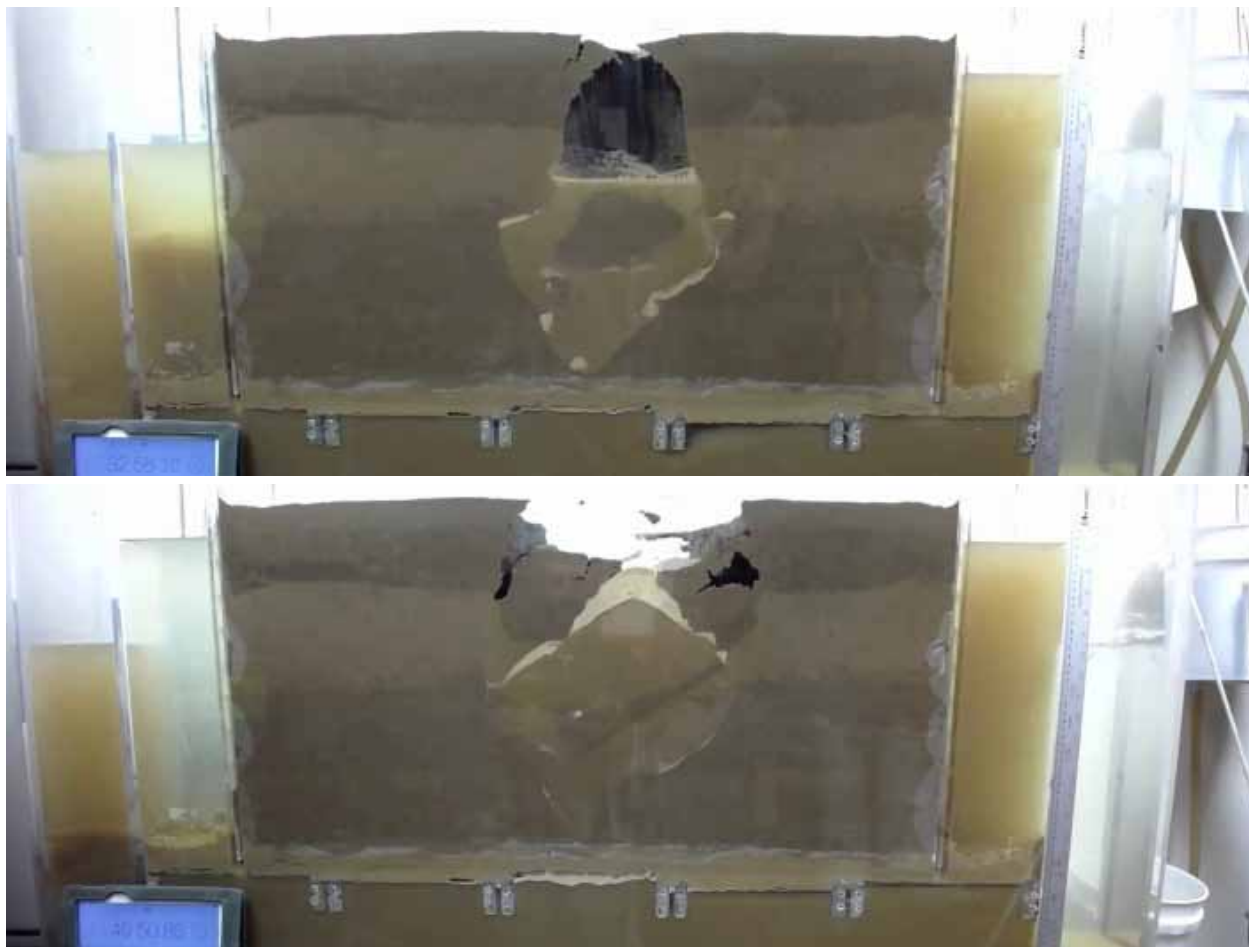


Figure 2. Physical simulation of a cover-collapse sinkhole. (d) Stage 4: Surface Collapse (e) Stage 5: Second Failure and Pond Formation

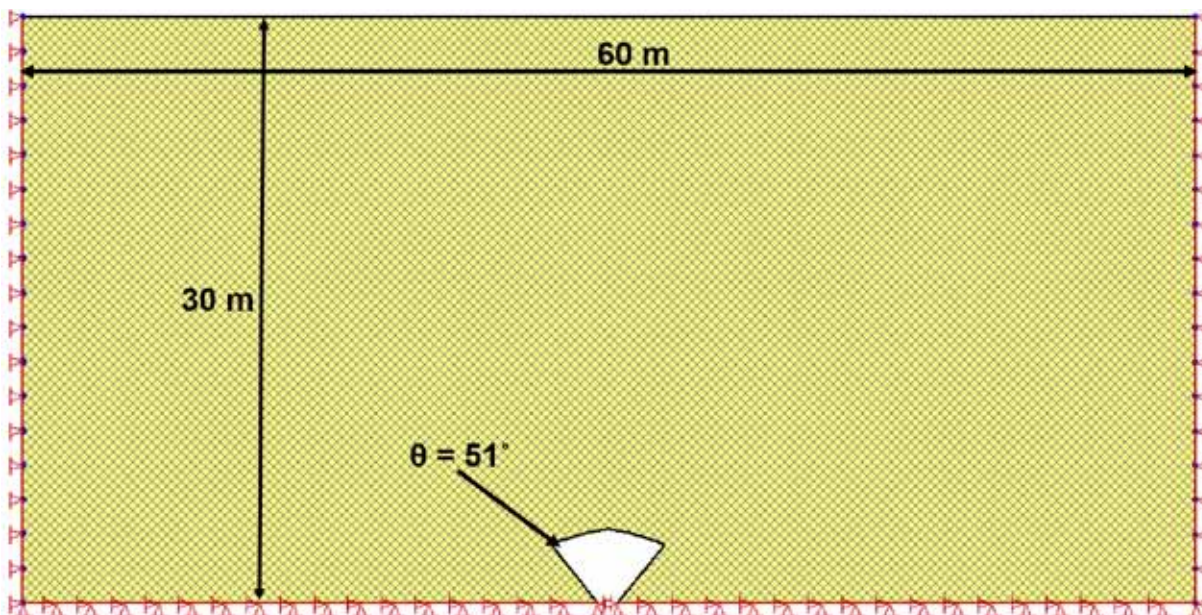


Figure 3. Numerical model

Parameter	Value
Cohesion (kPa)	50
Friction Angle (°)	30
Young's Modulus (kPa)	7000
Poisson's Ratio	0.333
Density (kN/m ³)	18
Saturated Hydraulic Conductivity (m/sec)	1x10 ⁻⁶

Table 1. Values of soil parameters

SEEP/W and SIGMA/W were simultaneously used in order to conduct a seepage-stress coupled analysis. The side boundaries of the model were assigned a total head value of 28 m to generate the initial hydrostatic water level. Total head values of 23 m, 18 m, and 13 m were used at the cavity boundaries in order to simulate the recharge (downward seepage) conditions, creating head differences of 5 m, 10 m, and 15 m, respectively. For each head difference, transient analysis was carried out until steady-state was reached. Figure 4 shows the groundwater drawdown, recharge vectors, and pore

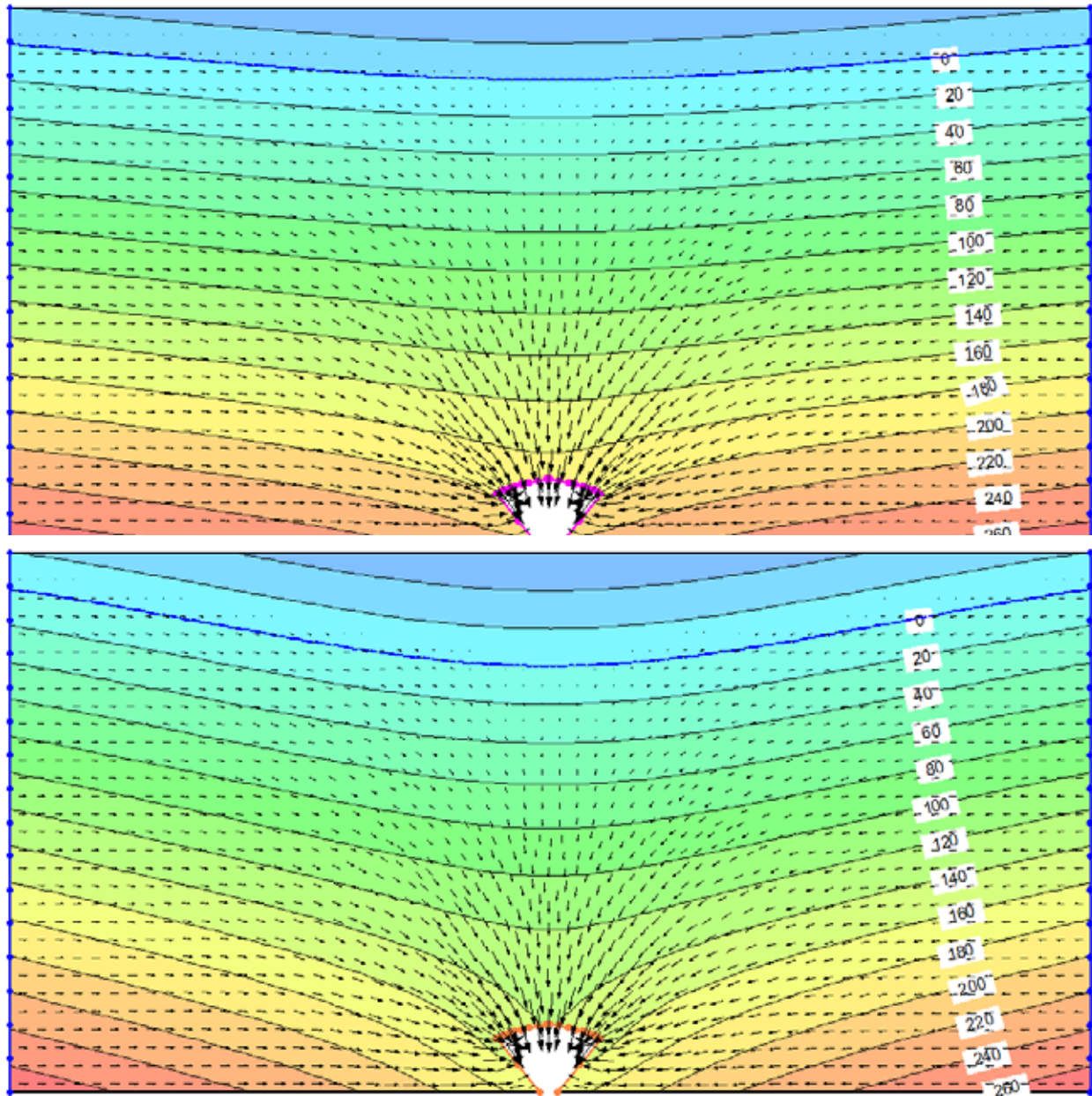


Figure 4. Cross-section showing groundwater drawdown (blue line), flow vectors (arrows), and pore pressure distribution (colored background) at different groundwater conditions (a) Head Difference = 5 m (b) Head Difference = 10 m (Continued on next page)

water pressure distribution corresponding to each head difference value at steady-state. A concentration of the flow (recharge) vectors is noticed at the top corners of the cavity. Therefore, the highest seepage forces take place at these locations. This explains the behavior of cavity growth which usually tends to evolve from the corners as observed in the experimental investigation.

This behavior can also be related to the effective stress redistributions around the cavity, which are explored in the following sections of this research.

Discussion and Results

Figure 5 display the effective vertical stress distribution for all the studied conditions in this research. A stress

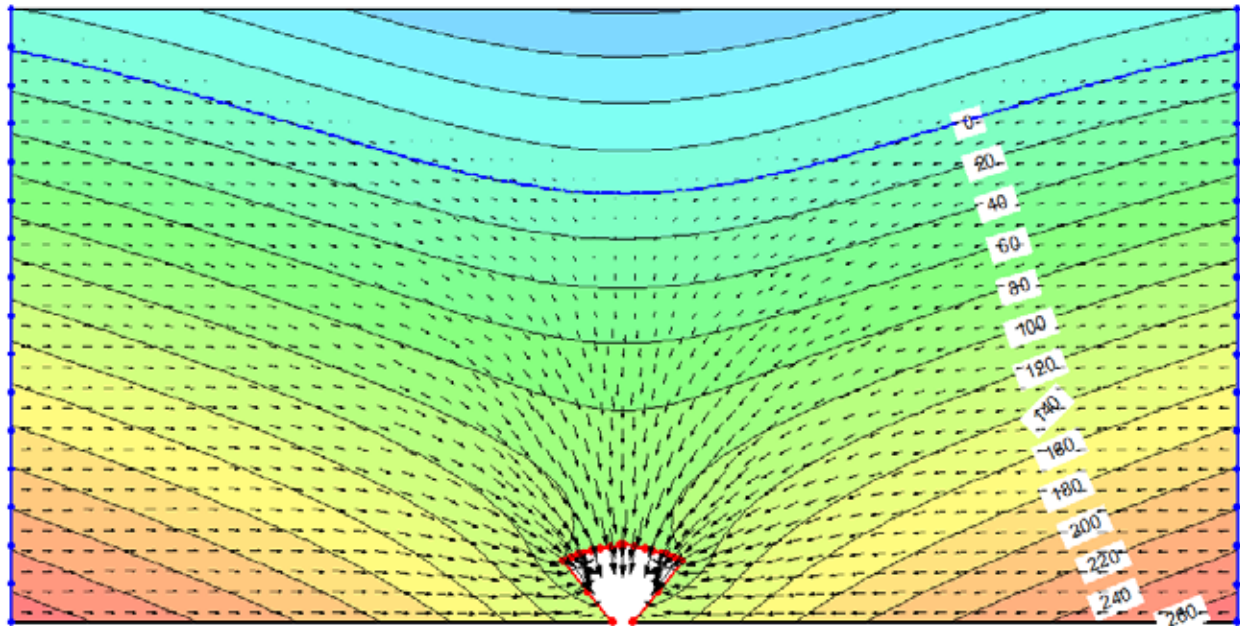


Figure 4. Cross-section showing groundwater drawdown (blue line), flow vectors (arrows), and pore pressure distribution (colored background) at different groundwater conditions. (c) Head Difference = 15 m

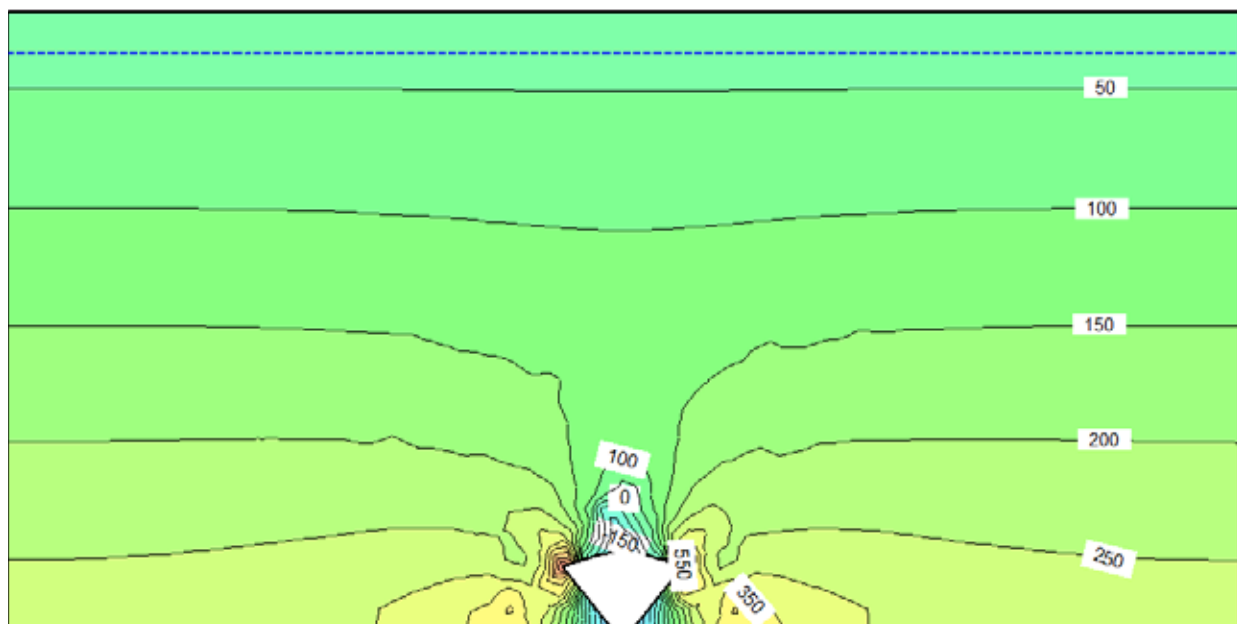


Figure 5. Effective stress distribution at different groundwater conditions. (a) Hydrostatic Condition (Continued on next page)

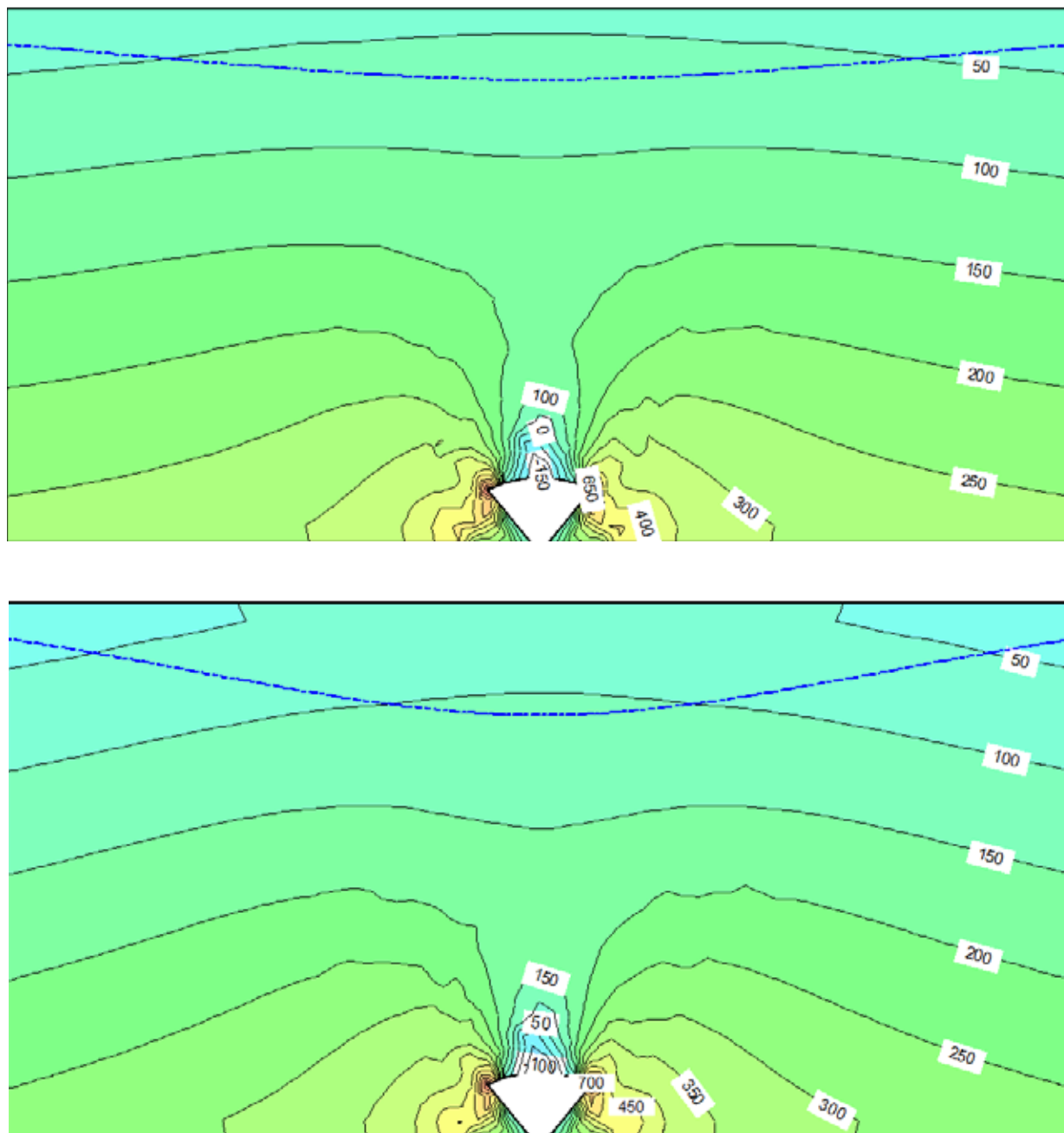


Figure 5. Effective stress distribution at different groundwater conditions. (b) Head Difference = 5 m
(c) Head Difference = 10 m (Continued on next page)

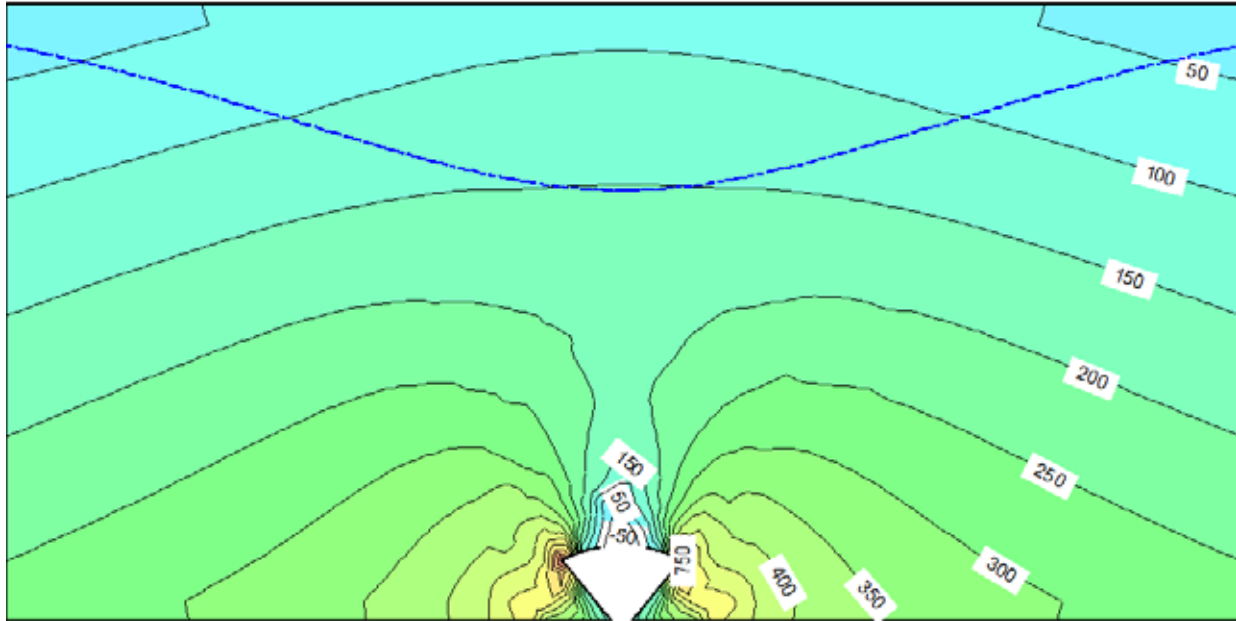


Figure 5. Effective stress distribution at different groundwater conditions. (d) Head Difference = 15 m

redistribution is observed around the cavity. A drop in the stress occurs on the top of the cavity along its center. The stresses are transferred to the corners of the cavity where stress concentrations take place. This behavior is due to the arching effect which governs the stress redistributions taking place around any underground opening (Tien, 1996).

Figure 6 presents the pore water pressure (pwp) with depth above the cavity at different groundwater conditions. The change in pwp values is 50 kPa at the cavity top which corresponds to a 5 m head difference, where the water density is 10 kN/m^3 . It is observed that the change in pwp decreases to 20 kPa at depths closer to the ground surface. The negative pwp values are due to capillary rise (suction) which is considered by the SEEP/W analysis. Figure 7 and 8 show the effective vertical stress distribution by depth above the center and the corners of the cavity, respectively, to emphasize on the changes due to the different recharge conditions. In Figure 7, the effective stress increases with depth until it reaches a peak value at a depth around 14 m, then it significantly decreases. In Figure 8, the effective stress increases with depth, and a drastic increase starts to occur from a depth of 14 m to the top of the cavity. Therefore, the decrease of stresses above the center is compensated by the increase of stresses above the corners along the same depths. An increase in the effective stress values is observed as the head difference increases. This increase ranges between 20 kPa and 30 kPa for each 5 m increase of head difference.

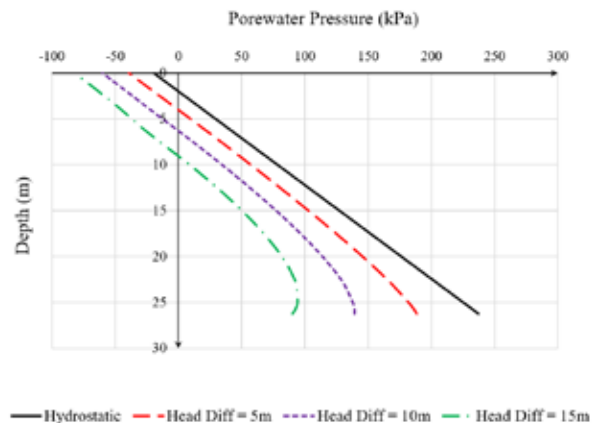


Figure 6. Porewater pressure above the cavity

Stress Paths Around Cavity

Stress changes at the corners of the cavity due variation in groundwater conditions are investigated for different cavity sizes. The cavity has the same inverted triangular shape (angle = 51°) with two different heights used in this analysis: 4 m and 8 m. The 8 m height cavity is also assessed when the angle of its sides changes to 66° with the horizontal. The same model dimensions (60 m width and 30 m height) are used for each analysis. Thus, the overburden depths above the 4 m height and the 8 m height cavities are: 26 m and 22 m, respectively. The Mohr-Coulomb (MC) model is used with the same parameter values as listed in Table 1. The MC failure envelope is defined in the MIT Stress-Space as shown

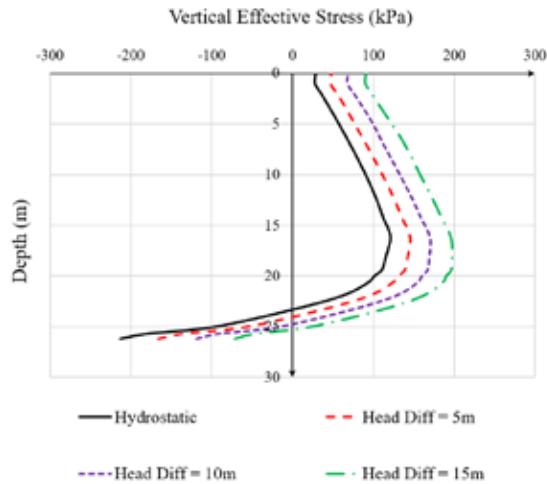


Figure 7. Effective vertical stress above center of the cavity

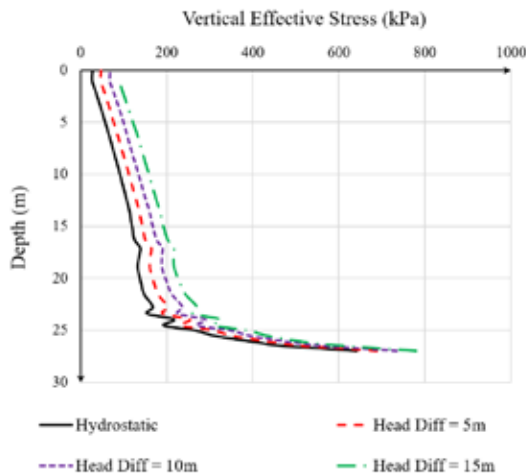


Figure 8. Effective vertical stress above the corners of the cavity

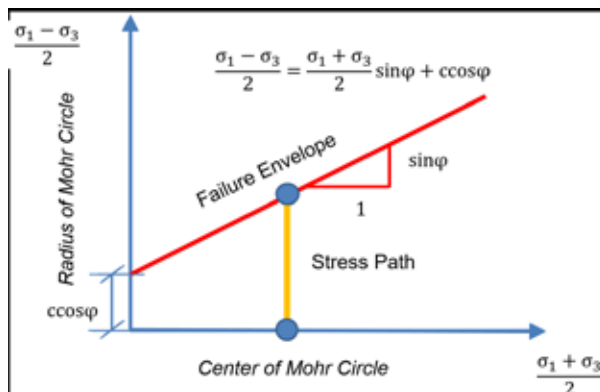


Figure 9. Failure surface of Mohr-Coulomb model in MIT stress-space (Akl, 2015)

in Figure 9, where the mean effective stress (p') is $(\sigma_1 + \sigma_3)/2$, and the deviator stress (q) is $(\sigma_1 - \sigma_3)/2$.

The stress paths at the corners of the cavity are plotted on the MIT Stress-Space for the different subterranean conditions in this analysis (Figure 10). It is observed that for different cavity sizes the mean effective stress (p') increases as the groundwater table is lowered with a relatively insignificant increase in the deviatoric stress (q). A significant change in the stress path is noticed when the side angles of the cavity change. Both p' and q values increase when the side angles increase from 51° to 66° at a constant cavity height. It is also noticed that p' and q values at the corners of the 8 m cavity are significantly larger than those at the corners of the 4 m height cavity, however, the overburden depth is smaller in the former case.

Summary and Conclusion

In this paper, the sinkhole formation due to subsurface cavities was assessed by experimental and numerical means. The research emphasized cover-collapse sinkholes in Central Florida. A physical model involving an unconfined aquifer and a confined aquifer was carried out, and the different stages of sinkhole evolution due to a fracture in the soil bottom were visually monitored. An inverted triangle-shaped cavity grows upwards due to soil erosion at its corners until collapse occurs.

In a stress-seepage coupled analysis, the cavity shape observed in the physical model was used to investigate numerically the effects of groundwater conditions and

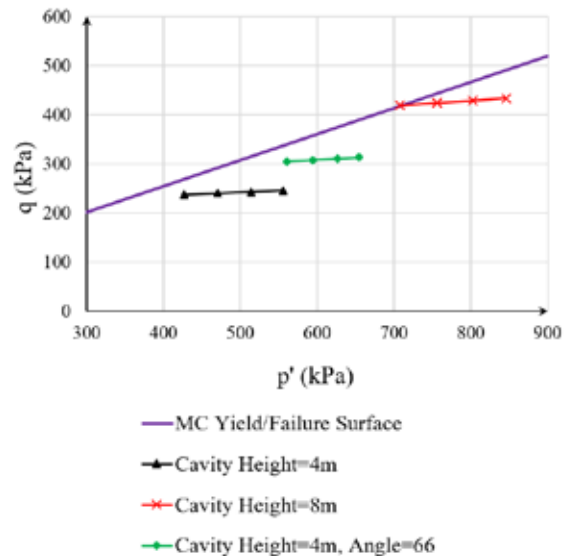


Figure 10. Stress relations at the corners of the cavity for various scenarios

cavity size on stress conditions. The study showed that a stress redistribution takes place around the cavity due to the soil arching effect. The effective stress increases significantly at the corners to compensate for the stress reduction that takes place above the center of the cavity. According to the seepage analysis, downward seepage due to a head drop in the confined aquifer results in the highest recharge values occurring at the corners of the cavity, and thus, the highest seepage forces exist at these locations.

The stress paths at the corners of the cavity were investigated at different groundwater conditions and cavity sizes. The analysis shows that increasing groundwater table causes the stress path closer to the failure envelope, which is more unstable condition. When the cavity height increases, both the mean effective and the deviator stresses increase towards the yields surface. A change in the side angles of the cavity or its shape affects the stress conditions around the cavity.

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A WAY TO PREDICT NATURAL HAZARDS IN KARST

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Abstract

Flooding, ground collapses, subsidence and contamination are hazards often encountered in a karst environment. All are strongly associated to water. A good knowledge of the distribution of groundwater potentiometric heads and fluxes in space and time is necessary to predict and prevent these hazards.

A series of karst-specific approaches are being developed by SISKa (Swiss Institute for Speleology and Karst-Studies) in order to provide this type of information within a reasonable effort. Most of these are based on a key-approach (KARSYS) and could be successively applied to address issues in karst environment. Applications for flood and sinkhole hazards are presented. These approaches are organized in a “Karst toolbox” which is being developed first and mainly for karst in temperate and mountainous regions (as we have in central Europe). Adjustments and extensions for other contexts (e.g. lowland karst or hypogenic karst areas) could be developed.

Introduction

The most frequent hazards in karst environment are flooding, ground collapse, subsidence and groundwater contamination. If water is the key factor for flooding and contamination, it may appear a little less direct for ground collapse and subsidence. However, when looking at the literature (e.g. Waltham et al., 2005) it turns out that most ground collapses and dolines are produced by changes in groundwater conditions, especially when the groundwater table is located within unconsolidated sediments covering the karstified rock.

Therefore a key issue concerning hazards is to characterize groundwater heads and fluxes under low to high flow conditions. Ideally karst hydrogeologists would like to know hydraulic heads and fluxes anywhere in the karst aquifer, i.e. have a clear image of groundwater flow systems and their variations in time!

Many studies are however mainly focused either on the temporal (e.g. time series analyses) or spatial (e.g. positioning of a drillhole) aspects. Usually, quantitative

modelling approaches are applied to link both aspects together, but they require a huge effort, and are thus mostly reserved to academic work.

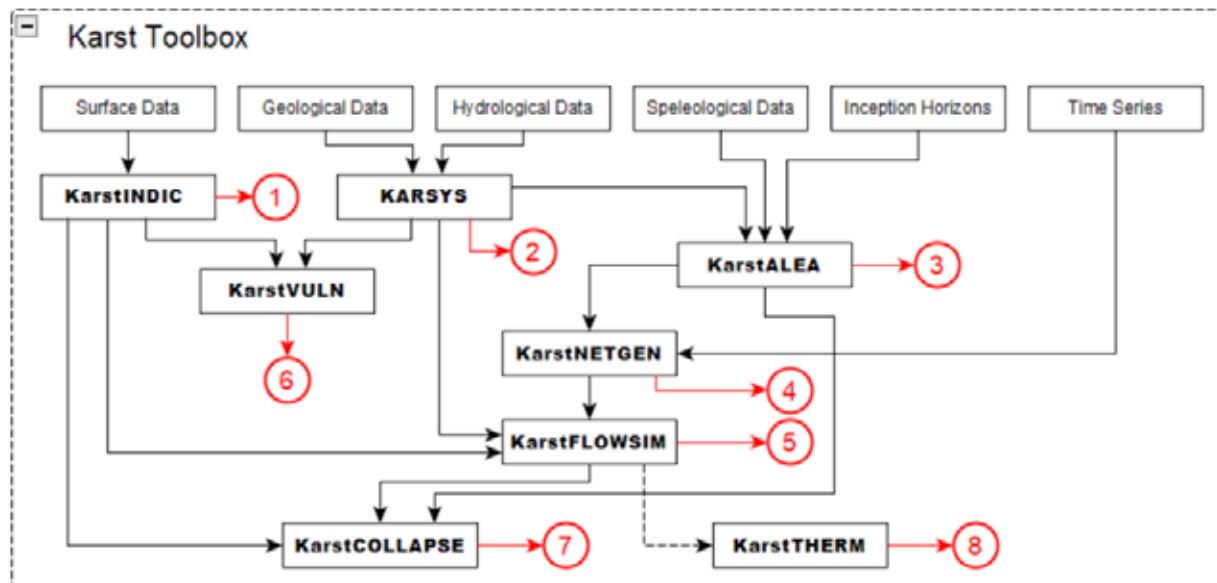
In most situations, a qualitative “conceptual 3D spatial model” of the groundwater flow-system is sufficient to address practical questions, as long as the model provides local information over the whole investigated region, not just a generalized scheme (e.g. a hydrogeological cross-section) as observed in many studies.

Here we present an approach for synthesizing all available data into such a conceptual 3D spatial model. We believe that this type of approach is more efficient for addressing practical questions such as ground collapses or flooding than classical groundwater flow modelling, which is highly time consuming and still contains a high uncertainty.

Approach

Over the past 10 years a series of practical approaches have been developed at SISKa to characterize karst flow systems. This “karst toolbox” is sketched on Figure 1, and the main approaches are briefly described hereafter. The assessment of hazards, such as floods (Number 5 on Figure 1) and karstic collapse (Number 7 on Figure 1), requires the application of most of these approaches sequentially.

KARSYS is the keystone of this toolbox. It provides an explicit model of the groundwater flow system, based on a 3D geological model of the karst aquifer (Figure 2). To construct the model, all existing geological data (geological map, cross-sections, borehole, etc.) are gathered and interpreted to describe the geometry of the karst aquifer. Then, hydrological data such as springs, swallow-holes, estavelles, water-levels in caves, or boreholes are introduced explicitly into the 3D geological model. The data are then interpolated according to two fundamental hydraulic principles: 1) hydraulic gradient is low in karst aquifers (close to zero, at least in low water situation) due to the high hydraulic conductivity of karst channels; 2) the hydraulic gradient is vertical in the unsaturated zone, meaning that flow is



OUTPUTS:

- ① Maps of karst characteristics at ground surface
- ② 3D model of karst aquifer, catchment delineation
- ③ Prediction of karst occurrences for underground construction
- ④ Prediction of the expected karst channels network
- ⑤ Simulation of recharge / discharge, and 3D field of heads and fluxes -> flood hazards assessment
- ⑥ Vulnerability maps, and protection zones
- ⑦ Collapses hazard maps
- ⑧ Dimensioning of geothermal probes in karst

Figure 1. Sketch of the “Karst Toolbox” showing methods leading to the various outputs (red numbers). KARSYS and KarstINDIC are the first steps, making possible to assess groundwater vulnerability to contamination (KarstVULN). KarstALEA takes the genesis of karst into consideration, making possible to assess the position and characteristics of karst features. It can be used to generate a network of karst conduits (KarstNETGEN), which in turn can be used for groundwater flow simulation (KarstFLOWSIM). This can be used for flood assessment (5). KarstCOLLAPSE makes possible to predict ground collapses by combining results of KarstINDIC, KarstFLOWSIM and KarstALEA mainly.

vertical or down-dip along the top of impervious layers. The modeler can thus produce a 3D scene of his vision of groundwater flows according to his knowledge of the aquifer and data. The resulting KARSYS model then provides maps of the saturated and confined zones, the main drainage axes, the expected groundwater heads, and the catchment area related to a spring or a group of springs.

KarstINDIC (Figure 3) aims at characterizing conditions of water infiltration, as well as to map the main morphological features which are significant for groundwater and the preservation of natural heritage.

KarstINDIC is a mapping procedure of karst features which are visible at land surface. Most data can be extracted from geological maps, geomorphological maps, aerial photos, digital elevation models, cave inventories, etc. Field observations can be added for improving the liability and precision, but are not systematically required. KarstINDIC is a necessary step for hazard assessment for which water infiltration is a key parameter.

KarstALEA (Figure 4) was developed for predicting karst occurrences in tunneling (Filipponi et al. 2012), and is recognized as an official method for assessing karst

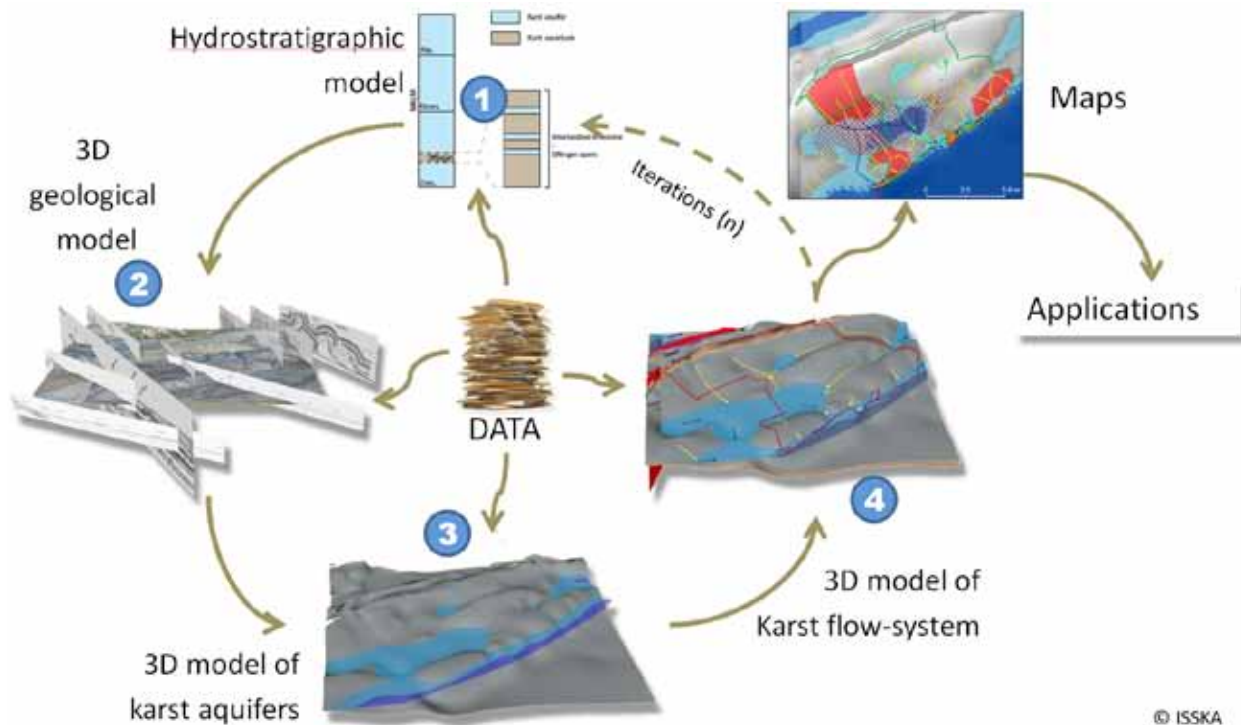


Figure 2. Steps and outputs of the KARSYS approach. 1) The modeler identifies karstified rocks (aquifer) and aquicludes based on geological data (hydrostratigraphic model). 2) A 3D geological model of the karstified rocks and aquicludes is built. 3) Hydrological information is added to the 3D geological model and a model of the karst aquifer is produced. 4) By applying some rules of the hydraulics of flow in karst, the groundwater flow system can be created explicitly. Finally maps and other outputting information can be produced for dedicated applications (e.g. groundwater resource assessment).

by Swiss civil engineers. A model of the speleogenetical conditions and inception horizons are added to the KARSYS model, making possible to predict the potential position of karst channels as well as their characteristics (expected size, shape, infilling, etc.). It can be applied to any type of underground construction in karst. The method can also be applied to the near-surface to identify the potential location of sinkholes. However, KarstALEA alone is not sufficient as most sinkholes are related to the collapse of unconsolidated sediments covering karstified rock (e.g. soils, tills or loess). Therefore, characteristics of the cover must be considered, as well as hydrologic conditions within the sediments.

KarstNETGEN (Figure 5) is being developed to generate karst conduit networks within the 3D geological model, considering probabilities inferred in the KarstALEA model. Compared to other models, it specifically accounts for the spatial distribution of recharge (zones of diffuse or discrete recharge), speleological zones and inception horizons. Details of this model are presented in Malard et al. (2015).

KarstFLOWSIM is being developed to simulate both heads and flow in a karst aquifer. Various levels of details can be used in KarstFLOWSIM, requiring a more or less precise description of the karst conduit network. The first level aims at simulating hydrographs (time series of discharge rate) of the whole flow-system. This simulation process includes the assessment of effective recharge into the aquifer. A second level can be achieved by introducing the hydraulics of flow (in using for example InfoWork© or SWMM©) in a partially saturated pipe network generated with KarstNETGEN. If necessary, flow and heads in the rock matrix between the karst channels can be simulated using results of the hydraulics of the conduit network. Most steps of KarstFLOWSIM have already been applied to practical cases (e.g. Jeannin et al. 2015). An example is presented in Figure 6. KarstFLOWSIM is permanently developed in order to improve its applicability: For example, a KarstFLOOD module is being developed according to some criteria, such as flooding probability classes (Vouillamoz et al. 2013).

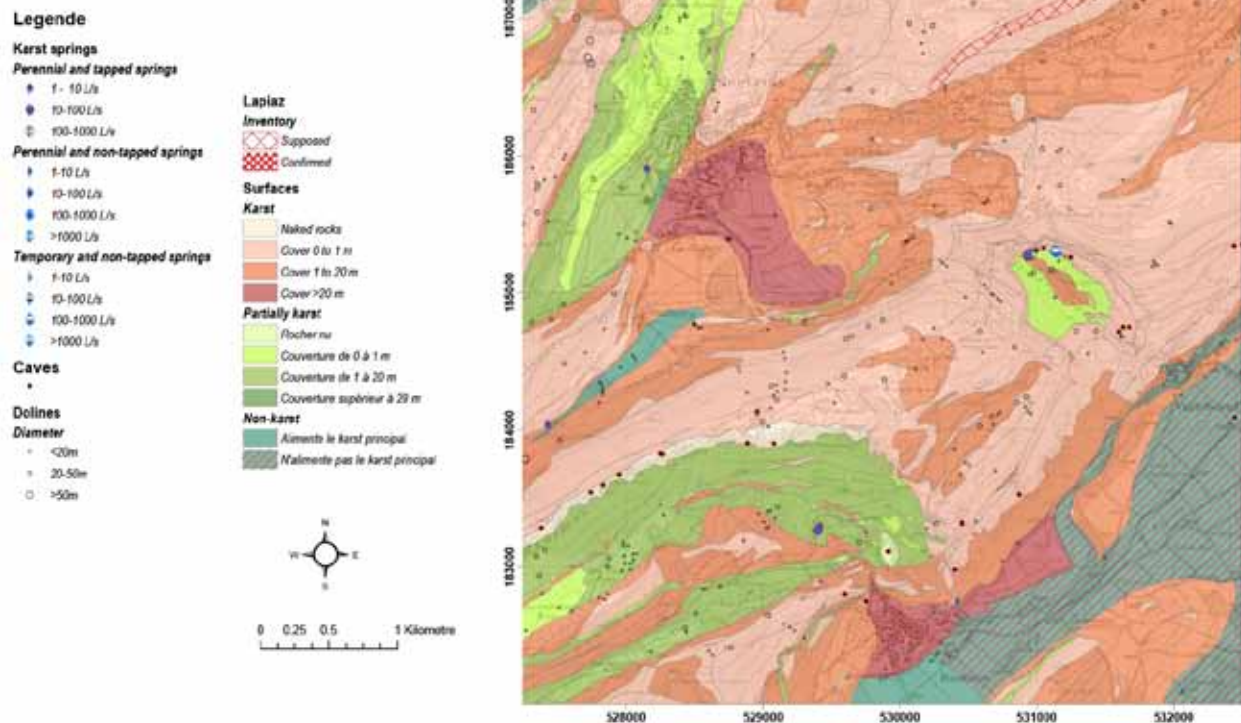


Figure 3. Example of a KarstINDIC map representing karst features controlling water infiltration, and providing indications about patrimonial issues.

Finally, KarstVULN and KarstCOLLAPSE are the next modules to be developed. The goal of KarstVULN is to produce vulnerability maps showing regions where groundwater is more vulnerable to contamination for surface pollutants. These maps can then be used to delineate groundwater protection zones according to water protection laws proper to each country. For these maps information of KarstINDIC and KARSYS will be combined based on a revised version of the EPIK method (Doerfliger et al. 1999), which is being prepared under the direction of the Swiss Office for the Environment.

KarstCOLLAPSE will combine data from KarstINDIC (e.g. type and thickness of the overburden) with data from KarstALEA (e.g. position of preferred karst development) and KARSYS (mainly the head data) in order to produce qualitative maps of potential ground collapses. A first example is presented on Figure 7. Further data will need to be collected and combined to refine the reliability of the map. For more quantitative results, the application of KarstFLOWSIM (Figure 6) is necessary, especially concerning groundwater heads and their variations in the aquifer, which is a key-factor for triggering karst collapses. Karst collapse hazard maps have been produced, but the approach needs to be refined.

Examples of Karst Toolbox Applications Flood hazard assessment in the Beuchire catchment area

The city of Porrentruy has expanded around a perennial karst spring (Beuchire spring). The city is occasionally flooded by water coming from an overflow spring (Creugenat) located several kilometers upstream along a dry valley. This valley, which becomes active only during high flow conditions, is settled by several villages. Authorities must provide a flood hazard map with indications about the probability, position, and intensity of potential flooding. No surface perennial rivers or streams are present in this region. One part of the dry valley becomes active during high water periods, but the part of the valley, which floods, depends on the intensity of the rainfall. The catchment area feeding the springs (perennial and overflow) was not well known. Hydrologists were asked to produce a map with the respective indications, but they were disappointed when they realized there was no river or mapped catchment area, i.e. no information for feeding the models used for making the assessment.

We used KARSYS to delineate the catchment area as well as the extension of the groundwater body (phreatic zone) present in this catchment. First it was made for

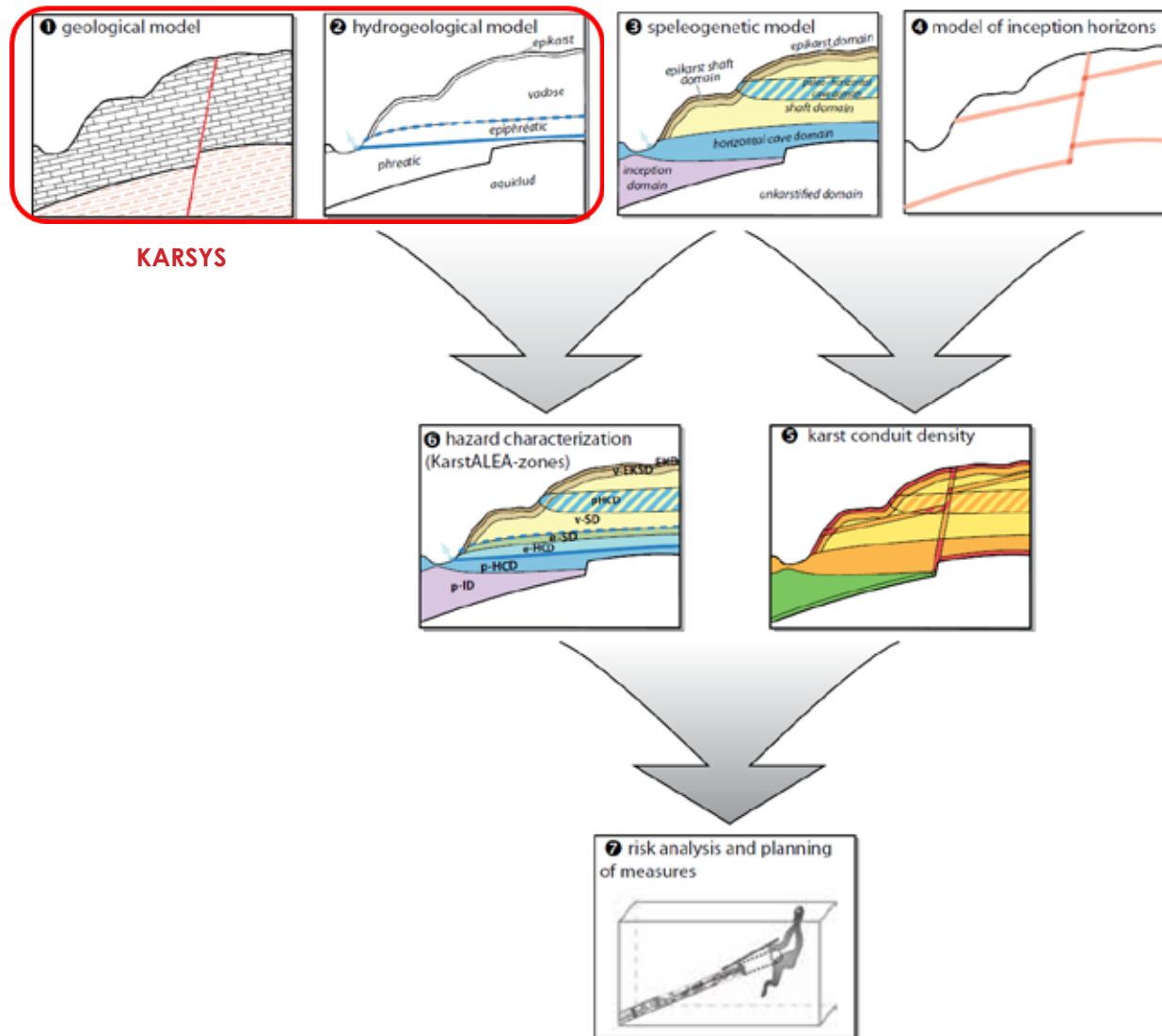


Figure 4. The 7 successive steps of the KarstALEA method as developed for a tunnel project. Four 3D models of the massif are constructed in steps 1 to 4 (1 and 2 being the KARSYS models). In steps 5 and 6 zones with the highest expected densities of karst conduits and their characteristics are interpreted. In step 7 hazards, risks, and mitigation measures are identified and discussed between the tunnel geologist and the tunnel engineer.

low water conditions. Next, and thanks to existing data of heads in caves, we assessed the extension under high flow conditions (within the range of measured data). Those analyses provided evidences that the catchment area changes depending on conditions. During low water conditions, two groundwater bodies are separated by an impervious anticline. The rising of groundwater during high water conditions activates an overflow over this anticline, bringing water from the nearby catchment towards the Beuchire catchment area. For assessing heads and discharge rates in the downstream part of the

catchment, where the flood hazard map was required, we linked recharge coming from the assessed catchment area with the region enclosing the outlets. To simulate those conditions, recharge and flow paths through the aquifer had to be assessed. A recharge model was calibrated first. For the routing, a network of pipes draining the whole aquifer had to be generated somehow. Considering the data available (flow at springs and groundwater heads in different caves in the downstream part of the system), we decided to simulate flow and heads in this part using a pipe-flow modelling software. After a few

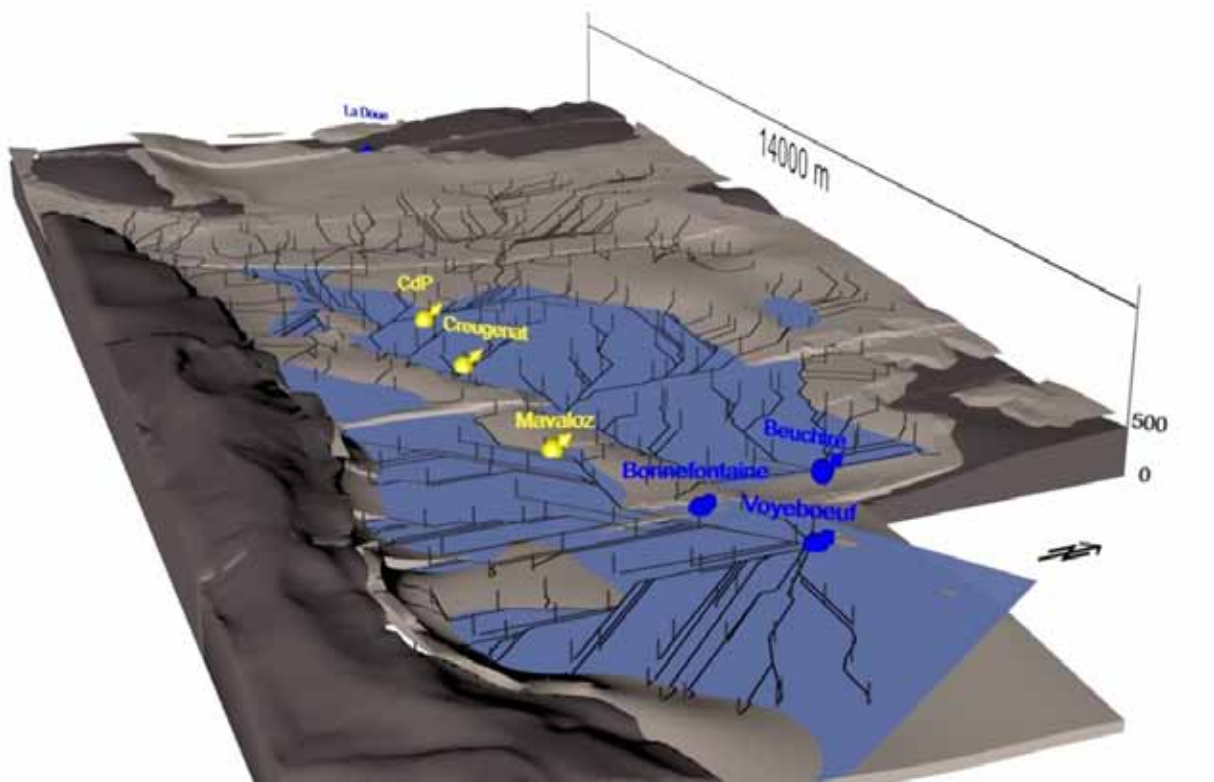


Figure 5. Example of a conduit network generated with KarstNETGEN based on KARSYS and KarstALEA results.

Adjust:

- Autochthonous & Allochthonous sub-catchments contribution
- conduits diameter, additional conduits, etc.

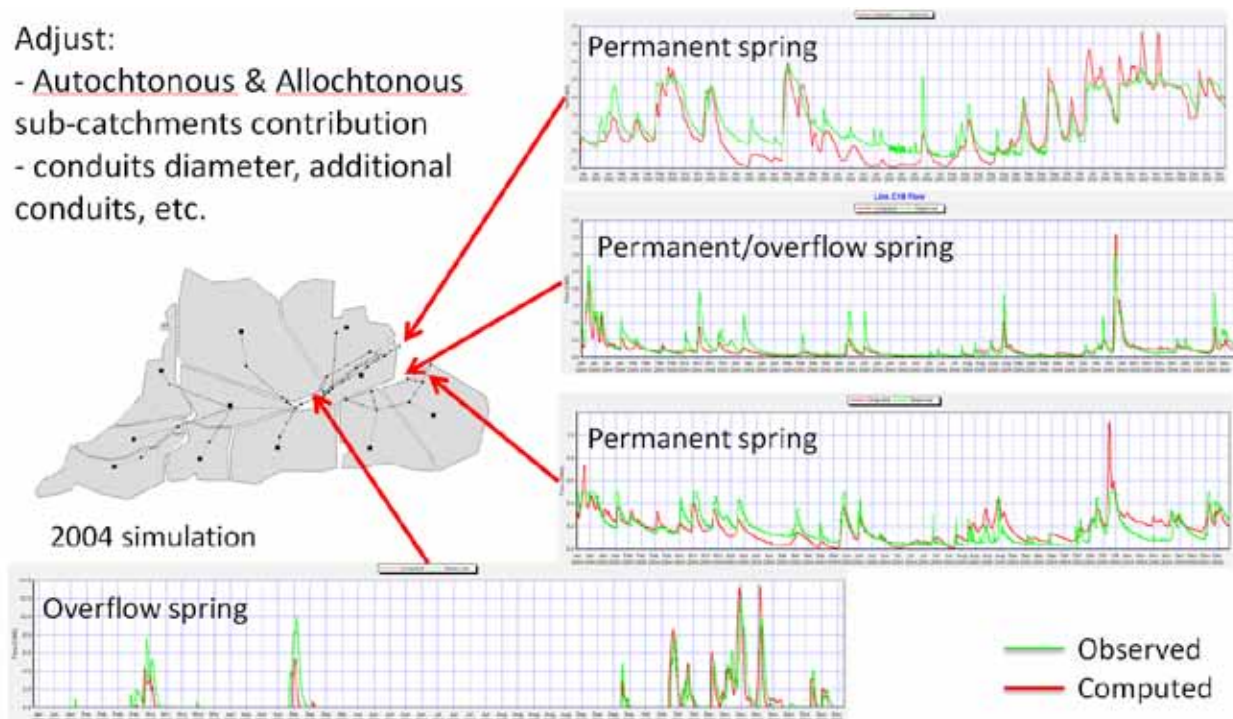


Figure 6. Example of hydrographs of four springs simulated with KarstFLOWSIM ("Permanent spring" means "perennial spring").

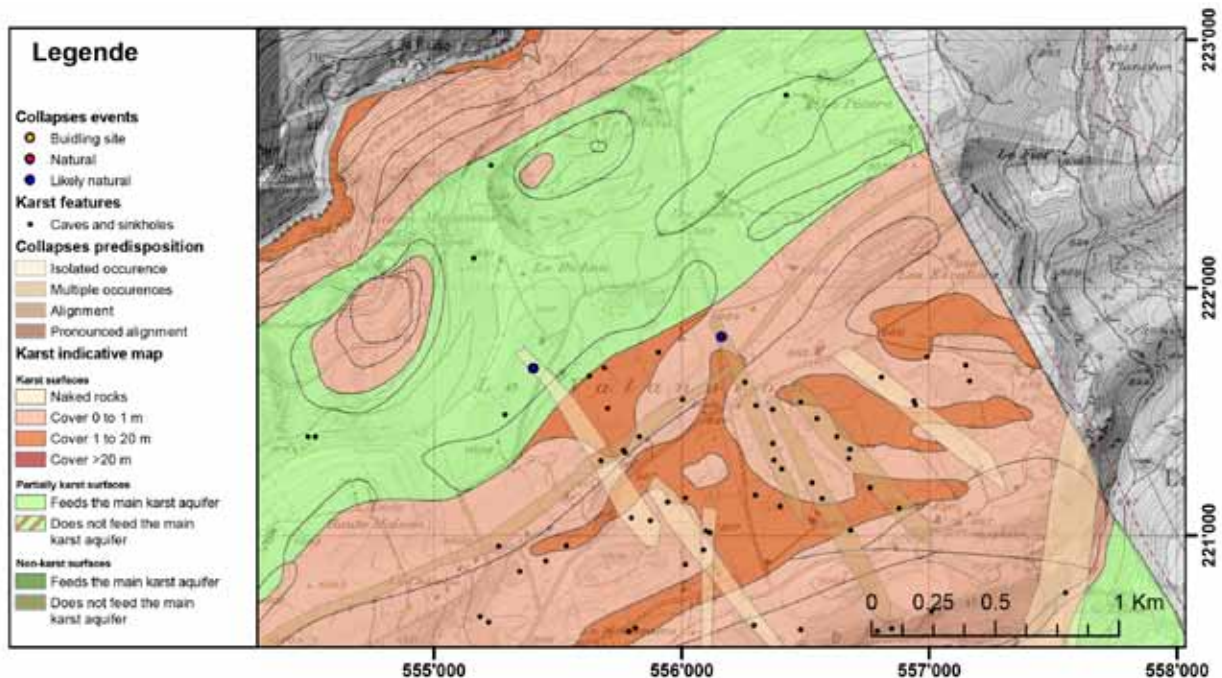


Figure 7. Example of karst hazard map produced with conceptual KarstCOLLPASE module principles.

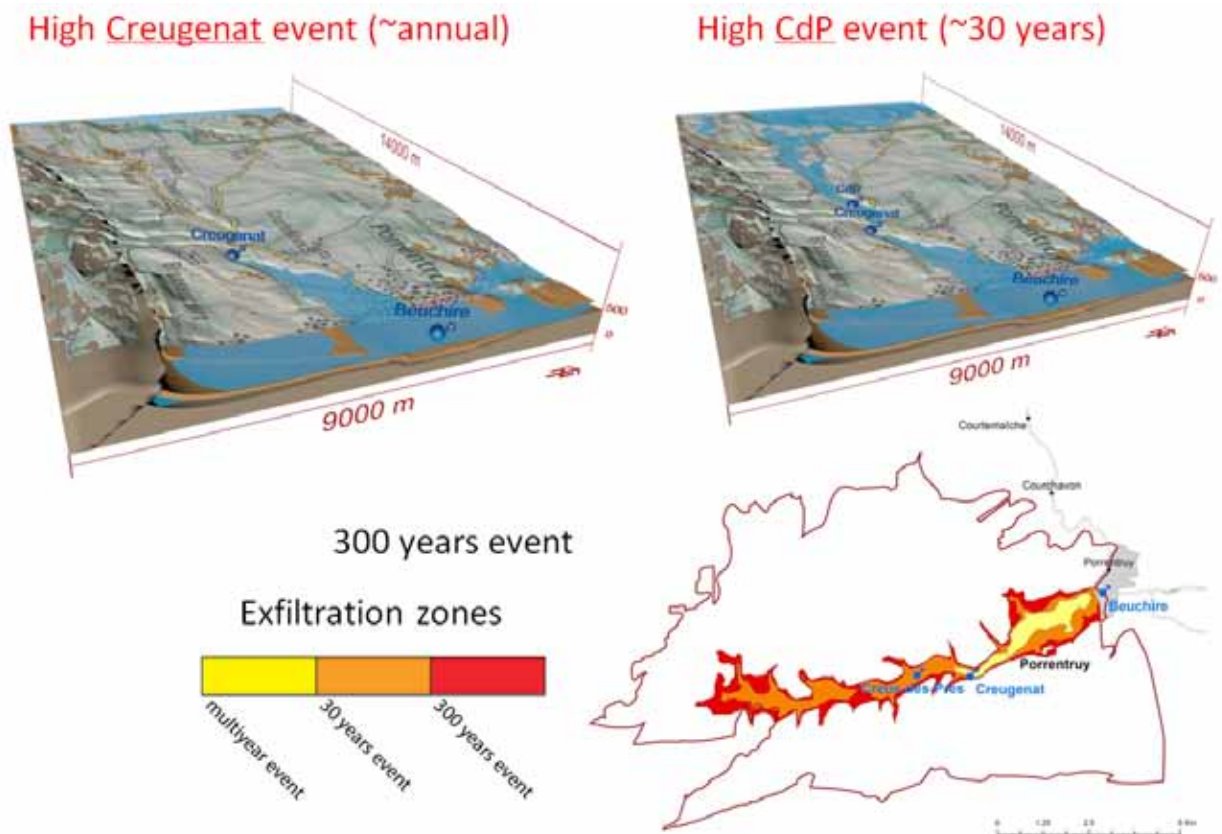


Figure 8. Map of flood hazards in the Beuchire catchment area (JU, Switzerland). Top left: areas vulnerable to floods during an usual overflow event of the Creugenat spring. Top right: areas vulnerable to floods during an overflow event of the Creugenat spring with a return period of 30 years.

iterations the modelled conduit network provided a good fit with groundwater observed heads and flow rates. Caves explored and surveyed by cavers were another set of information. For the upstream part we developed a karst channel network generator, based on results of KarstALEA and KARSYS. The complete network could thus be generated, linking all regions of the catchment area to the four outlets of the system (Figure 5). The complete pipe network was included into the pipe-flow model, which was calibrated by adjusting the pipe network topology and pipe size, until it reasonably reproduces discharge time series of the respective springs and heads measured at a few locations in the karst channels.

Extreme rainfall scenarios were discussed with engineers and introduced into the model, which provided an idea of how high the groundwater table could rise, where it would breach land-surface, and how much water is expected to flow at those locations. Results of that modelling are shown in Figure 8.

This case study helped us to develop and refine our tools and improve ways to connect one to another.

Ground collapse hazard in Northern Switzerland

The project associated with this case-study is not finished. Names and precise location are therefore not provided. The goal of the project is to answer the following questions: Where could piles of a bridge and water injection plants be placed on order to avoid or minimize the triggering of collapse sinkholes, which are known to frequently occur in the region?

The geology of the (flat) region is as follows: A series of unconsolidated rocks with a thickness ranging between 10 to 45 meters laying on top of a highly karstified limestone, presumably of hypogenic origin, containing a high density of voids. The analysis of existing data showed that collapse sinkholes are produced mainly by piping of unconsolidated sediment into the karst voids, producing voids in the unconsolidated sediment, which then migrate upwards to the surface as the sediment ravel. The piping is strongly related to hydrologic conditions. In this region the groundwater potentiometric surface is located and fluctuates mainly within the unconsolidated rock.

The application of KARSYS with few adjustments made it possible to show regions where groundwater does not reach the unconsolidated sediment, i.e. where the danger of collapse sinkholes is lower, and to see where piles

could be placed, and how identified dangers could be mitigated.

Discussion

The methods of the Karst Toolbox are applicable to assess most applied problems in karst, including natural hazards such as floods and collapse sinkholes. Once one method is applied (usually KARSYS first) for one problem, the other methods which provides very useful information for mitigating problems.

Karst Toolbox has limitations. The tools are developed following demands and problems specific to central Europe, i.e. temperate mountainous regions. They might be less efficient or even not applicable in other karst terrains (e.g. lowland karst or hypogenic karst areas). Adjustments and extensions for other terrains should be developed.

Another aspect is that results may appear to be precise and accurate. However, the models are only as precise as the data used to make them. This must never be forgotten. A possible future addition may include tools for uncertainty assessment. This is however a very challenging task. Nevertheless, along the construction of the models, the modeler identifies aspects which are the most unreliable and can target complimentary investigations (e.g. geophysical survey) in places where they are really needed. If all or most existing data have been introduced in the model, it can be a very effective tool to assess if the level of detail of the existing data is sufficient for addressing the question. Another advantage is any new data is directly integrated in context of existing data (e.g. a groundwater level can be directly viewed in the aquifer, confined or artesian).

Another aspect is most results produced by these tools include 3D visualizations of conceptual model which hydrogeologists usually try to express through maps and profiles. Showing them explicitly is a strong advantage for explaining to decision makers or even to the public. A lot of words and time are saved by showing a 3D model which visually explains the underground flow conditions. The tools also help the modeler refine ideas, and raise new unexpected ones. Finally the Karst Toolbox enables other hydrogeologists to criticize the model if it does not fit their own ideas.

Conclusion

In this paper we briefly sketched a way to chain and combine models and approaches to cope with practical issues in karst. Too often investigations are according to what an investigator can do, rather than the most

effective way to address the question. Our experience is it is very effective to gather all existing data into our well-structured database, visualize in 3D and target further investigations based on this explicit compilation. With some practice, this work can be achieved with reasonable effort (and money) and it increases objectivity and decreases liability of the assessments. The communication of the principles, assumptions, and results is strongly improved.

With remote sensing and new techniques a lot of new data are becoming available and being developed for improving our knowledge of the underground. Computers are no longer a limitation to managing these data. The main limitation is the absence of efficient tools to make this compilation work. GIS helps, but is essentially 2D (or 2.5D), which is a strong limitation for hydrogeology. The Karst Toolbox is an attempt to develop such tools for karst, which could be applied in other hydrogeological contexts.

The sketched Karst Toolbox is applicable at our place. Making it available outside is a difficult task because our whole know-how must be merged into user-friendly tools, which is a considerable piece of work! Visual KARSYS is now being developed with this purpose. That effort started in 2016 and will continue until 2019. This web application will explain and provide all the necessary tools for any user, to apply KARSYS for making his own model. KARSYS will be available by 2019, and further pieces of the Karst Toolbox will be progressively implemented, depending on demand for applications.

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