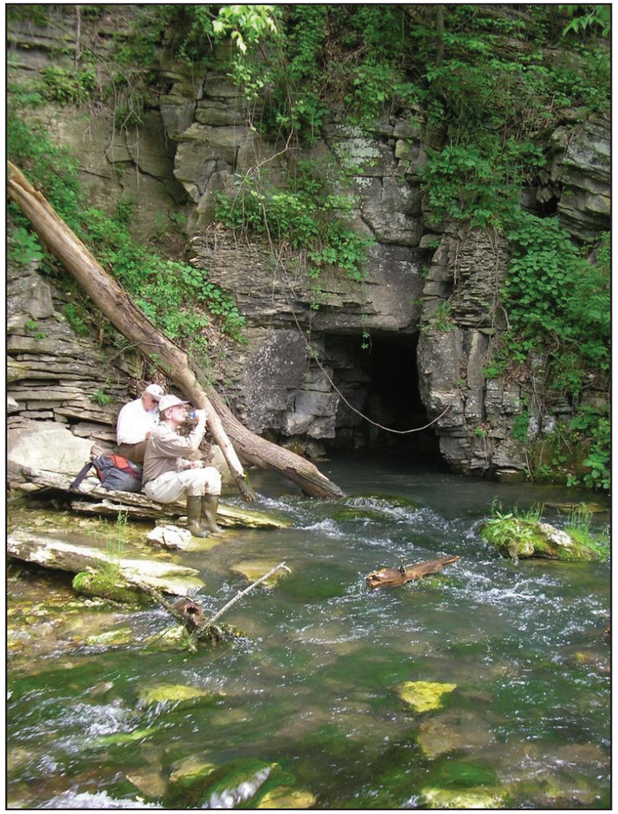
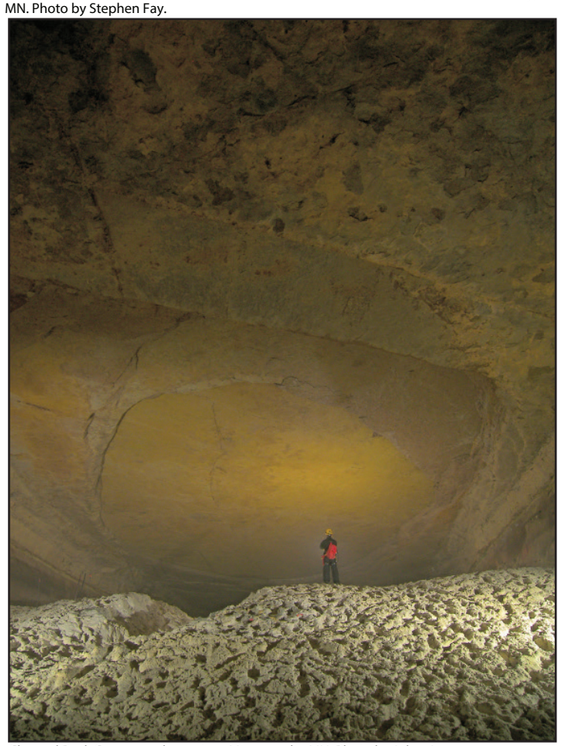
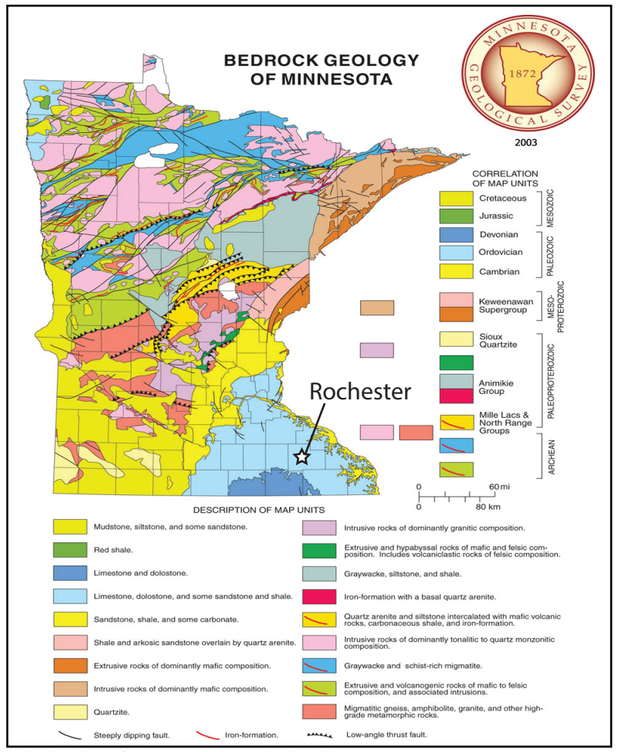


Odessa Spring, Fillmore County, MN. Photo by Andrew Peters.

Cover-collapse sinkhole in the pool area of a water-retention structure, Goodhue County, MN. Photo by Stephen Fay.



Channel Rock Cavern, under eastern Minneapolis, MN. Photo by Johns Lovaas.



Bedrock Geology of Minnesota, Minnesota Geological Survey

Passageway of Niagara Cave. Courtesy of Mark Bishop

THE SINKHOLE CONFERENCE

Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst

National Cave and Karst Research Institute

Minnesota Ground Water Association
www.mgwa.org

PELA

Barton Springs Edwards Aquifer
CONSERVATION DISTRICT

EDWARDS AQUIFER AUTHORITY

ILLINOIS STATE GEOLOGICAL SURVEY
PRAIRIE RESEARCH INSTITUTE

MNDNR

"Integrating Science and Engineering to Solve Karst Problems"

THE SINKHOLE CONFERENCE

Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst

October 5-9, 2015
Rochester, Minnesota, USA

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Credits: Program with Abstracts prepared by Brian A. Smith, Brian B. Hunt and Justin P. Camp, Barton Springs/Edwards Aquifer Conservation District, Austin, Texas.

Cover photograph: Stagecoach Spring, the entrance to the Stagecoach Caverns cave system and the headwater of Watson Creek, a state-designated trout stream. Photo by Jeff Green.

Release: *By submitting the registration form, you hereby release any photographs that may be incidentally taken of you during these events by Sinkhole Conference 2015 to be used for any purpose.*

Waiver: *By registering, you agree and acknowledge that you are participating in the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst (Sinkhole Conference 2015) and its activities intentionally and of your own free will, and you are fully aware that possible physical injury might occur to you as a result of your participation. You give this acknowledgement freely and knowingly that you are, as a result, able to participate in Sinkhole Conference 2015, and you hereby assume responsibility for your own well-being.*

Recording of Presentations: *The recording of any oral or poster presentation is prohibited without the prior approval of the author.*

Sponsors

Rochester Public Utilities (RPU) has been the municipal utility of Rochester, Minnesota for more than 120 years. RPU serves over 50,000 electric customers and over 37,000 water customers in Rochester. With a focus on customer service and efficiency in operations, we continue to strive for excellence through effective water quality programs, robust infrastructure, and customer education efforts that will ensure a safe and reliable drinking water supply for years to come.

Rochester's water supply comes from the Jordan aquifer, in which RPU has 32 deep wells, with another well planned to go in-service by the end of 2016. Additionally, RPU works with customers to lower usage of electricity and water by offering incentives for qualifying conservation and efficiency equipment purchases through RPU's Conserve & Save® rebate program. In 2014, RPU helped customers save over 9 million gallons of water through these efforts.

Additional Water Highlights:

- There are 20 water storage facilities in Rochester.
- RPU was voted by the AWWA Southeast Minnesota Chapter "Best Tasting Drinking Water" in 2014.
- RPU developed and installed a number of water conservation and water quality interactive exhibits at St. Mary's University-Cascade Meadow Wetlands & Environmental Science Center.

RPU is also a significant employer in Rochester, employing over 160 full-time employees. For more information on RPU visit RPU at www.rpu.org.

Braun Intertec assists public and private organizations and property owners with site evaluations, site preparation recommendations, and construction support services. With more than 800 employees corporate wide across 16 offices, Braun Intertec staff represents multiple technical disciplines including karst investigations and engineering, environmental consulting, geotechnical engineering, testing, special inspections, geothermal consulting and facilities evaluations.

Advanced Geosciences is the manufacturer of the SuperSting, geophysical resistivity imaging system. It is used for investigations in geotechnical applications such as; detecting cavities and sinkholes, mapping of bedrock topography, mapping of soil profile, moisture content is clay, locating leakage through dams, environmental work and checking soil resistance for corrosion studies.

GeoTDR applies Time Domain Reflectometry (TDR) technology throughout the world for automated remote monitoring of subsidence over active and abandoned mines as well as monitoring sinkhole subsidence in karst areas. GeoTDR is a subsidiary of Geotechnical Consultants Inc, which provides geotechnical engineering, environmental services, and consultation materials, engineering and testing.

The Edwards Aquifer Authority is a groundwater district, mandated by the 1993 Edwards Aquifer Authority Act. The Act grants all of the powers, rights, and privileges necessary to manage, conserve, preserve, and protect the aquifer. The EAA regulates the portion of the Balcones Fault Zone Edwards Aquifer – a jurisdictional area that provides water to over 2 million people, and covers more than 8,000 square miles across eight Texas counties.

The Barton Springs/Edwards Aquifer Conservation District is a groundwater district in central Texas. The agency has the mission to conserve, protect, recharge, and prevent the waste of groundwater and preserve all aquifers in the District. The District manages well drilling and groundwater production from the Barton Springs segment of the Edwards Aquifer and the underlying Trinity Aquifer—two major karst aquifers in Texas.

Cover-collapse sinkhole in the Edwards Formation within a stormwater retention pond, Austin Texas. Left photo taken soon after collapse, right photo showing rock fill and concrete plug. Photo by BSEACD.

THE SINKHOLE CONFERENCE

Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst

5 October 2015

Welcome Karst Engineers and Scientists!

We are delighted to be your hosts for the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. For the past 31 years, this series of meetings has been among the most important in developing a better understanding of karst processes that result in environmental problems, and in creating effective measures that identify those problems before they occur, remediate them when they occur, and prevent them from occurring in the first place.

This year's conference is the first in the series that is jointly organized with another conference and organization. We are happy to be working with the Minnesota Ground Water Association (MGWA) and to combine our convention with the MGWA Fall Conference. We hope this merging of conferences will make this the biggest Sinkhole Conference and greatest exchange of knowledge to date. We are also delighted to award a record four Barry Beck Sinkhole Conference Student Scholars this year, each from a different country. We thank the generous sponsors who made that possible.

This year's Sinkhole Conference offers an excellent series of papers, thought-provoking keynote addresses, two fascinating and fun field trips, and ample time for you to meet new and old friends to discuss and collaborate on karst engineering and environmental research projects. Don't forget to visit the booths of our generous exhibitors and sponsors and support them for supporting the Sinkhole Conference! If you have any questions or concerns about the meeting, please tell us directly or leave a message at the registration desk and we will address them as soon as possible. We look forward to visiting with you soon.

Sincerely,

George Veni
Conference Co-chairman
Executive Director
National Cave & Karst Research Institute

James W. LaMoreaux
Conference Co-chairman
President
PELA GeoEnvironmental

Kelton Barr
Conference Co-chairman
Past-President
Minnesota Ground Water Association

Minnesota Ground Water Association
www.mgwa.org

5 October 2015

Welcome to Minnesota!

On behalf of the Minnesota Ground Water Association, I welcome you to Minnesota's karst country. We are proud to co-host this important conference in a part of the world where karst is a bit secretive, but often at the root of things (literally). Our karst country is mostly obscured beneath a thick layer of plant roots, sometimes with a nice layer of glacial drift to keeps things interesting. This conference uncovers the deep inner workings of karst landscapes, and it helps to hone the many skills needed to research and manage them.

The purpose of our Association is to promote public policy and scientific education about groundwater. This 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst serves our objectives very well:

- Promotes and encourages efforts that address the scientific and public policy aspects of groundwater;
- Establishes a forum for scientists, engineers, planners, educators, attorneys, and others concerned with groundwater Educates the general public regarding groundwater;
- Shares information on groundwater through meetings of our membership.

This is the first time that the Minnesota Ground Water Association has partnered with the National Cave and Karst Research Institute, and this conference is the satisfying result. The outstanding presenters, short courses, field trips, and social events are a testament to the immense dedication and cooperation of many people working together across the globe. If you find yourself with the opportunity, I encourage you to offer up a hearty thank you to our Organizing Committee members and volunteers who generously support this work.

I encourage you to enjoy yourselves, share your expertise across disciplines, and learn something new. And have fun!

Sincerely,

Lanya Ross
President
Minnesota Ground Water Association

Organizing Committee

General Conference Co-Chairs

- George Veni, Ph.D., P.G., National Cave and Karst Research Institute (NCKRI), Carlsbad, NM
- Kelton Barr, P.G., Braun Intertec, Minneapolis, MN
- Jim LaMoreaux, Ph.D., P.E., PELA GeoEnvironmental, Tuscaloosa, AL

Program Co-Chairs

- Lynn B. Yuhr, P.G., Technos, Inc., Miami, FL
- Michael Alfieri, P.G., Water Resource Associates, Tampa, FL
- Audrey Van Cleve, Hydrologist, Minnesota Pollution Control Agency, *retired,* Minneapolis, MN

Proceedings Managing, Assistant and Copy Editors

- Daniel H. Doctor, Ph.D., U.S. Geological Survey, Eastern Geology & Paleoclimate Science Center, Reston, VA
- Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute, Carlsbad, NM
- J. Brad Stephenson, P.G., L.R.S., CB&I Federal Services, Knoxville, TN
- Rebel Cummings-Sauls, Kansas State University
- Julie Fielding, University of Michigan

Proceedings Associate Editors

- Gregory Brick, Ph.D., Minnesota Department of Natural Resources, St. Paul, MN
- James Kaufmann, U.S. Geological Survey, Rolla, MO
- Mustafa Saribudak, Ph.D., P.G., Environmental Geophysics Associates, Austin, TX
- Samuel V. Panno, CGWP, Illinois State Geological Survey, Prairie Research Institute, University of Illinois, Champaign, IL
- Jason Polk, Ph.D., Western Kentucky University, Bowling Green, KY
- David J. Weary, U.S. Geological Survey, Reston, VA
- Ming Ye, Ph.D., Florida State University, Tallahassee, FL
- Lynn B. Yuhr, P.G., Technos, Inc. Miami, FL

Field Trips

- E. Calvin Alexander, Jr., Ph.D., Department of Earth Sciences, University of Minnesota, Minneapolis, MN
- Jeff Green, LPG, Minnesota Department of Natural Resources, Rochester, MN
- Jeffrey Broberg. LPG, WSB Associates, Inc., Rochester, MN

Short Courses

- Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute, Carlsbad, New Mexico
- Joe Fischer, Ph.D., P.E., Geoscience Services, Clinton, NJ

Invited Speakers

- Yongli Gao, Ph.D., University of Texas-San Antonio, San Antonio, TX

Logo

- Samuel V. Panno, CGWP, Illinois State Geological Survey, Prairie Research Institute, University of Illinois, Champaign, IL

Public Relations

- Lanya Ross, President, Minnesota Ground Water Association
- George Veni, Ph.D., P.G., National Cave and Karst Research Institute, Carlsbad, NM

Beck Scholarship

- E. Calvin Alexander, Jr., Ph.D., Department of Earth Sciences, University of Minnesota, Minneapolis, MN
- Ira D. Sasowsky, Ph.D., P.G., Dept. of Geosciences, University of Akron, Akron, OH

Beck Scholarship Silent Auction

- John Barry, Minnesota Dept. of Natural Resources, St. Paul, Minnesota

Circulars and Publicity

- Samuel V. Panno, CGWP, Illinois State Geological Survey, Prairie Research Institute, University of Illinois, Champaign, IL

Program with Abstracts

- Brian A. Smith, Ph.D., P.G., Barton Springs/Edwards Aquifer Conservation District, Austin, TX
- Brian B. Hunt, P.G., Barton Springs/Edwards Aquifer Conservation District, Austin, TX
- Justin P. Camp, Barton Springs/Edwards Aquifer Conservation District, Austin, TX

Website

- Gheorghe Ponta, P.G., P.E., Geological Survey of Alabama, Tuscaloosa, AL
- Sean Hunt, Hydrologist, Minnesota Dept. of Natural Resources, St. Paul, MN

Registration

- Sean Hunt, Hydrologist, Minnesota Dept. of Natural Resources, St. Paul, MN
- Audrey Van Cleve, Hydrologist, Minnesota Pollution Control Agency, *retired,* Minneapolis, MN

Hotel/ Conference facilities

- Audrey Van Cleve, Hydrologist, Minnesota Pollution Control Agency, *retired,* Minneapolis, MN
- Kelton Barr, P.G., Braun Intertec, Minneapolis, MN
- Mindy L. Erickson, Ph.D., P.E., Hydrologist, U.S. Geological Survey, Minnesota Water Science Center, Mounds View, MN

Treasurer

- Jeanette Leete, Minnesota Department of Natural Resources, St. Paul, MN

Professional Organization Liaisons

- Lanya Ross, Minnesota Ground Water Association, St. Paul, MN
- Wanfang Zhou, Ph.D., P.G. ERT Inc. International contacts

Members at Large

- Scott Alexander, University of Minnesota, Minneapolis, MN
- Phil Carpenter, Dept. of Geology and Environmental Geosciences, Northern Illinois University
- Ralph Ewers, Ewers Water Consultants Inc., Richmond, KY
- Bashir Memon, PELA GeoEnvironmental, Tuscaloosa, AL
- Deana Sneyd, Golder Associates, Atlanta, GA

History of Conference

The roots of the Sinkhole Conference can probably be traced back to when Barry Beck became interested in caves as a teenager where he lived in Rochester, New York. His interest in caves and karst studies eventually led him to Texas, Mexico, Puerto Rico, Georgia, and Florida for extended periods, plus visits to many other karst areas around the world. Barry organized the First Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, which was held in Orlando, Florida, October 15-17, 1984. Subsequently, second and third conferences were held under the sponsorship of the Florida Sinkhole Research Institute, a division of the University of Central Florida in Orlando, in 1987 and 1989, which he directed. These conferences were established to meet a critical need for applied research information on the very complex hydrogeological environment of karst areas of the world.

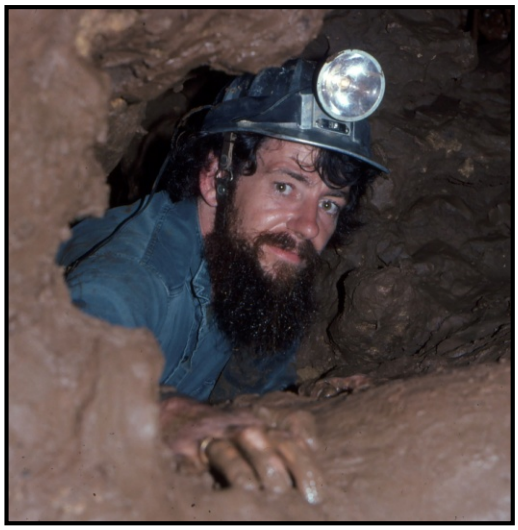
In 1992, following the closing of the Florida Sinkhole Research Institute, Barry joined the staff of P.E. LaMoreaux & Associates, Inc. (PELA) and opened the company's Oak Ridge, Tennessee office. Beginning with the Fourth Multidisciplinary Conference in 1993, PELA sponsored the continuation of this important series of conferences along with many other distinguished organizations. The Geo-Institute of the American Society of Civil Engineers took the lead in sponsoring the conference in 2003, 2005, and 2008 after which PELA took over the sponsorship again for the 2011 conference. Since the 2011 conference, this conference series has come under the management of the National Cave and Karst Research Institute (NCKRI). As a government-established non-profit organization, NCKRI is focused on karst phenomena and organized in part to conduct and support such conferences. PE LaMoreaux & Associates, Inc., as cosponsor, and the Organizing Committee remain an integral part of the conference. This year's Sinkhole Conference is co-organized with the Minnesota Ground Water Association.

The proceedings of these conferences have been valuable additions to karst libraries around the world. Below is a list of the proceedings from the beginning conference to 2013

Previous Conferences and Proceedings

No.	Proceedings	Year	Location
1st	Sinkholes: Their Geology, Engineering and Environmental Impact	1984	Orlando, FL
2nd	Karst Hydrogeology: Engineering and Environmental Applications	1987	Orlando, FL
3rd	Engineering and Environmental Impacts of Sinkholes and Karst	1989	St. Petersburg Beach, FL
4th	Applied Karst Geology	1993	Panama City, FL
5th	Karst GeoHazards: Engineering and Environmental Problems in Karst Terranes	1995	Gatlinburg, TN
6th	The Engineering Geology and Hydrogeology of Karst Terranes	1997	Springfield, MO
7th	Hydrogeology and Engineering Geology of Sinkholes and Karst	1999	Harrisburg/Hershey, PA
8th	Geotechnical and Environmental Applications of Karst Geology and Hydrology	2001	Louisville, KY
9th	ASCE Geotechnical Special Publication No. 122	2003	Huntsville, AL
10th	ASCE Geotechnical Special Publication No. 144	2005	San Antonio, TX
11th	ASCE Geotechnical Special Publication No. 183	2008	Tallahassee, FL
12th	Carbonates and Evaporites volume 27, nos. 2-3	2011	St. Louis, MO
13th	NCKRI Symposium 2: 13th Multidisciplinary Conference on Sinkholes and Karst	2013	Carlsbad, NM

Barry F. Beck Sinkhole Conference Student Scholarship



The Barry F. Beck Sinkhole Student Scholarship (Beck Scholarship) is a competitive grant awarded to one or more students who presents the results of their research at the bi-annual Sinkhole Conference. The award is being inaugurated at this year's conference in memory of the late Dr. Barry Beck, a pioneer in the scientific study of sinkholes who founded the Sinkhole Conference.

At least one Beck Scholarship will be awarded for each conference. Additional scholarships may be awarded if funded from donors for the conference. Beck Scholars receive:

1. One free Sinkhole Conference registration.
2. One free registration to a field trip and short course (pending space availability).
3. An award certificate.
4. Recognition through name badge ribbon, mention in the Sinkhole Conference program and website, and announcements at the opening ceremony and banquet.
5. Reimbursement for up to $1000 of personal individual travel, food, and lodging expenses associated with attending the Sinkhole Conference.

For more information about the Beck Scholarship and to fund future scholars, watch for future Sinkhole Conference websites or visit the National Cave and Karst Research Institute website at https://support.nckri.org/barry-beck-scholarship and contact info@nckri.org or by calling 575-887-5518.

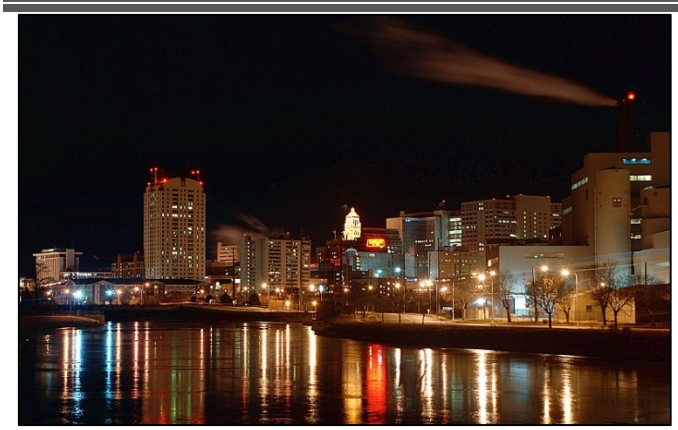
Barry F. Beck 2015 Sinkhole Conference Student Scholarship Recipients

Laurentiu Artugyan
West University of Timisoara
Romania

Tamsin Brittany Green
University of Leeds
UK

John Wall
North Carolina State University
USA

Caren Raedts
University of Western Ontario
Canada



Host City: Rochester, MN

Rochester welcomes the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst! Rochester combines the best aspects of an innovative and cosmopolitan city with the charm of a small town environment. Named "Best Small City" in America by nationally recognized magazines, Rochester merges a multicultural atmosphere with midwestern hospitality, giving convention attendees a most memorable experience.

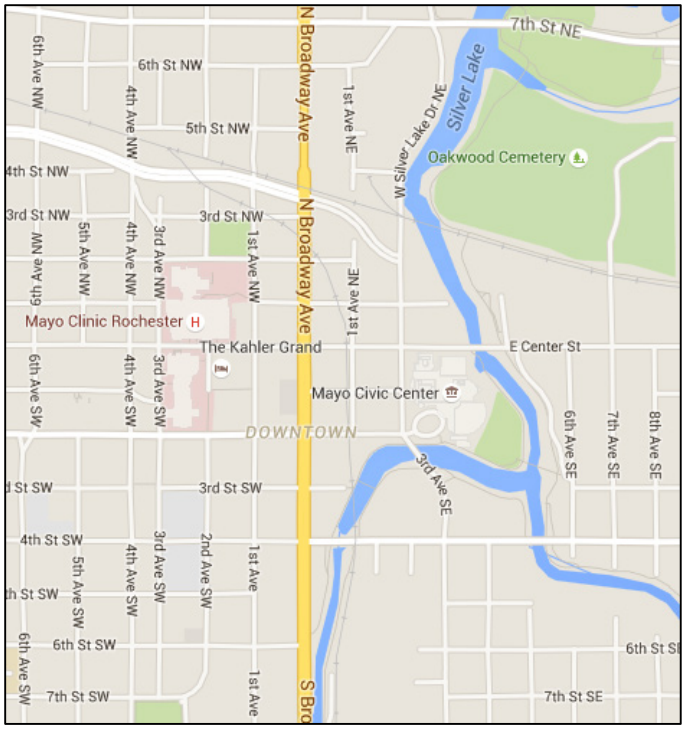
Rochester will pleasantly surprise you with the new developments and amenities downtown and throughout and around the city. Start experiencing Rochester by strolling along the dynamic Peace Plaza, around Peace Fountain and into The Shops at University Square. We offer traditional and new restaurants, fine shops and food courts-all connected by our convenient climate-controlled pedestrian skyway/subway system downtown.

Conference Location: Mayo Civic Center

30 Civic Center Drive SE, Rochester, MN 55904

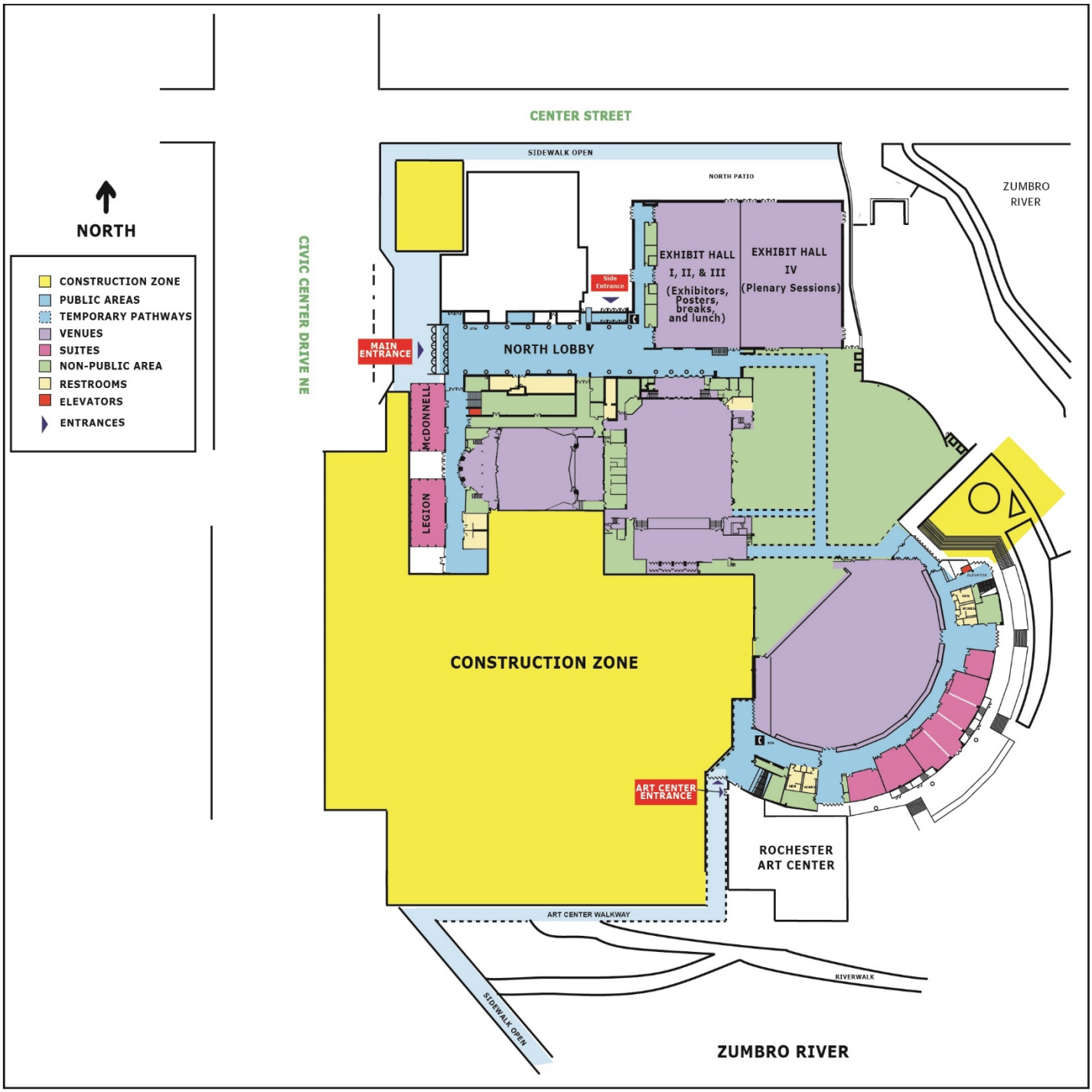
Mayo Civic Center is Southern Minnesota's premier destination for local, regional, national and international conventions, entertainment, social and sporting opportunities. Designed as a dual-venue complex to provide much needed entertainment for the citizens of a growing community, the Mayo Civic Center first opened its doors in 1938. The 1700 seat arena was designed to promote athletic events and included a rink for skating and ice hockey. The 1340 seat theatre was intended as a showcase for fine arts and was designed to accommodate midsized theatrical and musical productions. (Source: mayociviccenter.com)

During this year's Sinkhole Conference, the Civic Center will undergo another major renovation and expansion. We appreciate your patience and understanding if some details in this program or announced during the conference must change due to construction activities.

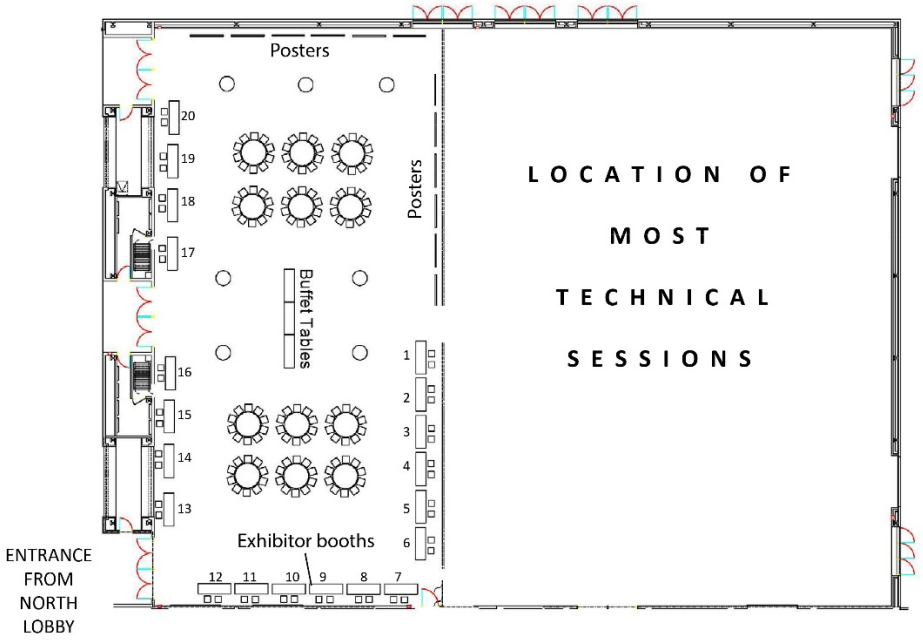


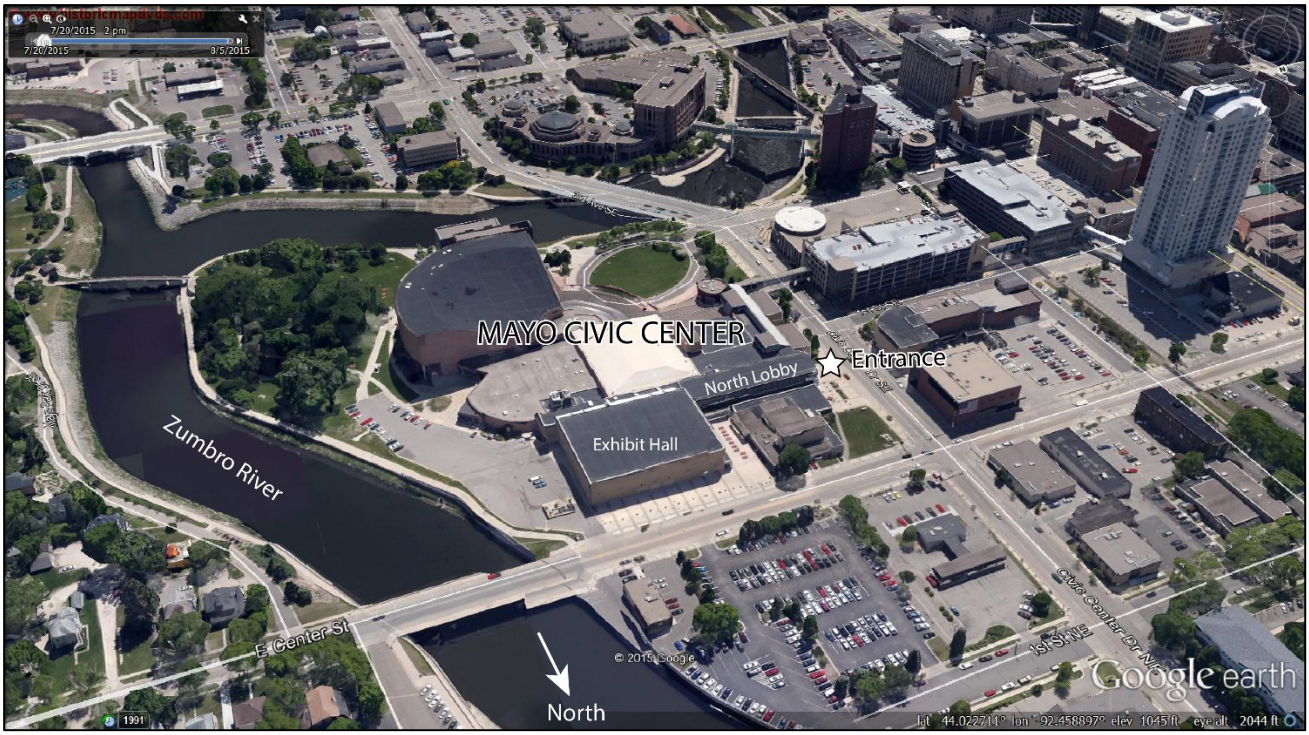
Map of downtown Rochester with the conference location indicated by the star.

Mayo Civic Center Map



MAYO CIVIC CENTER – EXHIBIT HALL





Map of conference location and venues. Image courtesy of Google Earth.

Field Trips

Main Field Trip: Karst Features in the Ordovician Rocks of Southeast Minnesota

Tuesday, 6 October, 7:30 am – 6:00 pm

Trip Co-Leaders: Jeff Green, E. Calvin Alexander, Jr., Tony Runkel and John Barry

Assemble and board buses at the Rochester Civic Center at 7:00 to 7:20. Buses will depart promptly at 7:30 AM

On Tuesday we offer a full-day tour of sinkholes, stream sinks, springs, blind valleys, caves and other karst features developed in the glacio-fluvial landscape of Olmsted and Fillmore counties in southeast Minnesota. Although often referred to as the "Driftless Area" of southeast Minnesota, the area has been glaciated several times during the Pleistocene – but has not been covered with ice in the last few hundred thousand years. The Pleistocene processes are relatively recent perturbation on the karst processes, which have been shaping the surface and subsurface of this area ever since the rocks were deposited 400 to 500 million years ago. The major human activity in southeast Minnesota is modern intensive row crop agriculture (corn and soybeans) and confined animal operations. These human activities directly affect the karst landscapes and the underlying karst aquifers. The karst processes in turn directly affect and limit modern agricultural practices. We will visit on of two commercial caves, Niagara Cave, near Harmony, Minnesota or Mystery Cave in Forestville/Mystery Cave State Park near Spring Valley Minnesota. The cave temperature is about 8 C and a light jacket is recommended. We will also be hiking to several stops across uneven terrain. Hats, sturdy shoes, field clothing and cameras are recommended.

Post-Conference Field Trip: Karst in our Built Environment: the Rochester Area

Friday, 9 October, 12:00 noon – 4:00 pm

Trip Leader: Jeff Broberg

Assemble and board buses at the Rochester Civic Center at 11:45 am to 12:00 noon. Buses will depart promptly at 12:00 noon. Lunch will be provided.

This field trip will present the karst features and sinkhole challenges in and around Rochester and will orient participants to the karst geology and hazards, land use controls, and engineering solutions in this rapidly developing community.

A number of sites will be visited, including:

- A sinkhole plain developed as a high-value residential subdivision in a township with a sinkhole ordinance where developers are required to identify sinkholes on official maps, plats and site plans and where some owners have preserved sinkholes, while others have sealed them.
- A sinkhole plain with dozens of sinkholes surrounding a large beef cattle feedlot.
- An exposed sandstone breccia pipe next to a theater complex where subterranean karst on an Ordovician conformity has resulted in the collapse of overlying sandstone.
- The restored site and bedrock cores of a major sinkhole collapse in a blocked drainageway that threatened a major highway and commercial property.
- The site and viewing of bedrock cores where a Pleistocene-age sinkhole at the base of the St. Peter Sandstone was mitigated to build a 9-story hospital building.
- A building stone quarry where saw-cut rock faces dissect solution enlarged joint planes and paleo-karst surfaces.

Caving Trips at the 14th Sinkhole Conference

Mr. John Ackerman is allowing wild caving trips in his Minnesota Cave Preserve by 14th Sinkhole Conference participants. Preferential access will be given to out-of-state and international participants. See http://www.cavepreserve.com/ for information about the individual caves and the Minnesota Cave Preserve. Spring Valley Caverns, Goliath's Cave, Holy Grail Cave and Tyson's Spring Cave will be available for potential trips. These trips are being coordinated by Calvin Alexander independent of the 14th Sinkhole Conference.

The White-nose Syndrome (WNS) that is devastating bat populations in the eastern and central U.S. has not yet reached Minnesota. Our sincere hope is that WNS does not reach Minnesota. All cavers will be required to follow the USFS decontamination guideline for all caving gear – see https://www.whitenosesyndrome.org/topics/decontamination for the most up to date protocols.

Each trip will be restricted to 5 (five) cavers plus a guide. None of the trips require vertical gear but most caves are entered through 30 inch (0.76 m) diameter vertical shafts with permanently installed ladders. Trips to Spring Valley Caverns, Goliath's Cave and Holy Grail are relatively dry. Trips to Tyson Spring Cave will require thick wet suits. Trips to Tyson Spring Cave do not require SCUBA gear, i.e. do not involve diving, but Tyson's is a river cave that involves wading, crawling and some swimming in water that will be about 8 C (47 °F) and require thick wet suits to avoid hypothermia.

Depending on demand, trips may be organized on Sunday 4 October 2015, Monday evening 5 October 2015, Friday afternoon 9 October 2015 and or Saturday 10 October 2015.

There will be a $25 per trip charge – mainly to cover transportation from the Rochester Civic Center to each cave and return. The caves are about 25 to 45 miles south of Rochester, Minnesota.

King's and Queen's Bluff overlooking Mississippi River Valley, Great River Bluffs State Park, MN. Photo by MNDNR.

Short Courses (Monday, October 5, 2015)

Four courses are offered to expand your knowledge of practical applications of karst science. Space is limited and registrations are processed on a first-come, first-served basis. Onsite registrations can only be accepted on a space-available basis.

Short Course 1: Geologic Site Characterization with Emphasis on Karst

Instructor:
Lynn Yuhr, Technos, Inc.

Location: McDonnell Suite, Mayo Civic Center

A geologic site characterization is the technical foundation for all geotechnical and environmental projects. The objective of a geologic site characterization is to gain an understanding of subsurface conditions that will impact the engineering or environmental decisions made at a site. This effort can be fairly straightforward in a uniform geologic setting. However, karst often provides some of the most variable and diverse geologic settings to deal with.

A wide range of topics will be covered to include a discussion of the problem, a strategy using an integrated systems approach of appropriate methods, using adequate levels of site coverage and considering the impact of scale. Case histories will be presented to illustrate the process. If the geologic site characterization is done right, subsequent geotechnical and environmental decisions can be made with a high degree of confidence and be supported by reliable technical data.

This course is based upon many decades of experience, which is presented in the book ***Site Characterization in Karst and Pseudo-Karst Terrains*** written by Richard C. Benson and Lynn B. Yuhr being published by Springer in 2015. Lynn Yuhr has specialized in site characterization with an emphasis on karst for more than three decades.

Short Course 2: Groundwater Tracing as a Hydrogeologic Tool in Karst and Other Landscapes

Instructors:
Shiloh Beeman, RG, Sr. Hydrogeologist, Ozark Underground Laboratory, Inc.
Tom Aley, PG, PHG, President and Sr. Hydrogeologist, Ozark Underground Laboratory, Inc.
Jeff Green, Springshed Mapping Hydrologist, Minnesota Department of Natural Resources

Location: Legion Suite, Mayo Civic Center

Over the last 50 years, groundwater tracing has been developed as an important tool for the assessment of the hydrogeology of karst environments. In more recent years, it has also been applied successfully in many other subsurface environments for both environmental and engineering applications. However, groundwater tracing is still an often overlooked and underutilized tool for understanding subsurface hydrology.

This short course focuses on the application of groundwater tracing through the examination of a variety of case histories. Case histories will include natural resource evaluations, environmental contaminant transport, highway construction, and leaking reservoirs. In addition, participants will receive an overview of dye tracing methodologies, commonly used tracer dyes, and sampling and analysis techniques.

Short Course 3: Grouting in Karst

Instructors:
Joseph A. Fischer, P.E., Geoscience Services
Michael J. Miluski, P.E., Compaction Grouting Services

Location: McDonnell Suite, Mayo Civic Center

There will be an overview of the differing karst environments and how they influence the most effective grouting procedures. Types of grout, procedures, equipment descriptions and examples will be discussed. Handouts of the course content will be provided. Also discussed will be the design and preparation of a grouting program. Instructors Joseph A. Fischer, P.E. of Geoscience Services and Michael J. Miluski, P.E. of Compaction Grouting Services, Inc. have extensive experience in grouting in karst environments from both the geotechnical engineer's and contractor's viewpoints.

Short Course 4: Minnesota Environmental Management Rules, Regulations and Permits for Southeast Minnesota Karst Landscapes and Karst Aquifers

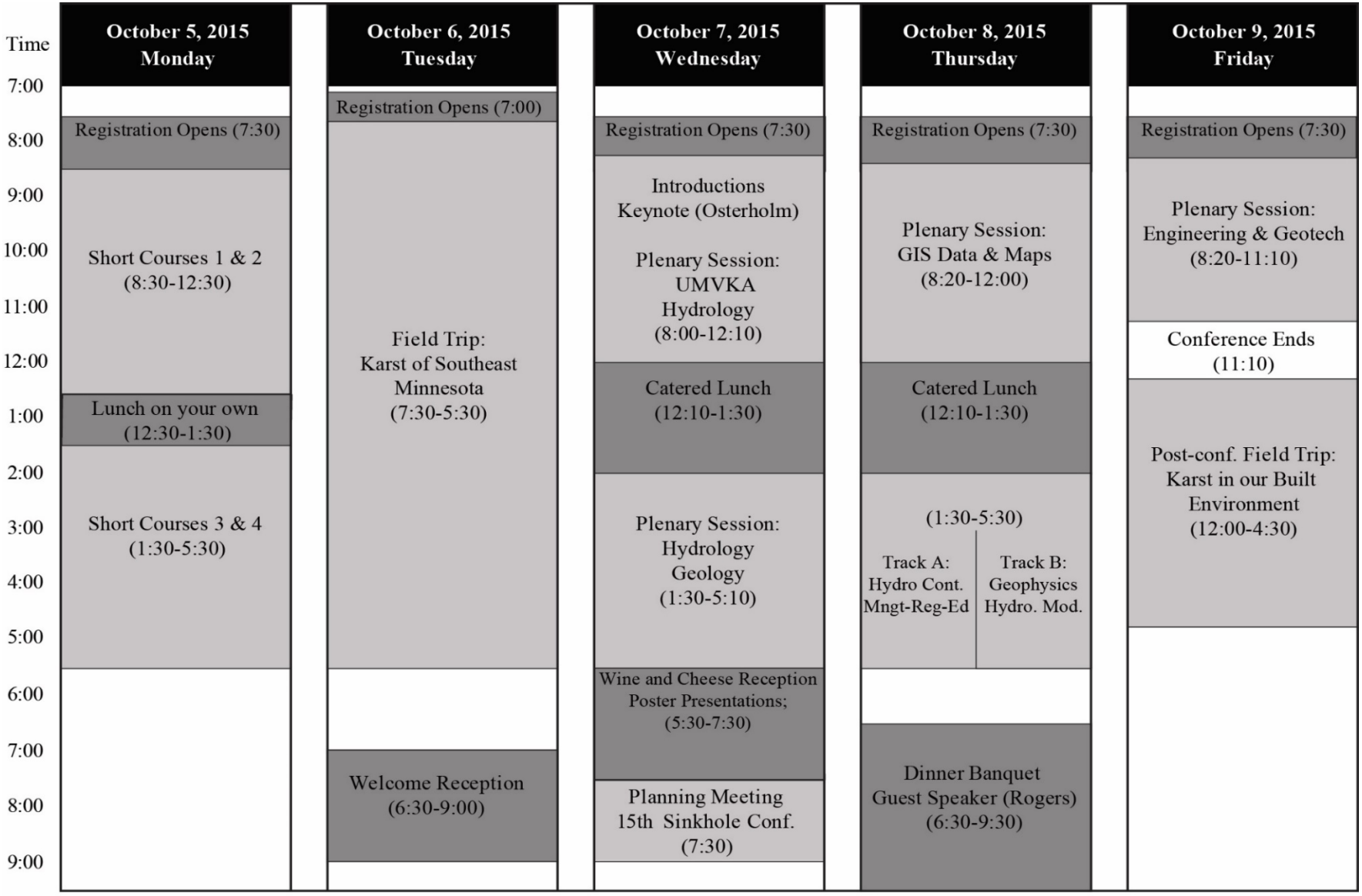
Presenters:
George Schwint, Principal Engineer Feed Lots, Minnesota Pollution Control Agency
Scot Johnson, MS, PG, Hydrologist 3, Minnesota Department of Natural Resources
Daniel Stoddard, Assistant Director, Pesticide & Fertilizer Management Division, Minnesota Department of Agriculture

Moderator: E. Calvin Alexander Jr., University of Minnesota
Location: Legion Suite, Mayo Civic Center

This short course will present an overview of the various rules, regulations and permits that are in place to help environmental managers deal with the challenges associated with southeast Minnesota's karst landscapes and karst aquifers. Rules pertaining to feed lots, spill sites, silica sand mining, landfills, pesticides, nutrients, etc. will be presented and discussed. Handouts will present URLs and contact people for the various Minnesota karst rules, regulations and permit requirements and the basics of each will be discussed.

The short course is meant to give Minnesota environmental managers an overview of the karst related regulations and to present enough information that environmental managers from other states and countries can compare to their own management tools.

Program at-a-Glance



20 minute breaks scheduled during Plenary Sessions at 10:10 am and 3:10 pm.

Detailed Program

Monday, October 5

7:30 AM	**Registration opens, Continental breakfast in Civic Center Suites Lobby**
8:30 AM	**Short Courses 1 and 2 (McDonnell and Legion Suites)**
	SC 1: Geologic Site Characterization with Emphasis in Karst (4 hrs); Instructor: Lynn B. Yuhr
	SC 2: Groundwater Tracing as a Hydrogeologic Tool in Karst and Other Landscapes (4 hrs); Instructors: Shiloh Beeman, Thomas Aley, and Jeff Green,
12:30 PM	**Lunch on your own**
1:30 PM	**Short courses 3 and 4 (McDonnell and Legion Suites)**
	SC 3: Grouting in Karst (4 hrs); Instructors: Joseph A. Fischer and Michael J. Miluski
	SC 4: Minnesota Environmental Management Rules, Regulations and Permits for Southeast Minnesota Karst Landscapes and Karst Aquifers (4 hrs)

Tuesday, October 6

7:00 AM	**Registration opens (Civic Center Suites Lobby)**	
7:30 AM-5:30 PM	**Field Trip: Karst of Southeast Minnesota; Trip Co-Leaders: Jeff Green, E. Calvin Alexander, and Tony Runkel**	*Note: Board Buses on Center Street (north side of civic center). Lunch will be provided.*
6:30 PM	**Welcome reception, Legion Suite**	

Wednesday, October 7

7:30 AM	**Registration opens North Lobby**	
7:40 AM	**Continental breakfast in Exhibit Hall I-III**	
8:00 AM	**Introductory Remarks from George Veni (NCKRI) and Lanya Ross (MGWA)**	
8:10 AM	**Remarks from Mayor of Rochester, Ardell F. Brede**	
8:20 AM	**Remarks from Harvey Thorleifson, Minnesota Geologic Survey**	
Plenary Session: Upper Mississippi Valley Karst Aquifers, Greg Brick (chair); Exhibit Hall IV		
9:10 AM	Joel T. Groten, US Geological Survey; E. Calvin Alexander, Jr., University of Minnesota	Karst Hydrogeologic Investigation of Trout Brook
9:30 AM	Sophie M. Kasahara, Scott C. Alexander and E. Calvin Alexander, Jr., University of Minnesota	Human Impacts on Water Quality in Coldwater Spring, Minneapolis, Minnesota
9:50 AM	Daniel H. Doctor, US Geological Survey; E. Calvin Alexander, Jr., University of Minnesota; Roy Jameson; Scott Alexander, University of Minnesota	Hydrologic and Geochemical Dynamics of Vadose Zone Recharge in a Mantled Karst Aquifer: Results of Monitoring Drip Waters in Mystery Cave, Minnesota
10:15 AM	**Break in Exhibit Hall I-III**	

10:30 AM	John D. Barry and Jeffrey A. Green, Minnesota Dept. of Natural Resources; Julia R Steenberg, Minnesota Geological Survey	Conduit Flow in the Cambrian Lone Rock Formation, Southeast Minnesota, U.S.A.
10:50 AM	Kimm Crawford, Crawford Environmental Services; Terry Lee, Olmsted County Environmental Resources Department	Using Nitrate, Chloride, Sodium, and Sulfate to Calculate Groundwater Age
11:10 AM	Garre A. Conner, Pangea Geoservices	Karst Spring Cutoffs, Cave Tiers, and Sinking Stream Basins Correlated to Fluvial Base Level Decline in South-Central Indiana
11:30 AM	Samuel V. Panno, Illinois State Geological Survey and Dr. Walton R. Kelly, Illinois State Water Survey	Driftless Area Karst of Northwestern Illinois and its Effects on Groundwater Quality
Plenary Session: Karst Hydrology: Sam Panno (chair); Exhibit Hall IV		
11:50 AM	Amaël Poulain, Gaëtan Rochez and Vincent Hallet, University of Namur, Belgium	Hydrogeological Dynamic Variability in the Lomme Karst System (Belgium) as Evidenced by Tracer Tests Results (KARAG project)
12:10 PM	**Catered Lunch in Exhibit Hall I-III**	
1:30 PM	James W. Duley, Cecil Boswell and Jerry Prewett, Missouri Geological Survey	Recharge Area of Selected Large Springs in the Ozarks
1:50 PM	Zaza Lezhava, Nana Bolashvili, Kukuri Tsikarishvili, Lasha Asanidze and Nino Chikhradze, Javakhishvili Tbilisi State University	Hydrological and Hydrogeological Characteristics of the Platform Karst (Zemo Imereti Plateau, Georgia)
2:10 PM	Keith A. White, ARCADIS; Thomas J. Aley, Ozark Underground Laboratory; Michael K. Cobb, ARCADIS; Ethan O. Weikel, US Army Corps of Engineers; Shiloh L. Beeman, Ozark Underground Laboratory	Tracer Studies Conducted Nearly Two Decades Apart Elucidate Groundwater Movement Through a Karst Aquifer in the Frederick Valley of Maryland
2:30 PM	James Nepstad, National Park Service	Dye Tracing Through the Vadose Zone Above Wind Cave, Custer County, South Dakota
2:50 PM	Gheorghe M. Ponta, Geological Survey of Alabama; Nguyen Xuan Nam, Vietnam Institute of Geoscience and Natural Resources; Ferenc L. Forray, Babes-Bolyai University; Florentin Stoiciu, Viorel Badalita, Lenuta J. Enache and Ioan A. Tudor, R&D National Institute for Nonferrous and Rare Metals	A Comparative Study Between the Karst of Hoa Quang, Cao Bang Province, Vietnam and Tuscumbia, Alabama, USA
3:10 PM	**Break in Exhibit Hall I-III**	
Plenary Session: Karst Geology, John Barry (Chair); Exhibit Hall IV		
3:30 PM	Gongyu Li, Xi'an Research Institute of China Coal Technology & Engineering Group Corp.; Wanfang Zhou, Ph.D., P.G. ERT, Inc.	Karst Paleo-Collapses and Their Impacts on Mining and the Environment in Northern China
3:50 PM	Beverley Lynn Shade, University of Texas; E. Calvin Alexander, Jr. and Scott C. Alexander, University of Minnesota	The Sandstone Karst of Pine County, Minnesota
4:10 PM	E. Calvin Alexander, Jr. and Betty J. Wheeler, University of Minnesota	A Proposed Hypogenic Origin of Iron Ore Deposits in Southeast Minnesota Karst
4:30 PM	Tamsin Green, University of Leeds	Down the Rabbit Hole: Identifying Physical Causes of Sinkhole Formation in the UK

4:50 PM	Brian B. Hunt, Brian A. Smith and Alan Andrews, Barton Springs/Edwards Aquifer Conservation District; Douglas Wierman, The Meadows Center for Water and the Environment; Alex S. Broun, Hays Trinity Groundwater Conservation District; Marcus O. Gary, Edwards Aquifer Authority	Relay Ramp Structures and Their Influence on Groundwater Flow in the Edwards and Trinity Aquifers, Hays and Travis Counties, Central Texas
5:30 PM	**Poster Presentations; Wine and Cheese Reception; Exhibit Hall I-III**	
	E. Calvin Alexander, Jr., University of Minnesota; Scott C. Alexander, University of Minnesota; Kelton Barr, Braun Intertec; Andrew Luhmann, University of Minnesota; Cale Anger, University of Minnesota (deceased)	Goliath's Cave, Minnesota: Epigenic Modification and Extension of Preexisting Hypogenic Conduits
	Nozad Hasan Azeez, Dr. Landis Jared West, Professor Simon H Bottrell, University of Leeds	Numerical Simulation of Spring Hydrograph Recession Curves for Evaluating Behavior of the East Yorkshire Chalk Aquifer
	BJ Bonin, Greg Brick, Minnesota Department of Natural Resources and Julia Steenberg, Minnesota Geological Survey	Seeps and Springs at a Platteville "Observatory" on the River Bluffs
	Toby Dogwiler and Blake Lea, Missouri State University	Using Electrical Resistivity Imaging to Characterize Karst Hazards in Southeastern Minnesota Agricultural Settings
	Zhanfei Gu, Qi Liu, Yaoru Lu, and Zhenming Shi, Tongji University; Gaoyu Su, Guangdong Freeway Co, Ltd.	Analysis and Prevention of Sinkhole Collapses During the Reconstruction and Extension of the Guang-Qing Freeway, China
	Fuwei Jiang, Guizhou Institute of Technology; Mingtang Lei and Dai Jian-ling, Institite of Karst Geology	Study on the Critical Velocity of Groundwater to Form Subsidence Sinkholes in Karst Area
	Mason Johnson and Ashley Ignatius, Minnesota Pollution Control Agency	Finding Springs in the File Cabinet
	Philippe Machetel, Geosciences Montpellier; David A. Yuen, University of Minnesota and China University of Geosciences	Evaluation of First Order Error Induced by Conservative-Tracer Temperature Approximation for Mixing in Karstic Flow
	Michael G Raines, Dr. Vanessa J. Banks, and Jonathan E. Chambers, British Geological Survey; Philip E. Collins, Brunel University London; Peter F. Jones, University of Derby; Dave J. Morgan, James B. Riding and Katherine Royse, British Geological Survey	The Application of Passive Seismic Techniques to the Detection of Buried Hollows
	Tim Stokes, Vancouver Island University; Paul Griffiths, Consultant; Carol Ramsey, Vancouver Island University	New Methodologies and Approaches for Mapping Forested Karst Landscapes, Vancouver Island, British Columbia, Canada.
	Kamal Taheri, Kermanshah Regional Water Authority; Milad Taheri, Bu-Ali Sina University;Fathollah Mohsenipour, Kermanshah Regional Water Authority	LEPT, A Simplified Approach for Assessing Karst Vulnerability in Regions by Sparse Data; A Case in Kermanshah Province, Iran
	Sam B. Upchurch, SDII Global Corporation	Determination of the Relationship of Nitrate to Discharge and Flow Systems in North Florida Springs
	Min Yang, Feng'e Zhang, Sheng Zhang, Miying Yin and Guoqing Wu, Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences	Hydrochemical Characteristics and Formation Mechanism of Groundwater in the Liulin Karst System, Northwestern China
	Wei Zhang, Wang Guiling and Liu Feng, Institute of Hydrogeology and Environmental Geology, CAGS	Environmental effects of rational utilization of karst geothermal resources in the North China Plain

	Feng'e Zhang, Sheng Zhang, Miying Yin, Guoqing Wu, Institute of Hydrogeology & Environmental Geology, Chinese Academy of Geological Science	Chemical Evidence for Biokarst Development in the Ordos Basin (Northwest China) in Laboratory Batch Experiments
	Edward D. Zisman, Cardno ATC; Stephen West, BTL Engineering Services, Inc.	Hydrocompaction Considerations in Sinkhole Investigations
7:30 PM	**Planning Meeting for 15th Sinkhole Conference; Board Room off the North Lobby**	

Thursday, October 8

7:30 AM	**Registration opens North Lobby, Continental breakfast in Exhibit Hall I-III**	
8:20 AM	**Announcements/Reminders in Exhibit Hall IV**	
Plenary Session: GIS Databases and Mapping of Karst Regions: Jason Polk (Chair); Exhibit Hall IV		
8:30 AM	Jeffrey A. Green, Minnesota Dept. of Natural Resources, E. Calvin Alexander, Jr., University of Minnesota	Creation of a Map of Paleozoic Bedrock Springsheds in Southeast Minnesota
8:50 AM	Vanessa J. Banks, H. J. Reeves, E. K. Ward, E. R. Raycraft, H. V. Gow, D. J. R Morgan and D. G. Cameron, British Geological Survey	Media, Sinkholes and the UK National Karst Database
9:10 AM	Sam B. Upchurch and Thomas M. Scott, SDII Global Corporation; Michael C. Alfieri, Water Resource Associates; Thomas L. Dobecki, SDII Global Corporation	Shallow Depressions in the Florida Coastal Plain: Karst and Pseudokarst
9:30 AM	Clint Kromhout and Alan E. Baker, Florida Geological Survey	Sinkhole Vulnerability Mapping: Results from a Pilot Study in North Central Florida
9:50 AM	John Wall, North Carolina State University; Daniel H Doctor and Silvia Terziotti, US Geological Survey	A Semi-Automated Tool for Reducing the Creation of False Closed Depressions from a Filled LiDAR-Derived Digital Elevation Model
10:10 AM	**Break in Exhibit Hall I-III**	
10:30 AM	Robert G. Tipping, Mathew Rantala, E. Calvin Alexander, Jr., University of Minnesota; Yongli Gao, University of Texas; Jeffrey A. Green, Minnesota Department of Natural Resources	History and Future of the Minnesota Karst Feature Database
10:50 AM	Gregory Brick, Minnesota Dept. of Natural Resources	Legacy Data in the Minnesota Spring Inventory
11:10 AM	Yongli Gao, University of Texas; Raghav Ramanathan, Bulent Hatigoplu and M. Melih Demirkan, Rizzo Associates; Mazen Elias Adib, Abu Dhabi City Municipality; Juan J. Gutierrez, Hesham El Ganainy and Daniel Barton Jr., Rizzo Associates	Development of Cavity Probability Map For Abu Dhabi Municipality Using GIS and Decision Tree Modeling

11:30 AM	Raghav Ramanathan, Rizzo Associates; Yongli Gao, University of Texas; M. Melih Demirkan; Bulent Hatipoglu, Rizzo Associates; Mazen Elias Adib, Abu Dhabi City Municipality; Michael Rosenmeier, Juan Gutierrez, and Hesham El Ganainy, Rizzo Associates	Evaluation of Cavity Distribution Using Point-Pattern Analysis
11:50 AM	Alexandra L. Todd and Lindsay Ivey-Burden, University of Virginia	A Method of Mapping Sinkhole Susceptibility Using a Geographic Information System: A Case Study for Interstates in the Karst Counties of Virginia
12:10 PM	**Catered Lunch in Exhibit Hall I-III**	
Track A-- Session: Contamination of Karst Aquifers: Ming Ye (Chair); Mc Donnell Suite		
1:30 PM	Larry Boot Pierce, Missouri Geological Survey; Honglin Shi, Missouri University of Science and Technology	Evaluation of Veterinary Pharmaceuticals and Iodine for Use as a Groundwater Tracer in Hydrologic Investigation of Contamination Related to Dairy Cattle Operations
1:50 PM	Virginia Yingling, Minnesota Department of Health	Karst Influence in the Creation of a PFC Megaplume
2:10 PM	Caren Raedts and Christopher Smart, Western University of Ontario	Tracking of Karst Contamination Using Alternative Monitoring Strategies: Hidden River Cave Kentucky
2:30 PM	Ingrid Y Padilla, Vilda L Rivera and Celys Irizarry, University of Puerto Rico	Spatiotemporal Response of CVOC Contamination and Remedial Actions in Eogenetic Karst Aquifers
Track A--Session: Geophysical Exploration of Karst: Mustafa Saribudak (Chair); Legion Suite		
1:30 PM	Mustafa Saribudak, Environmental Geophysics Associates	The Million Dollar Question: Which Geophysical Methods Locate Caves Best Over the Edwards Aquifer? A Potpourri of Case Studies from San Antonio and Austin, Texas, USA
1:50 PM	Lewis Land, National Cave and karst Research Institute; Lasha Asanidze, Tbilisi State University	Rollalong Resistivity Surveys Reveal Karstic Paleotopography Developed on Near-Surface Gypsum Bedrock
2:10 PM	Brian Bruckno, Virginia Department of Transportation; Andrea Vaccari, University of Virginia; Edward Hoppe, Virginia Center for Transportation Innovation and Research; Scott T. Acton, University of Virginia; Elizabeth Campbell, Virginia Department of Transportation	Integration and Delivery of Interferometric Synthetic Aperture Radar (InSAR) Data Into Stormwater Planning Within Karst Terranes
2:30 PM	Khiem T. Tran, Clarkson University; Michael McVay, University of Florida; Trung Dung Nguyen, Clarkson University	Detection of Voids in Karst Terrain with Full Waveform Tomography
2:50 PM	Laurentiu Artugyan, Adrian C. Ardelean and Petru Urdea, West University of Timisoara	Characterization of Karst Terrain Using Geophysical Methods Based on Sinkhole Analysis: A Case Study of the Anina Karstic Region (Banat Mountains, Romania)
3:10 PM	**Break in Exhibit Hall I-III**	
Track A--Session: Karst Management, Regulation and Education: David Weary (Chair); McDonnell Suite		
3:30 PM	David Weary, US Geological Survey	The Cost of Karst Subsidence and Sinkhole Collapse in the United States Compared with Other Natural Hazards
3:50 PM	Fang Guo and Guanghui Jiang, Institute of Karst Geology, Chinese Academy of Geological Sciences; Kwong Fai Andrew Lo, Chinese Culture University; Qingjia Tang, Yongli Guo and Shaohua Liu, Institute of Karst Geology, Chinese Academy of Geological Sciences	Hazard of Sinkhole Flooding to a Cave Hominin Site and its Control Countermeasures in a Tower Karst Area, South China

4:10 PM	Martin Larsen, Olmsted County Soil and Water Conservation District	Case Studies of Animal Feedlots on Karst in Olmsted County, Minnesota
4:30 PM	Chiara Calligaris, Stefano Devoto, Luca Zini, and Franco Cucchi, Trieste University	Evaporite Geo-Hazard in the Sauris Area (Friuli Venezia Giulia Region - NE Italy)
4:50 PM	George Veni, National Cave and Karst Research Institute; Connie Campbell Brashear and Andrew Glasbrenner, Bracken Engineering, Inc.	Building Codes to Minimize Cover-Collapses in Sinkhole-Prone Areas
5:10 PM	Jason S. Polk and Leslie A. North, Western Kentucky University; Ric Federico, Brian Ham and Dan Nedvidek, EnSafe; Kegan McClanahan and Pat Kambesis, Western Kentucky University; Michael J. Marasa, Hayward Baker	Cars and Karst: Investigating the National Corvette Museum Sinkhole
Track B--Session: Geophysical Exploration of Karst, Mustafa Saribudak (Chair); Legion Suite		
3:30 PM	Philip J Carpenter and Lauren M. Schroeder; Northern Illinois University	Investigation of a Sinkhole in Ogle County, Northwestern Illinois, Using Near-Surface Geophysical Techniques
3:50 PM	Zhende Guan, X Z Jiang, Y B Wu, Z Y Pang, Institute of Karst Geology, China University of Geosciences	Study on Monitoring and Early Warning of Karst Collapse Based on BOTDR Technique
4:10 PM	Cathleen E Jones and Ronald G Blom, Jet Propulsion Laboratory, California Institute of Technology	Pre-Event and Post-Formation Ground Movement Associated with the Bayou Corne Sinkhole
Track B--Plenary Session: Modeling of Karst Systems: Ming Ye (Chair); Legion Suite		
4:30 PM	Long Jia, Yan Meng and Zhen-de Guan, Institute of Karst Geology; Li-peng Liu, China Institute of Water Resources and Hydropower Research	Numerical Simulation of Karst Soil Cave Evolution
4:50 PM	Xiaohu Tao, Ming Ye, Dangliang Wang, Roger Pacheco Castro and Xiaoming Wang, Florida State University; Jian Zhao, Hohai University	Experimental and Numerical Investigation of Cover-Collapse Sinkhole Development and Collapse in Central Florida
5:10 PM	Justin L. Blum, Minnesota Department of Health	Accounting for Anomalous Hydraulic Responses During Constant-Rate Pumping Tests in the Prairie Du Chien-Jordan Aquifer System - Towards a More Accurate Assessment of Leakage
6:30pm	**Banquet and Guest Speaker: David Rogers, Missouri University of Science and Technology; Location: The Kahler Grand Hotel, Heritage I-II, 20 SW Second Ave, Rochester**	***Hales Bar and the Pitfalls of Constructing Dams on Karst***

Friday, October 9

7:30 AM	**Registration opens North Lobby, Continental breakfast in Exhibit Hall I-III**
8:20 AM	**Announcements/Reminders in Exhibit Hall IV**
Plenary Session: Engineering and Geotechnical Investigations in Karst, Lynn Yuhr (Chair); Exhibit Hall IV	
8:30 AM	Joseph A. Fischer and Joseph J. Fischer, Geoscience Services — Concepts for Geotechnical Investigation in Karst

8:50 AM	Mohamed Alrowaimi, Hae-Bum Yun and Manoj Chopra, University of Central Florida	Sinkhole Physical Models to Simulate and Investigate Sinkhole Collapses
9:10 AM	Kevin M O'Connor, GeoTDR, Inc; Matthew Trainum, Iowa Department of Transportation	Monitoring the Threat of Sinkhole Formation Under a Portion of US 18 in Cerro Gordo County, Iowa Using TDR Measurements
9:30 AM	Edward D Zisman, Cardno ATC	Predicting Compaction Grout Quantities in Sinkhole Remediation
9:50 AM	Chase L Kicker, New Mexico Institute of Mining and Technology	A Feasibility Study of the Implementation of a Flowable Fill Material to Prevent Sinkhole Occurrence at the I&W Brine Well Site in Carlsbad, New Mexico
10:10 AM	**Break in Exhibit Hall I-III**	
10:30 AM	Steven W Shifflett, US Army Corps of Engineers	Pre-Construction Rock Treatment and Soil Modification Program Using Low Mobility Grout to Mitigate Future Sinkhole Development in a 2,787.1 Square Meter (30,000 SF) Maintenance Facility
10:50 AM	David M Robison, U.S. Army Corps of Engineers	Successful Foundation Preparations in Karst Bedrock of the Masonry Section of Wolf Creek Dam
12:00 AM	**Post-conference field trip: Karst in Our Built Environment** **Trip Leader: Jeff Broberg**	*Note: Box lunches will be provided.*

Moth Spring, Fillmore County, MN. Photo by Jeff Green

Keynote Speaker: Michael T. Osterholm, PhD, MPH

The Midwest Karst and Historic Tall Grass Prairie: An Overlooked International Treasure

Dr. Osterholm is the McKnight Presidential Endowed Chair in Public Health at the University of Minnesota and director of the Center for Infectious Disease Research and Policy (CIDRAP), a professor in the Division of Environmental Health Sciences, School of Public Health, a professor in the Technological Leadership Institute, College of Science and Engineering, and an adjunct professor in the Medical School, University of Minnesota.
He is also a member of the Institute of Medicine (IOM) of the National Academy of Sciences and the Council of Foreign Relations. In June 2005 Dr. Osterholm was appointed by Michael Leavitt, Secretary of the Department of Health and Human Services (HHS), to the newly established National Science Advisory Board on Biosecurity. In July 2008, he was named to the University of Minnesota Academic Health Center's Academy of Excellence in Health Research. In October 2008, he was appointed to the World Economic Forum Working Group on Pandemics.

In the late 1960s Mike was part of the cave diving teams that dove the Coldwater Spring sump, discovered and mapped the initial exploration of Coldwater Cave which is now the longest cave (currently at17 miles) in the Upper Mississippi Valley Karst. In the early 1970s Mike's PhD thesis at the University of Minnesota concerned the impact of bacterial contamination of groundwater on children's health in southeast Minnesota's karst lands

Dr. Osterholm served for 24 years (1975-1999) in various roles at the Minnesota Department of Health (MDH), the last 15 as state epidemiologist and chief of the Acute Disease Epidemiology Section. While at the MDH, Osterholm and his team were leaders in the area of infectious disease epidemiology.

Dr. Osterholm has been an international leader on the critical concern regarding our preparedness for an influenza pandemic. His invited papers in the journals *Foreign Affairs*, the *New England Journal of Medicine*, and *Nature* detail the threat of an influenza pandemic before the recent pandemic and the steps we must take to better prepare for such events. Dr. Osterholm has also been an international leader on the growing concern regarding the use of biological agents as catastrophic weapons targeting civilian populations. In that role, he served as a personal advisor to the late King Hussein of Jordan. Dr. Osterholm provides a comprehensive and pointed review of America's current state of preparedness for a bioterrorism attack in his *New York Times* best-selling book, *Living Terrors: What America Needs to Know to Survive the Coming Bioterrorist Catastrophe*.

One of Mike's passions is the Prairie Song Farm in northeastern Iowa karst. (Google Prairie Song Farm). With 380 feet of vertical relief the farm stratigraphically spans from the Galena Limestone down to the Prairie du Chien Group. Mike notes that the Upper Mississippi Valley is the only place on Earth where Tall Grass Prairie on loess soils occur on top of karst. This unique superposition creates a unusual landscape the Mike is working to restore.

Banquet Speaker: David J. Rogers, PhD

Hales Bar and the Pitfalls of Constructing Dams on Karst

Hales Bar Dam was built on the Tennessee River 33 miles downstream of Chattanooga by a private company to generate power in 1905-1913. The dam site was selected because it was the narrowest reach in the downstream end of the Walden Ridge Gorge. The site is underlain by Mississippian Bangor Limestone on the southeast flank of the Sequatchie Anticline. Three different contracts failed to complete the dam because of difficult foundation conditions. From 1910-1913 diamond drill core holes were used to explore the site and a series of reinforced concrete caissons 40x45 ft on upstream side and 30x32 ft on the downstream side were installed. Excessive leakage soon appeared near the eastern abutment, and gradually increased. Soundings were made in 1914 to ascertain the areas of gross leakage thereafter rags were placed over suction holes on the river bed and concrete pumped over these. Once a leak was stemmed, leakage would resume at other, adjacent locations. The owners tried to stem the leaks by inserting hay bales, old mattresses, chicken wire, and even corsets! In 1919 the owners began drilling grout holes from the inspection gallery within the dam and pumping hot asphalt into the voids. This was followed by the injection of 78,324 cubic feet of hot asphalt grout into the dam foundation, using 6,266 lineal feet of boreholes with average hole depth of 92 ft. By 1922 the problem appeared solved, but leakage gradually resumed between 1922-1929, rising to the same level as had been observed previously.

In 1930-1931 a new program of exploration was undertaken, using dyes and oils to identify conduits under the dam. Leakage was found to vary between 100 and 1200 cubic feet per second (cfs). When the dam was acquired by the Tennessee Valley Authority (TVA) in 1939 they employed fluorescein dyes to track the under-seepage. Dye tests revealed that the leakage varied between 1720 and 1650 cfs; about 10% of the river's normal flow. They also noted seepage boils forming in the gravel bars, which increased each year. The TVA began constructing the most expensive cutoff wall ever built, drilling 750 18-inch diameter holes along the dam's centerline and backfilling this with concrete to a maximum depth of 163 feet, extending 25 to 103 feet below the river bed. In April 1963 the TVA announced it was abandoning Hales Bar Dam, due to increasing leakage.

Biography: J. David Rogers holds the Karl F. Hasselmann Chair in Geological Engineering at the Missouri University of Science & Technology in Rolla, Missouri. He is presently representing the geological and geotechnical engineering professions on the National Academies panel that has been charged with examining "Levees and the National Flood Insurance Program: Improving policies and practices," being funded by FEMA.

Dr. Rogers has been fascinated by dam and levee failures, evaluating the stability of natural slopes, embankments, stream channels, highways, and hydraulic structures. He has served as principal investigator for research funded by the NSF, U.S. Geological Survey, National Geospatial Intelligence Agency, Federal Highway Administration, Department of Defense, and several state departments of transportation.

He has served on numerous panels, including the Mississippi Delta Science & Engineering Special Team, the Coastal Louisiana Recovery Panel, the NSF Independent Levee Investigation Team and USGS Investigation Teams evaluating the impacts of Hurricanes Katrina and Rita, the NSF team evaluating the 2008 and 2011 Mississippi River floods, and the Resilient and Sustainable Infrastructure Networks team funded by NSF to make a five year examination of the California Bay Delta flood protection systems.

He recently completed a book on the Engineers Who Built the Panama Canal and delivered one of principal history and heritage presentations at the 100th anniversary of the completion of the Panama Canal, down in Panama for the ASCE annual meeting. He is a frequent guest on newscasts and television documentaries on geologic and man-caused hazards.

Dr. Rogers received his B.S. degree in geology from California State Polytechnic University at Pomona, his M.S. degree in civil engineering from the University of California, Berkeley, and his Ph.D. in geological and geotechnical engineering at the University of California, Berkeley. He served on the Berkeley faculty in civil engineering for seven years prior to accepting his current position in 2001.

Presentation Abstracts
(in order of presentation)

Wednesday, October 7th
9:10am-11:50pm
Upper Mississippi Valley Karst Aquifers

Karst Hydrogeologic Investigation of Trout Brook

Joel T. Groten, US Geological Survey
E. Calvin Alexander, Jr., University of Minnesota

Trout Brook in the Miesville Ravine County Park of Dakota County Minnesota is the trout stream with the highest nitrate concentration in the karst region of southeastern Minnesota. Water quality data from 1985 and 1995 (Spong, 1995) and from 2001, 2002, 2006, 2010, and 2014, collected by the Dakota County Soil and Water Conservation District (Dakota SWCD, 2014) document an increasing level of nitrate in Trout Brook. A karst hydrogeologic investigation was designed to measure nitrate levels at sampling points along the stream and to increase our understanding of the source and movement of nitrates throughout the length of Trout Brook. Eighteen springs and seeps have been located in the Main Branch and tributaries of Trout Brook. A previously unreported flowing section and stream sieve, Weber Sieve, were found above what had been thought to be the head of perennial flow in the East Branch of Trout Brook. Two new sinkholes developed after the 14-15 June 2012 flood in a field northeast of the East Branch of Trout Brook. This investigation included regular monitoring of major anions in the streams and springs, synoptic stream flow measurements, and a dye trace of a sinking stream in the Trout Brook drainage.

The initial assumption was that the majority of the baseflow of Trout Brook was from discrete springs. However, synoptic baseflow and nitrate measurements show that only 30-40 percent of the total flow in Trout Brook is from discrete springs, and the rest appears to be from distributed groundwater discharge directly into the stream. Both the discrete springs and the distributed recharge occur along reaches of Trout Brook that drain the significant high transmissivity zone near the bottom of the regionally important Shakopee aquifer. Dye traces have confirmed flow-paths from Weber Sieve to LeDuc and Bridgestone Springs and have begun to define springsheds for these head water springs. Nitrate concentrations and chloride/bromide ratios decreased systematically from the upstream springs to the downstream springs.

The nitrate concentrations have been increasing at four springs from 1985 to 2014 and at two surface sampling points from 2001 to 2014. The nitrate concentration of another surface sampling point increased from 2001 to 2006, decreased from 2006 to 2012, and increased from 2012 to 2014. Snowmelt and rainfall runoff was sampled on 2 March 2012 and showed no detectable nitrate in the runoff from a watershed with no row-crop agriculture, but elevated nitrate was detected in an adjacent watershed with row-crop agriculture. All of these trends illustrate the dominance of agricultural sources of nitrate in Trout Brook.

Human Impacts on Coldwater Spring Water Quality, Minneapolis, Minnesota

Sophie M. Kasahara, University of Minnesota
Scott C. Alexander, University of Minnesota
E. Calvin Alexander, Jr., University of Minnesota

Coldwater Spring in Minneapolis, Minnesota was the water supply for Fort Snelling from the 1840s to 1920. The spring site has been declared a sacred site by some federally recognized Native American tribes. The site is managed by the National Park Service. This project has monitored the water chemistry of Coldwater Spring to document human impacts on the spring's water quality. Temperature, dissolved oxygen, conductivity, pH and anions were monitored weekly and cations and alkalinity monitored monthly at Coldwater Spring and the adjacent Wetland A from 15 February 2013 through 18 January 2015. Coldwater Spring's water flows through fractures in Platteville Limestone of Ordovician age. The basic chemistry of Coldwater Spring should be the calcium magnesium bicarbonate water typical of carbonate springs. However, on an equivalent basis, Coldwater Spring's water currently contains almost as much sodium as calcium + magnesium and more chloride than bicarbonate. The chloride concentrations are about 100 times the levels from 1880. Maguire (1880) reported the chloride levels of Coldwater Spring were about 4.5 ppm. During the current study the chloride content in the spring increased from about 320 ppm from March 2013 to about 410 ppm in December 2014. In April, May and June of 2013 and 2014, the chloride rose about 100 ppm in three month-long pulses. The chloride concentration of the water in Wetland A ranges from about 400 ppm to over 600 ppm with a pattern that is a mirror image of the Coldwater Spring pattern. This major anthropogenic chloride component has a chloride to bromide ratio of 2,500 ± 300, well within the range of chloride to bromide ratios of road salt, 1,000 to 10,000. Road salt is applied to two major multi-lane highways close to the spring and is used extensively in this heavily urbanized area throughout the

winter. The temperature of the spring is variable and higher than its pre-settlement temperature. Nicollet (1841) recorded the temperature of Coldwater Spring multiple times in summer of 1836 as 46 °F (7.8 °C) and multiple times in winter of 1837 as 45.5 °F (7.5 °C). More recently the temperature of Coldwater Spring fluctuates smoothly between 10.7 and 13.1 °C. The higher temperature of the springs' discharge also indicates an anthropogenic source of heat within the spring-shed or spring recharge area. The spring water is coldest in May and June and warmest in October and November. The temperature of the water in Wetland A fluctuates from 6.4 to 13.8 °C – in a pattern that is opposite of that in Coldwater Spring. Coldwater Spring also contained a significant, increasing nitrate-nitrogen component which ranged from 2.5 to 5.2 ppm – with dips at the same times as the chloride pulses. Wetland A's nitrate-nitrogen level varied between 0.2 to almost 6 ppm with large pulses at the same time as Coldwater Spring's dips. A 2014 study performed by the U.S. Geological Survey came to the conclusion that increasing chloride levels in lakes and streams are likely driven by increasing road salt application, rising baseline concentrations, as well as an increase in snowfall in the Midwestern area of the U.S. during the time of the study (Corsi 2014). The significant chloride, temperature and nitrate levels are likely to be driven by anthropogenic sources.

Hydrologic and Geochemical Dynamics of Vadose Zone Recharge in a Mantled Karst Aquifer: Results of Monitoring Drip Waters in Mystery Cave, Minnesota

Daniel H. Doctor, US Geological Survey
E. Calvin Alexander, Jr., University of Minnesota
Roy Jameson
Scott Alexander, University of Minnesota

Caves provide direct access to flows through the vadose zone that recharge karst aquifers. Although many recent studies have documented the highly dynamic processes associated with vadose zone flows in karst settings, few have been conducted in mantled karst settings, such as that of southeastern Minnesota. Here we present some results of a long-term program of cave drip monitoring conducted within Mystery Cave, Minnesota. In this study, two perennial ceiling drip sites were monitored between 1997 and 2001. The sites were located about 90 m (300 ft) apart along the same cave passage approximately 18 m (60 ft) below the surface; 7 to 9 m (20 to 30 ft) of loess and 12 m (40 ft) of flat-lying carbonate bedrock strata overlie the cave. Records of drip rate, electrical conductivity, and water temperature were obtained at 15 minute intervals, and supplemented with periodic sampling for major ion chemistry and water stable isotopes. Patterns in flow and geochemistry emerged at each of the two drip sites that were repeated year after year. Although one site responded relatively quickly (within 2-7 hours) to surface recharge events while the other responded more slowly (within 2-5 days), thresholds of antecedent moisture needed to be overcome in order to produce a discharge response at both sites. The greatest amount of flow was observed at both sites during the spring snowmelt period. Rainfall events less than 10 mm (0.4 in) during the summer months generally did not produce a drip discharge response, yet rapid drip responses were observed following intense storm events after periods of prolonged rainfall. The chemical data from both sites indicate that reservoirs of vadose zone water with distinct chemical signatures mixed during recharge events, and drip chemistry returned to a baseline composition during low flow periods. A reservoir with elevated chloride and sulfate concentrations impacts the slow-response drip site with each recharge event, but does not similarly affect the fast-response drip site. Nitrate concentrations in drip waters were generally less than 4.0 mg/L as NO_3^- (or less than 1 mg/L as N). Nitrate was either stable or slightly increased with drip rate at the fast-response drip site; in contrast, nitrate concentrations decreased with drip rate at the slow-response drip site.

Conduit Flow in the Cambrian Lone Rock Formation, Southeast Minnesota, U.S.A.

John D. Barry, Minnesota Dept. of Natural Resources
Jeffrey A. Green, Minnesota Dept. of Natural Resources
Julia R. Steenberg, Minnesota Geological Survey

The karst lands of southeast Minnesota contain more than one hundred trout streams that receive perennial discharge from Paleozoic bedrock springs. Several of the Paleozoic bedrock units that provide discharge are karst aquifers. Field investigations into the flow characteristics of these formations have been conducted using fluorescent dyes to map groundwater springsheds and characterize groundwater flow velocities for use in water resource protection.

Recent field work has focused on the Cambrian Lone Rock Formation, a siliciclastic unit consisting of very fine-grained sandstone and siltstone with minor beds of shale and dolostone. The formation is mapped within tributary valleys of the Mississippi River throughout southeastern Minnesota and southwestern Wisconsin. Overlying the Lone Rock is the Cambrian St. Lawrence Formation. Over a dozen streams have been observed to disappear into stream sinks where the upper St. Lawrence is the bedrock unit closest to the land surface. At three of these sinking stream locations, dye was recovered emanating from springs located in the basal St. Lawrence or from springs located in two distinct zones in the Lone Rock. Dye-breakthrough velocities calculated using passive charcoal detectors ranged between 21-214 meters/day at one location and 88-153 meters/day at another. At a third site, automatic

water samplers were placed at a spring that had been previously demonstrated to be connected to a St. Lawrence stream sink through dye tracing. In that trace, an eight-hour sampling frequency determined the dye-breakthrough velocity was 314 meters/day.

Based on outcrop and borehole observations in Minnesota, secondary pore networks in siliciclastic-dominated units generally have bedding-parallel and vertically oriented apertures less than a few centimeters. The process by which the bedding-parallel secondary pore networks form remains obscure; some appear to be mechanically developed. However, interstitial carbonate cement within these units leads to the possibility of dissolution being a minor factor in the formation's groundwater flow characteristics. These dye traces were conducted at three different sites across a twenty-three kilometer distance and are evidence that the siliciclastic Lone Rock Formation has a conduit-flow component similar to that found in carbonate karst aquifers.

Using Nitrate, Chloride, Sodium, and Sulfate to Calculate Groundwater Age

Kimm Crawford, Crawford Environmental Services
Terry Lee, Olmsted County Environmental Resources Dept.

Regression analysis is used to identify monotonic trends to assign water age using ion data from two large well water databases from southeast Minnesota (SE MN). Nitrate (NO_3-N), chloride (Cl), sodium (Na), and sulfate (SO_4) ions in the commonly used aquifers in SE MN can be used as groundwater tracers since they are either entirely or partly anthropogenic in their sources, their loading occurs on a regional scale, and they are almost entirely conserved.

Ion concentrations over time are used to establish six trend patterns. Two patterns are unchanging (background and stable above background), and four are changing (linear up, exponential up, peaking, and down). These patterns are then used to assign specific age values or age ranges to the well based upon that ion. For ions with linear upward trends, specific ages are derived from the "Intercept Year" representing a time when water extracted from the well first infiltrated from the land surface containing the ion at detectable concentrations and the "Marker-Year" representing the beginning of large scale trend changes for that ion source.

Karst Spring Cutoffs, Cave Tiers, and Sinking Stream Basins Correlated to Fluvial Base Level Decline in South-Central Indiana

Garre A. Conner, Pangea Geoservices

The Mitchell Aquifer averages 80 m in thickness and underdrains a karst region in the Crawford Upland and Mitchell Plateau region in south-central Indiana (110,000 km^2). The Springville Escarpment is a transitional boundary between the upland and plateau. Cave stream linking between cave tiers in the aquifer and correlation of cave tier inception horizons to a base level decline surface is interpreted for the Kirby Watershed, encompassing the prekarst headland of Indian Creek (42 km^2). The watershed was severed from lower Indian Creek at Eller Col by limestone cavern drainage on the ridge between White River and East Fork. Correlation of recharge basin topography and cave tiers is possible owing to the observation of 55 karst springs confined to lithostratigraphic contacts at three spring stratigraphic levels. Karst Spring Cutoffs are a specific type of vadose canyon diverting cave streams, bypassing around springs and passing into the laterally offset cave streams in the next lower cave tier. Cutoffs connect upper to middle tier cave streams and middle to lower tier cave streams as they enlarge below sinking stream basins and tributary spurs. Three speleogenic enlargement cycles characterize the eastern Leonard Springs Area, but only two cycles have enlarged in the western Garrison Chapel Area.

Driftless Area Karst of Northwestern Illinois and its Effects on Groundwater Quality

Samuel V. Panno, Illinois State Geological Survey
Walton R. Kelly, Illinois State Water Survey

The bedrock aquifer of the Driftless Area of northwestern Illinois is Ordovician-age Galena Dolomite. Previous work by the authors and others showed that the geology and hydrogeology of this area fall well within the definition of karst. Bedrock in the study area has been shown to be extensively fractured and creviced; karst features in the county are dominated by solution-enlarged crevices from 0.4 inches to 3 feet wide within most road cuts and quarries examined. Other karst features include cover-collapse sinkholes ranging from 3 to 25 feet in diameter overlying Galena Dolomite, karst springs and crevice caves.

A preliminary evaluation of the groundwater quality Jo Daviess County in the Driftless Area of northwestern Illinois was conducted to assess the susceptibility of the Galena Dolomite aquifer to surface-borne contaminants. This was done by evaluating available groundwater quality data from published sources and the Illinois State Water Survey

Groundwater Quality Database (i.e., wells and springs), and also by sampling 11 private wells across the county and analyzing for inorganic chemistry, dissolved organic carbon, stable isotopes and tritium. We found that groundwater in the study area is of a Ca-Mg-HCO_3 type as would be expected for an aquifer dominated by dolomite. In parts of the county, the upper part of the carbonate-hosted aquifer contains elevated concentrations of chloride, nitrate and potassium. Likely contamination sources are anthropogenic and include road salt, potash and nitrogen fertilizers, and livestock/human waste. The presence of these contaminants suggests movement of surface-borne contaminants into the aquifer and into wells screened at depths ranging from 65 to 150 feet.

Historic data reveal stratification of surface-borne contaminants (greatest concentrations nearest the surface) within the fractured and creviced aquifer to a depth of about 300 feet. Nitrate-N (NO_3-N) concentrations in karst springs are typically between 10 and 13 mg/L, but can exceed 30 mg/L. Because the predominant land use in the study area is row-crop agriculture, it is likely that much of the NO_3-N is derived from N-fertilizer. In the 11 water well samples, NO_3-N concentrations ranged from < 0.04 (detection limit) to 5.4 mg/L and concentrations were clearly related to tritium. Specifically, NO_3-N concentrations in groundwater containing less than 3 TU were below detection (0.04 mg/L), and above 3 TU, NO_3-N and tritium were positively correlated. This relationship suggests a nonpoint source of N and denitrification within the aquifer. Chloride (Cl^-) concentrations in karst springs were between 15 and 25 mg/L above background concentrations (1 to 15 mg/L). Water wells samples had lower Cl^- concentrations with 7 of 11 wells below background (ca. 15 mg/L), although the concentration in the shallowest well was 110 mg/L and was probably derived from road salt. Overall, the groundwater quality of the Galena Dolomite aquifer in Jo Daviess County is what would be expected in an open, dolomite-dominated karst aquifer.

Wednesday, October 7th 11:50am-3:10pm Karst Hydrology

Hydrogeological Dynamic Variability in the Lomme Karst System (Belgium) as Evidenced by Tracer Tests Results (KARAG project)

Amaël Poulain, University of Namur, Belgium
Gaëtan Rochez, University of Namur, Belgium
Vincent Hallet, University of Namur, Belgium

Paleozoic carbonate aquifers represent major groundwater resources in Belgium. Karstification processes affect most of them and Belgium counts many hydrologically active karst networks. Given the intrinsic vulnerability of such geological objects, comprehensive studies are required in order to improve their protection and management.

The KARAG project (Karst Aquifer ReseArch by Geophysic, 2013-2017) aims to identify the specific dynamic of karst aquifers by using geophysical and hydrogeological tools. This research is funded by the Belgium National Fund for Scientific Research (FNRS) and conducted by the University of Namur, University of Mons and the Royal Observatory of Belgium.

The LKS – Lomme Karst System (Rochefort, southern Belgium) was chosen as it is a major Belgian karst system (10 km long) in the Givetian carbonate aquifer (Middle Devonian). The system is formed by two parallel components: the surface system (the Lomme River) and a complex underground system (multiple sinkholes with one main resurgence). Based on this layout, it is possible to study the aquifer dynamic and its relationship with the surface river.

A high resolution monitoring has been installed since July 2013 in order to follow the system dynamic during several hydrogeological cycles.

Multi-tracing experiments with different injections and monitoring points highlight the complexity of underground flow dynamics. Investigations enlightened the connectivity between monitoring points and how dependent of the hydrological conditions were these connections. The breakthrough curves analysis allows to characterize the hydrodynamic behavior of the underground flows within the aquifer.

Modeling will be necessary to link hydrological and tracer tests data in order to build a detailed conceptual model for this karst system. This model will also be used to interpret geophysical data (ERT, gravimetry) collected in order to study the unsaturated and epikarst zones.

Recharge Area of Selected Large Springs in the Ozarks

James W. Duley, Missouri Geological Survey
Cecil Boswell, Missouri Geological Survey
Jerry Prewett, Missouri Geological Survey

Ongoing work by the Missouri Geological Survey (MGS) is refining the known recharge areas of a number of major springs in the Ozarks. Among the springs being investigated are: Mammoth Spring (Fulton County, Arkansas), and the following Missouri springs: Greer Spring (Oregon County), Blue Spring (Ozark County), Blue/Morgan Spring Complex (Oregon County), Boze Mill Spring (Oregon County), two different Big Springs (Carter and Douglas County) and Rainbow/North Fork/Hodgson Mill Spring Complex (Ozark County). Previously unpublished findings of the MGS and United States Geological Survey (USGS) are also being used to better define recharge areas of Greer Spring, Big Spring (Carter County), Blue/Morgan Spring Complex, Rainbow/ North Fork/Hodgson Mill Complex, Wilder Spring (Ozark County) and Althea Spring (Ozark County).

MGS is applying a graphical method of data analysis using spectrofluorometric scan results. Comparing the dye peak intensity to the intensity of the valley preceding the peak yields a ratio that can be used to standardize and quantify water traces. This method can be applied to current and some legacy traces with comparable results.

In some cases, past tracer injection sites were utilized in attempts to replicate older traces from those locations. The data clearly show that there is value in applying spectrofluorometric dye detection techniques in attempting to replicate older traces. Some repeat injections and subsequent monitoring confirmed earlier traces. Other replication efforts revealed multiple recovery points that were undetected by the legacy traces, thus expanding known recharge areas. Still other replication efforts indicate that some older traces are not repeatable. The effect of the replication efforts significantly changes the logical interpretation of a number of recharge area boundaries.

Among the findings of the overall study to date: Mammoth Spring and Greer Spring share a portion of their recharge, with the majority of Greer Spring's flow apparently passing under a gaining segment of the 11 Point River, ultimately emerging more than four kilometers to the southeast. This and other findings raise questions about how hydrology in the study area may be controlled by deep-seated mechanisms such as basal faulting and jointing. Research and understanding would be improved by 1:24,000 scale geologic mapping and increased geophysical study of the entire area.

Hydrological and Hydrogeological Characteristics of the Platform Karst (Zemo Imereti Plateau, Georgia)

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Nana Bolashvili, Javakhishvili Tbilisi State Univ., Georgia
Kukuri Tsikarishvili, Javakhishvili Tbilisi State Univ., Georgia
Lasha Asanidze, Javakhishvili Tbilisi State Univ., Georgia
Chikhradze, Javakhishvili Tbilisi State Univ., Georgia

The article discusses the hydrological and hydrogeological characteristics of the platform karst of Zemo Imereti plateau. The structural plateau of Zemo Imereti is the part of the intermountain plain karst zone of Georgia and one of the interesting parts of the karst relief development. The above mentioned karst region includes the easternmost part of western Georgia, which is characterized by peculiar natural conditions (relief, tectonics, climate, surface and underground streams) and represents one of the significant platform karst regions in the Caucasus. On the basis of the cartographic materials (GIS) analysis and borehole data the general scheme of hydrogeological setting of the Zemo Imereti structural plateau (two hydrogeological basins were defined) was created as confirmed by experiments. In addition, it was identified that underground karst water flowing from the periphery to the center determines sedimentation together with the broken dislocations within the frame of the structural plateau. The study found that within the Chiatura structural plateau the joint karst hydrogeological system (with enough dynamic water resources) has been established, which mainly is unloaded in sources of Ghrudo vaucluse and the surrounding area (local erosion basis). Ghrudo hydrogeological system and Chiatura structural plateau are characterized by the systems of isolated karst-fissure waters with different hypsometric location and orientation. Therefore, based on these studies, it could be said that in karst areas the structural features can define the characteristic of groundwater circulation, but karst age can also make a significant adjustment.

Tracer Studies Conducted Nearly Two Decades Apart Elucidate Groundwater Movement Through a Karst Aquifer in the Frederick Valley of Maryland

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Thomas J. Aley, Ozark Underground Laboratory
Michael K. Cobb, ARCADIS
Ethan O. Weikel, US Army Corps of Engineers
Shiloh L. Beeman, Ozark Underground Laboratory

A pair of groundwater tracer studies at a single karst test site were completed 18 years apart. The results of these studies have

provided evidence of both relatively rapid advective transport via conduits and an extreme capacity for dye storage and retardation. The tracer results, coupled with other subsurface investigation data, are used to develop a conceptual model for groundwater movement through this karst aquifer in the Frederick Valley of Maryland, as well as identify implications for remediation.

Three fluorescent tracer dyes used in the initial study were detected in several background monitoring locations established for the second study conducted 18 years later, demonstrating the persistence of these dyes in the aquifer. One of these dyes was not detected during the original study, providing useful information regarding flow and transport in the aquifer. At some of these sampling locations, at least one of the dyes was degraded, and would have gone undetected without the use of activated carbon samplers. Lastly, even though relatively rapid first detections occurred during both studies (as compared to non-karst groundwater systems) the majority of injected dye mass remained in the aquifer after the studies were completed. This suggests that the aquifer has a large capacity to store contaminants and that low levels of contaminants can be expected to persist in groundwater discharged from springs for a long period of time.

Dye Tracing Through the Vadose Zone Above Wind Cave, Custer County, South Dakota

James Nepstad, National Park Service

During the 1990s, in an attempt to better understand threats posed by surface developments overlying the cave, National Park Service staff at Wind Cave National Park in Custer County, South Dakota carried out a series of dye traces through portions of the vadose zone overlying the cave. Wind Cave is located within the 100m-thick Madison formation (limestone and dolomite), which in most locations is capped by varying thicknesses of the basal units of the Minnelusa formation (intermingled beds of sandstone, limestone, and shale). A variety of cave locations with dripping or pooled water were monitored for up to five years following dye injection. Transit times to the cave varied from less than six hours to as much as 4.8 years. Despite a variety of positive results, there appears to be little correlation between transit time and lateral or vertical distance from the injection site. Data analysis produced traditional-shaped dye recovery curves in some locations, albeit stretched out over hundreds and possibly even thousands of days beyond dye injection. The results strongly suggest that chemical or sewage spills in the vicinity of the dye injection sites would quickly enter multiple sites in the cave system, and could persist for years.

A Comparative Study Between the Karst of Hoa Quang, Cao Bang Province, Vietnam and Tuscumbia, Alabama, USA

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Ferenc L. Forray, Babes-Bolyai University
Florentin Stoiciu, R&D Nat. Inst. for Nonferrous & Rare Metals
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Some of the most beautiful karst features created by the dissolution of limestones are residual hills with steep or vertical sides rising from a flat plain, known as tower karst.

Tower karst to be developed requires a "mean annual temperature of minimum 170C to 180C and 1,000 to 1,200 mm/m² of annual rainfall (Jakucs, 1977).

Two sites matching this criteria were selected: the karst of Hoa Quang District, Cao Bang Province, Vietnam, and Tuscumbia, Colbert County, Alabama, U.S.A.

Preliminary observations regarding similarities and differences between these two sites are presented in this paper.

The Hoa Quang karst area is located in the northern Vietnamese Province of Cao Bang. In 2014, a large number of karst springs, caves, sinking streams, and karst landforms were identified. Eighteen water samples were collected and analyzed for anions, cations, oxygen and hydrogen stable isotope ratios.

The pH values are typical for karst waters and ranged from 7.23 to 7.97. Specific conductance values ranged from 153.2 to 421.6 µS/cm, the total alkalinity as $CaCO_3$ varies from 125 to 207 mg/L, carbon dioxide varies between 40.8 and 123.4 mg/L, whereas the values for the total hardness (as CaCO3) are between 143 and 220 mg/L.

The local meteoric water line, based on our measurements is $\delta 2H = 7.93(\pm 0.10)\ \delta 18O + 10.45\ (\pm 0.86)$ with r2=0.998, which is close to the global meteoric water line (GMWL) $\delta 2H = 8.17\ \delta 18O + 10.35$ defined by Craig (1961) and revised by Rozanski, et al. (1993). The intercept value differs very slightly from both local and global water lines. Due to the short sampling period, the information provided by the water stable isotopic composition is limited.

Carbonate rocks underlie many areas of north Alabama. Karst features can be found around Tuscumbia, in northwestern Alabama, which is part of the Tennessee-Alabama-Georgia karst area that is called TAG. TAG has the highest concentration of caves in United States, and home for a few large springs. Tuscumbia Spring is a municipal water supply with a base flow of 1,500 L/s. The field parameters measured in January 2014 were: pH 6.81, specific conductance 292 uS/cm, and temperature 5.310 Celsius.

In 1989-1990, the Geological Survey of Alabama conducted an extensive investigation in the area, performing dye studies in storm water drainage wells (SDW-1 through SDW-20) to

define the recharge area of Tuscumbia Spring. The storm water drainage wells can be a potential source of contamination for the springs. Two rock samples from Vietnam and one from Tuscumbia, Alabama (U.S.A.) were collected and examined using the X-ray diffraction (XRD) analysis, microscopic analysis in polarized light and Differential Scanning Calorimetry-Thermogravimetry (DSC–TG) analysis.

The quality of limestones in Vietnam and Tuscumbia (38.7 percent and 39.6 percent versus 31.10 percent calcium concentration) and the amount of precipitation (1,500 to 2,000 mm/m² in Vietnam versus 947 mm/m² to 1,960 mm/m² per year in Tuscumbia) are comparable. Thick limestone beds, massively jointed, combined with frequent tectonic uplifts and a complex geologic pattern result in the tower karst landscape in Vietnam versus a leveled landscape in Tuscumbia, Alabama. Tectonics is the primary driver for the formation of tower karst landscape in Cao Bang Province, Vietnam.

Wednesday, October 7th 3:30pm-5:15pm Karst Geology

Karst Paleo-Collapses and Their Impacts on Mining and the Environment in Northern China

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Wanfang Zhou, ERT, Inc.

Karst paleo-collapses are unique collapse structures widely found in the coal measures of northern China. Their geometric dimensions and internal properties indicate that a compound dissolution of carbonate and gypsum rocks may contribute to their formation. When these collapses are permeable to groundwater flow, they hydraulically connect the coal seams and the karst aquifers, which is a pre-requisite for 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 in northern China. Determination of locations and hydrogeological characteristics of the karst paleo-collapses are essential in preventing water inrush incidents through them. Advanced geophysical prospecting, aquifer testing and accompanied dye tracing are effective approaches to investigating these structures.

The Sandstone Karst of Pine County, Minnesota

Beverley Lynn Shade, University of Texas
E. Calvin Alexander, Jr., University of Minnesota
Scott C. Alexander, University of Minnesota

The glaciated, forested landscape of central Pine County in east-central Minnesota contains a series of sinkholes, stream sinks, springs and caves. The features are formed in Precambrian Hinckley Sandstone and overlying unconsolidated glacial deposits. This is a sandstone karst. The features serve the same function as in carbonate karst terrains: sinkholes and caves focus recharge into a heterogeneous subterranean flow system that discharges into springs. The Hinckley Sandstone is a quartz arenite. No carbonate grains or cements have been found in sandstone samples from the sinkhole area, nor is there evidence that calcite solution controls bedrock permeability. Three parameters appear to control the distribution of sinkholes: depth to bedrock, type of underlying bedrock, and meter-scale heterogeneity of surface sediments. The permeability structure of the Hinckley Sandstone appears to be controlled by fractures and depositional features at centimeter to meter scale. Field mapping in the area has revealed 309 karst features: 237 sinkholes, 25 stream sinks, 32 springs and 15 caves. Recent LiDAR coverage indicates that there are many more sinkholes and other karst features than the original mapping was able to locate. Interpretation of the LiDAR images is challenging because karst processes, glacial processes and human activity have all produced natural and anthropogenic closed depressions of a variety of sizes and shapes in this landscape.

A Proposed Hypogenic Origin of Iron Ore Deposits in Southeast Minnesota Karst

E. Calvin Alexander, Jr. University of Minnesota
Betty J. Wheeler, University of Minnesota

From 1942 through 1968 there was an active iron ore mining industry in western Fillmore, eastern Mower and southern Olmsted Counties of Minnesota. This iron mining district was 250 miles south of, and the ores were a billion years younger than, the ores of the classic iron mining districts in northern Minnesota. The high grade iron ore was mostly goethite and hematite and occurred as near-surface relatively small pods which unconformably filled paleokarst depressions in the Devonian Spillville Formation and the Ordovician Stewartville Formation.

The source of the iron has long been cryptic. The available field and textural evidence is consistent with a hypogenic origin of these iron deposits. Before the current Mississippi River drainage system was incised, regional ground water flow

systems could have emerged through the karst conduits in the Paleozoic carbonates. The waters in the deeply buried aquifers underlying this area currently are anoxic and enriched in dissolved ferrous iron and would have been more so before the entrenchment of the Mississippi River reorganized the regional ground water flow system. When that water emerged into the atmosphere the ferrous iron would have quickly been oxidized by a combination of biotic and abiotic processes producing the ferric oxide ore at the spring orifices. Numerous springs and seeps in Minnesota are currently building iron oxide deposits at their orifices.

Down the Rabbit Hole: Identifying Physical Causes of Sinkhole Formation in the UK

Tamsin Green, University of Leeds

Heavy precipitation in the UK in February 2014 induced ground subsidence and consequently a rapid increase in the frequency of sinkhole occurrences. These new sinkhole collapses emphasize the need to further analyze the causes of the increased occurrence by investigating the relative importance of various surficial factors.

Malham and the Mendips are two areas of particular interest, since both are underlain by limestone bedrock and are susceptible to subsidence. This is due to limestone being primarily permeable in joints, and so it dissolves to form an extensive network of karstic caves. It was therefore useful to compare two sites of similar geology, both from the Triassic and Jurassic periods, as this controlled the amount of presently exposed limestone from past glacial retreat, for accurate comparison of susceptibility.

Susceptibility maps of the two areas were created by integrating GIS application and statistical methods to develop algorithms to address the issue of dissolution. The maps aim to identify the physical surficial conditions, in addition to heavy precipitation that exacerbates subsidence development.

Statistical testing of the GIS data indicated that in Malham, slope is the most significant parameter (Kruskal-Wallis, $H=29.36$, $p<0.001$; $H=14.55$, $p=0.006$ respectively) in sinkhole formation; while in the Mendips altitude is the most significant parameter (Kruskal-Wallis, $H= 20.44$, $p<0.001$; $H= 86.51$, $p<0.001$ respectively). Curvature appeared less statistically significant with fewer values reported from post-hoc Mann-Whitney U tests. This integrated geological mapping and statistical approach will prove useful in delineating susceptibility zones in areas within the UK.

Relay Ramp Structures and Their Influence on Groundwater Flow in the Edwards and Trinity Aquifers, Hays and Travis Counties, Central Texas

Brian B. Hunt, Barton Springs/Edwards Aquifer Cons. Dist.
Brian Smith, Barton Springs/Edwards Aquifer Cons. Dist.
Alan Andrews, Barton Springs/Edwards Aquifer Cons. Dist.
Douglas Wierman, Meadows Center for Water & Environ.
Alex S. Broun, Hays Trinity Groundwater Conservation Dist.
Marcus O. Gary, Edwards Aquifer Authority

The Cretaceous Edwards and Middle Trinity Aquifers of central Texas are critical groundwater resources for human and ecological needs. These two major karst aquifers are stratigraphically stacked (Edwards over Trinity) and structurally juxtaposed (normal faulting) in the Balcones Fault Zone (BFZ). Studies have long recognized the importance of faulting on the development of the karstic Edwards Aquifer. However, the influence of these structures on groundwater flow is unclear as groundwater flow appears to cross some faults, but not others. This study combines structural and hydrological data to help characterize the potential influence of faults and relay ramps on groundwater flow within the karstic Edwards and Middle Trinity Aquifers. Detailed structure contour maps of the top of Walnut Formation in the study area were created from a geologic database (n=380) comprised of primarily geophysical and driller's logs. The data were then contoured in Surfer® (Kriging) with no faults. Structure contour surfaces revealed detailed structural geometries including linear zones of steep gradients (interpreted as faults) with northeast dipping zones of low gradients (interpreted to be ramps) between faults. Hydrologic data (heads, dye trace, geochemistry) were overlaid onto the structure contour maps in GIS. Results for the Middle Trinity Aquifer suggest relay ramps provide a mechanism for lateral continuity of geologic units and therefore groundwater flow from the Hill Country (recharge area) eastward into the BFZ. Faults with significant displacement (>100 m) can provide a barrier to groundwater flow by the juxtaposition of contrasting permeabilities, yet flow continues across fault zones where ramps exist, or where permeable units are juxtaposed with other permeable units. In the Barton Springs segment of the Edwards Aquifer the primary flow path defined by dye tracing and heads is coincident with the Onion Creek relay ramp dipping to the northeast. This work addresses the lateral continuity (intra-aquifer flow) of the Edwards and Trinity Aquifer systems, which has importance for conceptual models and ultimately resource management.

Wednesday, October 7th 5:30pm-6:30pm Poster Presentation (alphabetical)

Goliath's Cave, Minnesota: Epigenic Modification and Extension of Preexisting Hypogenic Conduits

E. Calvin Alexander, Jr., University of Minnesota
Scott C. Alexander, University of Minnesota
Kelton Barr, Braun Intertec
Andrew Luhmann, University of Minnesota
Cale Anger, University of Minnesota (deceased)

Goliath's Cave is developed in the Ordovician Dubuque and Stewartville Formations of the Galena Group in Fillmore County, MN. The cave currently functions as an epigenic karst system with allogenic surface water sinking into the cave and a vadose stream running through the cave and resurging at springs a few kilometers away. Passages in the cave are locally controlled by vertical joints in the nearly flat-lying carbonate bedrock, but the water flow directions often do not correspond to the systematic joint directions. The cave contains straight, joint-controlled passages that appear to pre-date the current epigenic drainage systems. These old passages contain hypogenic features and are connected and modified by distinct, younger epigenic passages – often with very sharp transitions back and forth between the two passage types. The epigenic flow incises vadose canyons into the hypogenic passages. The hypogenic passages represent ancient, deep, compartmentalized flow systems that predate the present topography. The concept "ancient" is poorly constrained, however. These ancient cave passages are being reactivated by epigenic processes, while undergoing destruction by general erosion of the landscape.

Numerical Simulation of Spring Hydrograph Recession Curves for Evaluating Behavior of the East Yorkshire Chalk Aquifer

Nozad Hasan Azeez, University of Leeds
Landis Jared West, University of Leeds
Simon H. Bottrell, University of Leeds

The Cretaceous Chalk aquifer is the most important in the UK for the provision of water to public supply and agriculture. The Chalk has both matrix and fracture porosity and is thus best considered as a dual porosity aquifer system. Although the matrix porosity is large, typically around 0.35 in the study area of East Yorkshire, UK (ESI, 2010), pore diameters are typically very small, and the water contained in them is virtually immobile. The high permeability fracture network is responsible for the ability of water to drain; spatial variations in fracture network properties mean conventional approaches to aquifer characterization such as borehole pumping tests are of limited utility. Hence this study attempts to better understand the flow system and characterize aquifer properties from the recession response seen at springs during the spring/summer period when recharge is minimal. This approach has the advantage that spring hydrographs represent the sum of the response from entire catchments.

This paper reports numerical modeling for simulating aquifer and spring responses during hydrological recession. Firstly, available geological and hydrogeological information for the study area was used to develop hydrogeological conceptual models. Four different numerical models have been constructed representing four possible scenarios that could represent the aquifer in the selected area. These are: single reservoir aquifer, double reservoir aquifer, single reservoir aquifer with highly permeable vertical zone intersecting the spring location and single reservoir aquifer containing tunnel shaped highly permeable zone at the spring elevation respectively. The sensitivity of spring recession response to various external and internal parameter values was investigated, to understand relations between spring recession, hydrological inputs (recharge) and aquifer structure. Spring hydrographs from the real aquifer were compared with the hydrographs generated from models, in order to estimate aquifer properties. The work aims to identify the utility of spring hydrographs in eliciting aquifer permeability structure, as well as identifying the conceptual scenario which best represents the Chalk Aquifer in East Yorkshire, UK.

Seeps and Springs at a Platteville "Observatory" on the River Bluffs

BJ Bonin, Minnesota Department of Natural Resources
Greg Brick, Minnesota Department of Natural Resources
Julia Steenberg, Minnesota Geological Survey

Residential building construction along the Mississippi River bluffs in the 1970s created a unique enclosed outcrop of the Late Ordovician Platteville Limestone at Lilydale, Minnesota. This outcrop was examined in early 2013 after a newly-formed spring flooded an elevator shaft the previous year, drawing attention to the foundation conditions.

The Lexington Riverside property is a six story condominium complex constructed within the top of the bluff. A two-level underground parking garage was built into the bluff. Bedrock was mechanically excavated to accommodate

the construction of the building, creating an unweathered rock surface. The space between the structure and the excavated rock face, running for 150 meters, was roofed over, and is used as a utility space. At least three dominantly carbonate members of the Platteville Formation are visible: Mifflin, Hidden Falls, and Magnolia, in ascending order. The foundation of the structure was constructed on the lowermost Platteville limestone and Glenwood shale and is tile-drained to the nearby river gorge.

Most of the seeps and springs on the property, both inside and on the grounds, belong to the three Platteville spring-lines identified for the Twin Cities Metropolitan (TCM) area by Brick (1997). Groundwater emanates from both vertical joints and horizontal bedding plane partings within the Platteville Limestone and at the Platteville – Glenwood Shale contact. Overall, the hydrostratigraphic attributes of this site are consistent with how the Platteville has been recently characterized in the TCM area in a fractured bluff edge setting (Anderson et al., 2011).

The enclosed outcrop features many seep- and spring-related mineral deposits. Most notable were the iron-stained flowstone and microgours near the seeps and springs along fractures in the limestone, and calcite rafts on the surfaces of the pools. At some damp locations a fungal ecosystem has developed. Gypsum beards have grown in dry portions of the cavern.

This man-made cavern, and others nearby, present unique opportunities to research groundwater flow in fractured bedrock settings. Studying the spring locations relative to joints and bedding, changes in spring flow rate over time, and mineral deposition rates, are possible in this accessible location without the complication of surface water inputs or instrumental interference from the general public.

Using Electrical Resistivity Imaging to Characterize Karst Hazards in Southeastern Minnesota Agricultural Settings

Toby Dogwiler, Missouri State University
Blake Lea, Missouri State University

Much of the Driftless Area of southeastern Minnesota is underlain by karstified carbonate bedrock. Land use in this karst terrain is dominated by agriculture, including row crop and dairy operations. The karst in this region is often mantled with up to 15 m of soil and unconsolidated sediments. As a result, underlying karst hazards such as incipient sinkholes are often hidden until they are suddenly revealed by the collapse of subsurface voids.

Regionally, the economics of the dairy industry is causing a trend toward the consolidation and expansion of existing operations. As concentrated animal feeding operations (CAFO) or feedlots expand, state and local agencies are charged with enforcing regulations designed to protect environmental and water resources in agricultural areas. One of the key challenges in reviewing and siting expanded dairies is identifying potential karst hazards, particularly where they might undermine manure storage facilities or where they occur on croplands where manure is applied. Uncertainty about the location of karst hazards relative to proposed feedlot facilities is one of the reasons that feedlot expansions in the Driftless Area are often controversial. Recently, the Minnesota Pollution Control Agency enacted strict guidelines that severely limit bedrock removal in order to facilitate the construction of manure storage containments. The purpose of this rule is to ensure that a minimum separation is maintained between intact bedrock and the containment liner to provide the opportunity for attenuation within the soil of contaminants that could potentially leak if the containment structure is compromised.

Electrical Resistivity Imaging (ERI) techniques have been employed to screen for karst hazards during the planning phase of feedlot expansions, and where present, to more accurately characterize the nature of the karst hazard. Because depth-to-bedrock is highly variable in the karst terrain of southeastern Minnesota, ERI has also been a useful tool to characterize this spatial variation under proposed manure containment sites. In this study, ERI was performed using a 56-channel AGI Supersting™ system with post-processing of the data in EarthImager™ software. Dipole-Dipole and Wenner electrical resistivity arrays have been the most useful for identifying karst hazards. Electrode spacing of 3 to 5 m has provided a good balance between depth-of-image and the spatial resolution necessary to locate and identify karst hazards. Soil boring data, which is typically collected during pre-construction site investigations, is critical to the interpretation of ERI data. Although individual sites vary, most surface materials in southeastern Minnesota have resistivities that fall within predictable ranges: 20-80 ohm-m for soils, 80-100 ohm-m for epikarst and weathered residuum, and >100 ohm-m for bedrock. Karst voids in the subsurface typically display resistivities greater than 1000 ohm-m, providing good contrast with the resistivities of the surrounding bedrock.

ERI has been an effective tool in identifying karst hazards in agricultural settings of southeastern Minnesota. In addition to improving pre-construction site assessments, ERI has also helped to reduce potential controversy surrounding the karst hazards of proposed projects by providing more certainty about the underlying geology.

Analysis and Prevention of Sinkhole Collapses During the Reconstruction and Extension of the Guang-Qing Freeway, China

Zhanfei Gu, Tongji University;
Qi Liu, Tongji University;
Yaoru Lu, Tongji University;
Zhenming Shi, Tongji University;
Gaoyu Su, Guangdong Freeway Co, Ltd.

The Guang-Qing freeway reconstruction and extension project is located in Guangdong province, China, extending from Guangzhou city to Qingyuan city. The total project length is 57.6 kilometers (km), 33 km of which is in a karst area where sinkhole collapses are common. Therefore, there were concerns about the safety and security of the roadbed, bridge piles, and other structures associated with the original roadway. The study addresses karst development, covering layer (overburden), and external factors that contribute to catastrophic sinkhole collapse along the project. The study found that the formation of sinkhole collapses is affected significantly by the degree of karst development and soil characteristics, including thickness. Collapses may be triggered directly by external factors that disturb the natural equilibrium. Such factors include heavy rainfall that impacts soil and groundwater conditions, as well as vibration and groundwater flow disruptions that are caused by pile construction and other engineering activities. Prevention measures were adapted to local conditions and optimized based upon safety, reliability and cost-effectiveness.

Study on the Critical Velocity of Groundwater to Form Subsidence Sinkholes in Karst Area

Fuwei Jiang, Guizhou Institute of Technology
Mingtang Lei, Institute of Karst Geology
Dai Jian-ling, Institute of Karst Geology

Subsidence sinkholes in karst area are a common geological hazard causing disaster accidents. However, the critical hydraulic conditions of forming subsidence sinkholes have not been well understood. Based on the theories of pipe flow, this paper derives expressions of a critical hydraulic condition for assessing whether it leads to subsidence sinkholes. A case study with samples of the cohesive soils taken from the Wuxuan county, Guangxi province, China, was conducted to evaluate the derived critical value. Combining the derived critical value and the monitoring data of hydraulic conditions in the study field, our results indicate that subsidence sinkholes are not forming under the current hydraulic conditions.

Finding Springs in the File Cabinet

Mason Johnson, Minnesota Pollution Control Agency
Ashley Ignatius, Minnesota Pollution Control Agency

The Minnesota Pollution Control Agency (MPCA), in partnership with other agencies, is currently undertaking comprehensive sub-basin assessments statewide over a ten-year period. Southeast Minnesota has over 17,500 kilometers of perennial and intermittent streams, making the task of comprehensive sub-basin assessment challenging; the task is further complicated by karst geology. In the summer of 2014, a pilot project began between the MPCA and Minnesota Department of Natural Resources (DNR) to digitally preserve paper documents which capture qualitative and quantitative data about the hydrology, water chemistry, geomorphology, biology, land use and karst features of southeast Minnesota streams. The paper documents in file cabinets were not in an accessible or easy-to-use format; as such, they were in a 'data silo.' The task was to preserve the documents so as to make the data usable by converting the documents into a digital format (Adobe PDF, GeoTIFF, ESRI Feature Class). To date, more than 4,000 documents (of an estimated more than 12,000) have been converted, made text-searchable, prepared for storage in a document management system, and made more accessible through a geographic information system (GIS). This previously inaccessible data is an important piece in understanding the karst region of southeast Minnesota. Within the documents scanned thus far, over 400 springs and other karst features have been identified, which are not currently recorded in Minnesota's Karst Feature GIS Database.

Evaluation of First Order Error Induced by Conservative-Tracer Temperature Approximation for Mixing in Karstic Flow

Philippe Machetel, Geosciences Montpellier
David A. Yuen, Univ. of Minn. and China Univ. of Geosciences

Fluid dynamics in karst systems is complex due to the heterogeneity of hydraulic networks that combine the Porous Fractured Matrix (PFM) and the interconnected drains (CS). These complex dynamic systems often need to be treated as "black boxes" in which only input and output properties are known. In this work, we propose to assess the first-order error induced by considering the temperature as a conservative tracer for flows mixing in karst (fluvio-karst). The fluvio-karstic system is treated as an open thermodynamic system (OTS), which exchanges water and heat with its surrounding. We propose to use a cylindrical PFM drained by a water saturated cylindrical CS, connected on one side to a sinkhole zone and, on the other side, to a resurgence flowing at the base level of

the karstic system. This framework allows us to develop the equations of energy and mass conservation for the different parts of the OTS. Two numerical models have been written to solve these equations: 1) the so-called AW (for Adiabatic Wall) configuration that assumes a conservative tracer behavior for temperature with no conductive heat transfer, neither in the liquid, nor in the PFM or even through the wall separating the CS from the PFM; and, 2), the CW (for Conductive Wall) configuration that takes into account the heat and mass transfers in water and from water to aquifer rocks both in the CS and in the PFM. Looking at the large variability of karstic system morphologic properties, dimensionless forms of the equations have been written for both AW and CW configurations. This approach allows us to gather the physical, hydrological and morphological properties of karstic systems into four dimensionless numbers: the Peclet, Reynolds, Prandtl and dimensionless diffusivity numbers. This formalism has been used to conduct a parametric exploration across several orders of magnitude based on the Peclet and the Reynolds numbers. The final errors, between the AW and CW configurations, remain less than 1% across the entire parametric range. The combination of error curves bounds a closed volume in error space that gives a first upper bound of the error made by considering the temperature as a conservative tracer. Applying the method to an illustrative example of karst allows us to reach a first order error within a few degrees °C.

The Application of Passive Seismic Techniques to the Detection of Buried Hollows

Michael G. Raines, British Geological Survey
Vanessa J. Banks, British Geological Survey
Jonathan E. Chambers, British Geological Survey
Philip E. Collins, Brunel University London
Peter F. Jones, University of Derby
Dave J. Morgan, British Geological Survey
James B. Riding, British Geological Survey
Katherine Royse, British Geological Survey

Pilot studies involving the use of passive seismic techniques in a range of geological settings and applications (e.g., mapping bedrock, studies of soil erosion and Quaternary surficial mapping) have shown that it is a versatile, non-invasive and economic technique. This paper presents the findings of three case studies that used passive seismic techniques for the detection and characterization of buried hollows in carbonate rocks: 1) a buried hollow in the Cretaceous chalk at Ashford Hill in the Kennet Valley, a tributary of the River Thames, UK; 2) buried karst in the foundation excavations for wind turbines in Carboniferous limestone at Brassington, Wirksworth, Derbyshire, UK; 3) defining the extent of solution hollows that host terrestrial Mio-Pliocene deposits, near Friden, Newhaven, Derbyshire, UK. Whilst case studies 2) and 3) are focused on areas of buried dolines, the geological context of the Ashford Hill site is more complex, including a deformation hollow with an uplifted "pinnacle" of chalk bedrock at the centre. The data were collected using Tromino®, a three-component, broadband seismometer, to measure background ambient noise (microtremors induced by wind, ocean waves, industrial machinery, road and rail traffic etc.). The Tromino is a small, portable device with an operating range of 0.1 Hz to 30 kHz and interpreted using proprietary software (Grilla), which subjects the data to Fourier transformation and smoothing. Where possible, "shear wave velocities" have been calibrated using borehole data or parallel geophysical techniques. In each case, the karst features were defined by Nakamura's horizontal to vertical (H/V) spectral ratio technique, where microtremors are converted to show impedance contrasts (velocity x density), or a pseudo-layered seismic stratigraphy of the near surface along each profile. An additional benefit of the use of this technique is its depth of penetration and potential for defining the structural and lithological context of the hollows, thereby contributing to the process understanding associated with their formation. To this end the technique has helped define the structural discontinuities (fault, joint or bedding) that guide formation of the hollows.

New Methodologies and Approaches for Mapping Forested Karst Landscapes, Vancouver Island, British Columbia, Canada

Tim Stokes, Vancouver Island University
Paul Griffiths, Consultant
Carol Ramsey, Vancouver Island University

Mapping is an essential tool for land management and is typically used to assess the nature and characteristics of a land surface, along with its resource features and values. Mapping of karst landscapes is of particular importance for the temperate rainforests Vancouver Island on the west coast of British Columbia (BC), where both forestry and natural resource development activities occur. A set of BC Government standards for mapping karst have been developed at varying scales (reconnaissance, planning-level and detailed), and incorporate procedures to assess the potential and vulnerability of karst, applying qualitative analysis of various surface and subsurface karst attributes. Previously, karst maps have been compiled by GIS mapping software and generated as static graphic images. However, it is now possible to make maps more accessible and interactive by uploading them as overlays within Google Earth (as KML files) or other imagery platforms. It is also possible for these maps to be taken into the field using tablets, phones or iPads, allowing for on-site data collection and resource evaluation. A key focus of this research is the

development of a `Karst Map of Vancouver Island' that outlines the known extent of the karst and the likely contributing non-karst catchments, and also identifies regions of varying karst potential/vulnerability and notable karst areas/features. Trials have been completed to see how detailed imagery of karst features and areas collected by UAV technology can be used for karst evaluation. Karst areas have also been mapped using LiDAR, which has the potential for both detecting surface karst features beneath the forested canopy and for assessing the overall sensitivity of forested karst areas.

LEPT, a Simplified Approach for Assessing Karst Vulnerability in Regions with Sparse Data; a Case Study from Kermanshah Province, Iran

Kamal Taheri, Kermanshah Regional Water Authority
Milad Taheri, Bu-Ali Sina University
Fathollah Mohsenipour, Kermanshah Reg. Water Authority

There are a variety of widely used methods for porous aquifer protection to assess the vulnerability of groundwater resources, such as DRASTIC; Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity, SINTACS; depth to ground water (S), effective infiltration (I), unsaturated zone attenuation capacity (N), soil attenuation capacity (T), hydrogeologic aquifer characteristics (A), hydraulic conductivity range (C) and hydrological role of the topographic slope (S). And GOD; Groundwater occurrence, Overlying lithology and Depth of groundwater . However, some more limited methods (including EPIK; Epikarst development, Protective cover, Infiltration conditions and Karst network development, PaPRIKa; Protection of karst Aquifers based on their Protection, Reservoir, Infiltration and Karstification type and COP; Concentration of flow, Overlying layers and Precipitation regime) are also suggested for karstic aquifer vulnerability analysis. The latter methods are applied using different parameters such as karst network development, depth of karstification, and protective cover. Due to the nature of the data, these methods are highly affected by local and regional climate conditions. Data gathering of these methods is difficult, time consuming and needs a full understanding of karst system. Data shortages, especially those related to karst formations in some parts of the world including the west part of Iran, and crucial demands for utilizing water resources demonstrate a great appeal to find a representative method for evaluation of these regions. Conventional methods of karst aquifer evaluations cannot be properly applied in the absence of a required karst data base; therefore, there is a need for a method that could be applied with the least amount of available data. The LEPT method introduced in this paper is a simple approach which provides rough evaluation of the general information gathered from karst areas of the west of Iran combined with field experiments. This method, which utilizes four parameters to assess the vulnerability of karst aquifers, was applied to the karst areas of Kermanshah (a province in the west of Iran) for the first time. Results of this approach categorize karst plains into four zones with very high, high, low and very low sensitivity in terms of their vulnerability to environmental impact; these classes positively correlated with field information.

Determination of the Relationship of Nitrate to Discharge and Flow Systems in North Florida Springs

Sam B. Upchurch, SDII Global Corporation

The Suwannee River Water Management District has collected quarterly discharge and water quality data from 30 1st and 2nd magnitude springs in the Suwannee River Basin since 1998. These data were collected quarterly well into the late 2000s and constitute a valuable database for characterizing spring discharge behavior.

Trend and correlation analyses were used to compare the relationships of $NO_3^- + NO_2^-$ (nitrate in this paper), specific conductance, and spring discharge. Trends were considered significant if alpha levels of the trend slopes were ≤ 0.05.

Data from 50% of the springs show that nitrate concentrations increase as discharge from the spring increases. Forty-five percent of the remaining springs showed no correlation between discharge and nitrate, and only 5% (2 springs with poor data) have relationships where high discharge was related to lower nitrate concentrations.

Twenty percent of the springs had positive correlations of specific conductance with discharge, 37% showed no correlation, and 43% had negative correlations between specific conductance and discharge.

Most important in terms of understanding the plumbing of the conduit systems, 40% of the springs had positive correlations between nitrate and specific conductance, 48% showed no correlation, and 12% had negative correlations.

Hydrochemical Characteristics and Formation Mechanism of Groundwater in the Liulin Karst System, Northwestern China

Min Yang, Inst. of Hydrogeology and Env. Geology, CAGS
Feng'e Zhang, Inst. of Hydrogeology and Env. Geology, CAGS
Sheng Zhang, Inst. of Hydrogeology and Env. Geology, CAGS
Miying Yin, Inst. of Hydrogeology and Env. Geology, CAGS
Guoqing Wu, Inst. of Hydrogeology and Env. Geology, CAGS

The Liulin karst system is typical of hydrogeological systems in northwestern China, with a group of springs as the dominant mechanism for regional groundwater discharge. To reveal the hydrochemical formation mechanism of the Liulin karst groundwater system, we studied the hydrogeochemical processes of karst groundwater in aquifers at the base of the hydrogeological investigation. Then starting from the chemical composition of karst groundwater together with the recharge-runoff - discharge process of groundwater systems, we analyzed the solutes origin and the dissolved mineral facies of the groundwater chemical composition. The results showed that the anionic and cationic compositions of karst water were different in recharge, runoff and discharge areas, with the main anions of HCO_3^- and SO_4^{2-} in recharge areas, and HCO_3^- and Cl^- in runoff and discharge areas, as well as the main cationic for Ca^{2+} and Na^+, of which the molar concentrations of Ca^{2+} was greater than Na^+ in recharge areas and contrary to the runoff and discharge areas. Karst water was influenced by carbonate and evaporite dissolution while flowing through the aquifers, of which carbonate rock dissolution dominated in recharge areas, and evaporite rock dissolution increased to be the dominate lithology in runoff and discharge areas. Based on analysis of water- rock interaction, the main dissolved mineral facies included dolomite, calcite, gypsum and halite. Dolomite is the most important dissolved mineral, followed by calcite and gypsum in recharge area, as well as calcite, gypsum and halite in runoff and discharge areas.

Environmental Effects of Rational Utilization of Karst Geothermal Resources in the North China Plain

Wei Zhang, Inst. of Hydrogeology and Env. Geology, CAGS
Wang Guiling, Inst. of Hydrogeology and Env. Geology, CAGS
Liu Feng, Inst. of Hydrogeology and Env. Geology, CAGS

As a clean energy, geothermal resources play an important role in protecting and improving the environment. This paper uses the well-known North China Plain, with a carbonate karst reservoir, to demonstrate how significant the geothermal resource is, and to highlight essential environmental differences between karst geothermal resources and coal resources. After analyzing the different geothermal areas, the maximum allowable drawdown method and mining coefficient method are applied as tools for evaluating geothermal recoverable reserves. Evaluation procedures include geological characteristics research; select an assessment method, and, a final comprehensive evaluation. The evaluation results show that the karst geothermal resource for the North China Plain is 5.28×10^{17}J. The exploration and utilization of the karst geothermal resource will beneficially result in energy savings of coal resources, of about 3×10^7t and emission reduction of carbon dioxide about 7.17×10^7 t.

Chemical Evidence for Biokarst Development in the Ordos Basin (Northwest China) in Laboratory Batch Experiments

Feng'e Zhang, Inst. of Hydrogeology and Env. Geology, CAGS
Sheng Zhang, Inst. of Hydrogeology and Env. Geology, CAGS
Miying Yin, Inst. of Hydrogeology and Env. Geology, CAGS
Guoqing Wu, Inst. of Hydrogeology and Env. Geology, CAGS

The present work is designed to simulate the dissolution of sulfate minerals (primarily gypsum) under various conditions of different bacterial cell numbers, temperatures and reaction times both in water-rock and water-rock-bacteria systems by laboratory experiment. The amount and rate of dissolved sulfate rock and sulfate reduction rates were estimated using the experimental data. The results suggest that sulfate-reducing bacteria promote gypsum dissolution and temperature plays a more important role on sulfate reduction rates than the number of bacteria. The dissolution of gypsum driven by bacterial sulfate reduction results in the formation of karst features. The research is an insight into biokarst, which provides a new perspective for the field of petroleum geology.

Hydrocompaction Considerations in Sinkhole Investigations

Edward D. Zisman, Cardno ATC
Stephen West, BTL Engineering Services, Inc.

The cause of ground settlement is a significant concern in sinkhole investigations where the potential for shallow and deep-seated instability in the subsurface is a major focus of the investigation. Complicating the investigation is the occurrence of hydrocompaction of surficial soils caused by introduction of large amounts of surface water particularly from improper maintenance of rainfall runoff. This condition is usually followed by the subsequent loss of soil moisture during dry

periods. This manuscript will discuss how hydrocompaction plays a role in the analysis of settlement in the investigation of sinkhole loss and how one can distinguish between hydrocompaction settlement and deep-seated settlement (note, that hydrocompaction is one of many factors that can account for settlement of structures). It will consider the effects of soil density as it impacts hydrocompaction in the investigation of building distress. Also discussed are the results of laboratory tests of simulated hydrocompaction on fine sand samples in loose and dense states. In one of the tests, the formation of a collapse sinkhole occurred at the end of the test. Photographs depicting the sequence of soil failure are attached at the end of this paper.

Thursday, October 8th 8:30am-12:10pm GIS-Databases and Mapping of Karst Regions

Creation of a Map of Paleozoic Bedrock Springsheds in Southeast Minnesota

Jeffrey A. Green, Minnesota Dept. of Natural Resources
E. Calvin Alexander, Jr., University of Minnesota

Springs are groundwater discharge points that serve as vital coldwater sources for streams in southeast Minnesota. The springs generally emanate from Paleozoic carbonate and siliciclastic bedrock aquifers. Use of systematic dye tracing began in the 1970s and continues through the present as a standard method for investigating karst hydrology and to map springsheds,. The work was accelerated in 2007 because of increased funding from the State of Minnesota's Environment and Natural Resources Trust Fund. A compilation springshed map of dye traces conducted over the last several decades has been assembled for the region.

In southeast Minnesota, the springs are the outlets of conduit flow systems in both carbonate and siliciclastic bedrock aquifers. Conduit flow dominates groundwater transport in carbonate aquifers and is an important component of groundwater flow in siliciclastic aquifers. Conduit flow in aquifers occurs independently of the presence or absence of surface karst features. The springsheds of these springs have three interacting components: Groundwater Springsheds (analogous to classic karst autogenic recharge areas), Surface Water Springsheds (analogous to classic karst allogenic surface runoff areas), and Regional Groundwater Springsheds.

Surface Water Springsheds can be up to several orders-of-magnitude larger than the Groundwater Springsheds to which they contribute water. Surface Water Springsheds can feed surface flow into one or several stream sinks. Those multiple stream sinks may be in one or more Groundwater Springsheds.

The leading edges of dye tracing breakthrough curves typically show groundwater flow velocities in the hundreds-of-meters to kilometers-per-day range in all of the bedrock aquifers tested. The width and duration of tails of breakthrough curves in these conduit flow systems vary with the bedrock aquifers. The Galena Group has Full Widths at Half Maximums (FWHMs) of a few hours and tails that are down to background in a few days. The Prairie du Chien Group also has FWHMs of hours but has tails that continue for weeks. The St. Lawrence and Lone Rock Formations have FWHMs of months to years.

Media, Sinkholes and the UK National Karst Database

Vanessa J. Banks, H. J. Reeves, E. K. Ward, E. R. Raycraft, H. V. Gow, D. J. R. Morgan and D. G. Cameron, British Geological Survey

The British Geological Survey (BGS) maintains a number of databases that feed into hazard susceptibility assessments, including karst, landslide and mining susceptibility. The winter period from December 2013 to January 2014 was one of, if not the most, exceptional periods of winter rainfall in the last 248 years for England and Wales. During this period the Jet Stream diverted easterly tracking cyclones along a more southerly route than is usual across the United Kingdom (UK). This resulted in south-east and central-southern England experiencing total rainfall values of 372.2 mm for this period, which was the wettest two-month period since 1910. This period was associated with extensive flooding and increased numbers of slope failures, landslides and sinkholes, which affected transport routes into and out of London, thereby generating considerable media attention. In addition to government and stakeholder requirements, the BGS experienced an unusually high level of enquiries from the public and the media pertaining to sinkholes, which put an additional strain on resources, but is an acknowledged component of the BGS remit. During February alone, the BGS received reports of 19 sinkholes. The majority of these occurred in the Cretaceous chalk of southern England. Approximately half were not naturally occurring sinkholes, but were due to the collapse of anthropogenic features. Typically, the anthropogenic subsidence collapse features included: the collapse of chalk shafts associated with historic extraction of chalk for brickworks; the collapse of deneholes (medieval chalk workings for chalk for ground improvement), and chalk mine

shaft collapses. This paper describes the National Karst Database, stakeholder requirements and how the BGS has responded with new and improved mechanisms for data collection, storage and dissemination.

Shallow Depressions in the Florida Coastal Plain: Karst and Pseudokarst

Sam B. Upchurch, SDII Global Corporation
Thomas M. Scott, SDII Global Corporation
Michael C. Alfieri, Water Resource Associates
Thomas L. Dobecki, SDII Global Corporation

In Florida, shallow depressions (i.e., depressions <1-2 m in depth) on the land surface are often attributed to sinkhole development. However, it has become evident that there are at least six different mechanisms through which these depressions can form in geologically young cover sediments. These mechanisms include:
1. Cover-subsidence sinkholes over shallow limestone;
2. Suffosion sinkholes over shallow limestone;
3. Cover settlement over shallow shell beds;
4. Large, aeolian deflation areas that resemble "Carolina bays;"
5. Depressions that mimic landforms developed on a shallow paleosol; and
6. Depressions created by pedodiagenesis (i.e., conversion of smectite to kaolinite) in a soil-forming environment.

Of these, only the first two appear to represent traditional mechanisms for sinkhole development in eogenetic karst. Cover settlement over shell beds is poorly understood and incorrectly attributed to sinkhole development processes. This type of depression has serious limitations in terms of cover thickness and shell content of the substrate. The last three mechanisms are pseudokarst created by aeolian and soil-forming processes.

In this paper we present examples of each and discuss their constraints and evidence.

Sinkhole Vulnerability Mapping: Results from a Pilot Study in North Central Florida

Clint Kromhout, Florida Geological Survey
Alan E. Baker, Florida Geological Survey

At the end of June in 2012, Tropical Storm Debby dropped a record amount of rainfall across Florida which triggered hundreds, if not thousands, of sinkholes to form which resulted in tremendous damage to property. The Florida Division of Emergency Management contracted with the Florida Department of Environmental Protection's Florida Geological Survey to produce a map depicting the state's vulnerability to sinkhole formation. The three-year project began with a pilot study in three northern Florida counties: Columbia, Hamilton and Suwannee. Utilizing the statistical modeling method Weights of Evidence, results from the pilot study yielded a 93 percent success rate of predicting areas where the geology is conducive to sinkhole formation. Lessons learned and field mapping techniques developed during the pilot study are now being applied to map the entire State's vulnerability to sinkhole formation.

A Semi-Automated Tool for Reducing the Creation of False Closed Depressions from a Filled LiDAR-Derived Digital Elevation Model

John Wall, North Carolina State University
Daniel H. Doctor, US Geological Survey
Silvia Terziotti, US Geological Survey

Closed depressions on the land surface can be identified by 'filling' a digital elevation model (DEM) and subtracting the filled model from the original DEM. However, automated methods suffer from artificial 'dams' where surface streams cross under bridges and through culverts. Removal of these false depressions from an elevation model is difficult due to the lack of bridge and culvert inventories; thus, another method is needed to breach these artificial dams. Here, we present a semi-automated workflow and toolbox to remove falsely detected closed depressions created by artificial dams in a DEM. The approach finds the intersections between transportation routes (e.g., roads) and streams, and then lowers the elevation surface across the roads to stream level allowing flow to be routed under the road. Once the surface is corrected to match the approximate location of the National Hydrologic Dataset stream lines, the procedure is repeated with sequentially smaller flow accumulation thresholds in order to generate stream lines with less contributing area within the watershed. Through multiple iterations, artificial depressions that may arise due to ephemeral flow paths can also be removed. Preliminary results reveal that this new technique provides significant improvements for flow routing across a DEM and minimizes artifacts within the elevation surface. Slight changes in the stream flow lines generally improve the quality of flow routes; however some artificial dams may persist. Problematic areas include extensive road ditches, particularly along divided highways, and where surface flow crosses beneath road intersections. Limitations do exist, and the results partially depend on the quality of data being input. Of 166 manually identified culverts, 125 are within 25 m of culverts identified by this tool. After three iterations, 1,735 culverts were identified and cataloged. The result is a reconditioned elevation dataset,

which retains the karst topography for further analysis, and a culvert catalog.

History and Future of the Minnesota Karst Feature Database

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Mathew Rantala, University of Minnesota
E. Calvin Alexander, Jr., University of Minnesota
Yongli Gao, University of Texas

Jeffrey A Green, Minnesota Department of Natural Resources

Since the 1990s, the University of Minnesota and the Minnesota Department of Natural Resources have maintained a karst features database that is used to conduct research on karst processes and inventory karst features. Originally designed as a tabular database only, the karst features database developed into a spatial database in 2002, with tabular data stored in Microsoft Access and a spatial component managed in ESRI ArcView. In 2012, the database was converted to a single, relational database platform, PostgreSQL, with both tabular and spatial components edited in ESRI ArcMap. Custom editing forms are written in Visual Basic and are accessed in ArcMap sessions by ESRI add-ins. The current database infrastructure allows for remote editing. Read-only versions of the data are available in GIS/spatial format for public use via web services. Future development plans include links to water chemistry data, water level measurements and other ancillary data, along with the addition of vectors to represent dye traces and polygons for larger karst features.

Legacy Data in the Minnesota Spring Inventory

Gregory Brick, Minnesota Dept. of Natural Resources

Past spring inventories have covered certain parts of Minnesota reasonably well, notably, the springs of the Minneapolis-St. Paul metropolitan area and the southeastern Minnesota karst. But hitherto, there has not been a systematic effort to create a uniform statewide inventory. The first step, before hunting down new springs, was to compile existing data and the most fruitful source of hydrological legacy data for the Minnesota spring inventory was the DNR Fisheries files. Once entered into a GIS-capable database, these spring locations can help "seed the ground" so that when crews finally do take to the field to map more springs, they will have known examples to work from. Good baseline and time-series data should also help evaluate the impact of climate change and land use changes on Minnesota's springs over time.

Development of Cavity Probability Map For Abu Dhabi Municipality Using GIS and Decision Tree Modeling

Yongli Gao, University of Texas
Raghav Ramanathan, Rizzo Associates
Bulent Hatigoplu, Rizzo Associates
M. Melih Demirkan, Rizzo Associates
Mazen Elias Adib, Abu Dhabi City Municipality
Juan J. Gutierrez, Rizzo Associates
Hesham El Ganainy , Rizzo Associates
Daniel Barton Jr., Rizzo Associates

Cavity collapse and settlement due to the presence of shallow solution cavities cause significant geotechnical and other engineering problems in certain areas within the Abu Dhabi City Municipality (ADM). A cavity probability map helps to identify regions that are more susceptible to the formation of cavities by identifying and analyzing influential factors contributing to its formation. Information relating to cavities was cataloged and reviewed based on available data from the Geotechnical Information Management System (GIMS), which is a consolidated geotechnical database developed by the ADM. Geological and geotechnical subsurface conditions are obtained from previous site investigation campaigns performed in the ADM region. All geotechnical, geological and cavity related information are stored in a GIS geodatabase system. Based on detailed literature review, primary factors influencing formations of cavities are identified: presence of soluble bedrock, depth to Gascharan Formation, cavity density, cavity thickness and distance to nearest neighbor. Another important factor in the formation of cavities is fluctuations in the groundwater table. Fluctuations are mostly caused by dewatering projects during constructions of buildings or infrastructure. The effect of variation in groundwater is not considered in this study due to lack of high quality data. A decision-tree model based on cavity distribution was developed for cavity hazard assessment. The primary controls on cavity development are lithostratigraphic position or bedrock geology and depth to the soluble Gachsaran Formation. Most cavities tend to form in highly concentrated zones. Implementation of the decision-tree model in ArcGIS resulted in a cavity probability map. This cavity probability map is mainly based on existing borehole data. Areas not fully mapped by boreholes must be re-evaluated for cavity risk when new borehole data is available. Low Probability, Low to Moderate Probability, Moderate to High Probability, High Probability, and Very High Probability areas were delineated in the probability map.

Evaluation of Cavity Distribution Using Point-Pattern Analysis

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Presence of solution cavities of different sizes poses major engineering problems in some areas of Abu Dhabi City Municipality (ADM) underlain by soluble rocks such as gypsum, calcarenite, or mudstone. This is especially critical if they are located at a relatively shallow level and are likely to cause settlement or sudden soil collapse. The Gachsaran Formation, which is composed of interlayered mudstone and gypsum, underlies all of the ADM and is known to be vulnerable to cavity formation in the area. The mudstone and gypsum beds within the upper part of the Gachsaran Formation are prone to dissolution. Numerous sinkholes have been reported, particularly in the zone between Abu Dhabi International Airport and Mafraq. Many geotechnical and geological reports and surveys were reviewed for extracting information related to geological and hydrogeological conditions causing cavities in the ADM. Information associated with cavities was cataloged and reviewed based on available data from an existing geotechnical borehole database maintained by the ADM. Cavity data obtained from borehole information was analyzed to examine cavity distributions based on the following factors: lithology, geographic clusters, cavity density, cavity size, depth to cavity, and depth to bedrock. All cavities were grouped into geographic clusters and lithological clusters for point-pattern analysis. Most cavities (87 percent) occur in mudstone or gypsum, or at an interface between these two rock types, which compose part of the Gachsaran Formation. The dissolution of carbonate and evaporites within this formation causes the formation of subsurface voids in the ADM area. Geographically, majority of cavities occurred in the Shakhbout City area, hence pattern analysis including average nearest neighbor analysis, Moran's I for measuring spatial autocorrelation, and G-statistics for measuring high/low clustering were conducted in this area using spatial statistics tools in ArcGIS. Average nearest neighbor analysis and Moran's- I show that cavities are strongly clustered in this area with a high confidence level (>99 percent). General G-statistics identified a high clustering (hot spot) of cavities with relatively high values of depth to cavity, depth to bedrock, and number of cavities per borehole. No highly clustered large cavities were detected by the General G-statistics. Additionally, distances to the first through the 9th nearest neighbors were determined for cavities in different lithological materials and geographical clusters. Outcome of these spatial correlation and statistical analysis can be used to conduct risk assessment and the probability of occurrences of future cavities.

A Method of Mapping Sinkhole Susceptibility Using a Geographic Information System: A Case Study for Interstates in the Karst Counties of Virginia

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Lindsay Ivey-Burden, University of Virginia

Karst is a landscape underlain chiefly by limestone that has been chemically dissolved by acidic groundwater, producing subsurface voids that may lead to sinkholes at the surface if the overlaying soils can no longer support their own weight and collapse. The western counties of Virginia have a high concentration of karst areas due to widespread occurrence of carbonate rock exposures, and their geomorphic development within the Appalachian Mountains. As a result, the Commonwealth of Virginia Hazard Mitigation Plan recommends that the Virginia Department of Transportation (VDOT) develop a method to determine the roadways and regions most susceptible to experiencing sinkholes, in an effort to reduce the possibility of reported sinkhole damage to property. While many noninvasive methods exist to detect subsurface voids, such as electric resistivity imaging, microgravity, ground penetrating radar, and seismic surveys, these methods are time consuming and costly. This study proposes the use of a geographic information system (GIS) to create a susceptibility map of regions in the karst counties of Virginia, and in particular along interstate highways, that are most susceptible to future sinkhole development. Five factors that have previously been shown to play a role in the acceleration of sinkhole formation in Virginia include: bedrock type, proximity to fault lines, drainage class, slope of incised river banks, and minimum soil depth to bedrock. The analysis compares 1:24,000 scale maps of existing sinkholes developed by Virginia Department of Mines Minerals and Energy (DMME) with a series of maps representing differing combinations of each of the five factors to determine which weighted combination is most appropriate to use for a final representative sinkhole susceptibility map. The layers representing each factor are created using publicly available tabular and spatial data taken from the United States Department of Agriculture (USDA) Soil Survey Geographic (SSURGO) Database, the United States Geological Survey (USGS) National Map, the USGS Mineral Resources Online Data, and the National Weather Service. The methodology used to gather information specifically from the SSURGO database is highlighted within this paper. Data from the SSURGO database is used to create the bedrock type, drainage class, and minimum soil depth to bedrock layers. A substantial benefit to

this methodology is that the new technique can be adjusted to accommodate for sinkhole susceptibility in other karst regions, by simply adjusting the input layers to consider the specific geology of a particular region.

Thursday, October 8th 1:30pm-3:10pm Track A: Contamination of Karst Aquifers

Evaluation of Veterinary Pharmaceuticals and Iodine for Use as a Groundwater Tracer in Hydrologic Investigation of Contamination Related to Dairy Cattle Operations

Larry Boot Pierce, Missouri Geological Survey
Honglin Shi, Missouri University of Science and Technology

Standard groundwater tracers such as Rhodamine WT, Fluorescein, Eosin and Tinopal CBX effectively provide a snapshot of hydrological conditions over a brief period of time and in a tightly controlled setting. However, in complex environmental situations with multiple potential sources, groundwater hydrologists are often seeking groundwater tracers that have extended longevity in the natural environment and the ability to directly pinpoint source locations.

After reviewing operations of the nearby dairy it was determined that emerging contaminants, specifically two bovine veterinary pharmaceuticals (antibiotics), cephapirin sodium (CEPNa) and cephapirin benzathine (CEPB), and a sanitation agent, elemental Iodine (I) may have potential as extended longevity groundwater tracers if analytical methodology could be established.

Initially, sample analysis indicated that cephapirin is undetectable in unconcentrated samples of lagoon wastewater at parts per billion (ppb) concentration; pre-concentrated samples which utilized solid phase extraction allowed for better detection at part per trillion level. Concentrated samples from one of the two lagoon cells sampled (cell #3), detected cephapirin at 13.14 ppt level, while cell #1 failed to detect any cephapirin present. Controlled laboratory testing later indicated that in a wastewater environment cephapirin degrades to approximately 20% of initial concentrations within 4 days, with complete degradation within 6 days. Degradation patterns in surface water and groundwater samples were less dramatic and at slower rates. Degradation curves of the surface and groundwater samples indicate that concentrations of cephapirin are still detectable for approximately 25 days. Unconcentrated Iodine samples collected in lagoon cells ranged from 50.896 ppb and 1,704.55 ppb with variations determined to be a result of the primary inflow of the lagoon.

Cephapirin's use as a long term groundwater tracer does not seem to be an immediate option. Further research may reveal that its degradation products are potentially useful as a tracer. In some instances, such as catastrophic discharges of large volumes of milk when samples can be collected and analyzed quickly, the use of cephapirin as an environmental tracer may prove possible. The validity of pharmaceutical iodine as a groundwater tracer appears to be much greater than that of cephapirin. Iodine was detected in all of the environmental samples including the highly organic and anaerobic environment of the dairy wastewater lagoon. This study concludes that iodine is capable of surviving the hostile wastewater environment. If sufficient data is collected to determine natural background levels, iodine may prove useful in determining hydrological connections between iodine laden dairy effluent and the underlying groundwater.

Karst Influence in the Creation of a PFC Megaplume

Virginia Yingling, Minnesota Department of Health

Perfluorochemicals (PFCs) are fully-fluorinated organic chemicals used to produce a wide range of industrial and commercial products. Their extreme persistence and mobility in the environment and nearly ubiquitous presence in humans and wildlife has raised serious concerns regarding their environmental and human health effects. In the 1940s to 1970s, PFC-bearing wastes were disposed of in three unlined landfills in Washington County, Minnesota. The resulting co-mingled PFC plumes created a "megaplume" that contaminated over 250 km^2 of groundwater and four major drinking water aquifers; affecting eight municipal water supply systems and thousands of private wells. Site investigations revealed that karst features, particularly in the Prairie du Chien Group (OPDC), and groundwater-surface water interactions played a critical role in contaminant migration.

Tracking of Karst Contamination Using Alternative Monitoring Strategies: Hidden River Cave Kentucky

Caren Raedts, Western University of Ontario
Christopher Smart, Western University of Ontario

Karst groundwater contamination presents great challenges for efficient monitoring because of rapid, discrete transport and the

diversity of contaminants. Here a low cost approach is described and applied to Hidden River Cave, Kentucky, where a long history of contamination has been experienced. Local knowledge was acquired through informal interviews and coupled with observations of contaminant residues, faunal distributions and fluorescence spectra in the cave. The resulting patterns were interpreted using Google Earth and Street View to identify specific contaminant sources in the affected sub-catchment of the cave. Despite success in matching contaminant sources with the contamination history and pattern, the informal nature of the investigation renders it unacceptable as the basis for any intervention. But such low cost studies will be needed for the majority of contamination occurrences where financial resources are very limited. A radical revision of our adversarial approach to environmental management will be required for such a change to occur.

Spatiotemporal Response of CVOC Contamination and Remedial Actions in Eogenetic Karst Aquifers

Ingrid Y. Padilla, University of Puerto Rico
Vilda L. Rivera, University of Puerto Rico
Celys Irizarry, University of Puerto Rico

The northern karst region of Puerto Rico has a long and extensive history of toxic spills, chemical waste, and industrial solvent release into the subsurface. High potential for exposure in the region has prompted aggressive remediation measures, which have extended for over 40 years. Of particular concern is contamination with chlorinated volatile organic compounds (CVOCs) because of their ubiquitous presence and potential health impacts. This work evaluates historical groundwater quality data to assess the spatiotemporal distribution of CVOC contamination in the karst aquifer system of northern Puerto Rico, and its response to remedial action in two superfund sites contaminated with CVOCs. Historical data collected from different information sources with different monitoring objectives is evaluated spatially and temporally using Geographic Information System (GIS) and statistical analysis. The analysis shows a significant extent of contamination that comes from multiple sources and spreads beyond the demarked sources of pollution. CVOCs are detected in 65% of all samples and 78% of all sampled wells. Groundwater shows continued level of contamination over long periods of time, demonstrating a strong capacity of the karst groundwater system to store and slowly release contamination. Trichloroethene and Tetrachloroethene are the most frequently found, although other CVOCs (e.g., Trichloromethane, Dichloromethane, Carbon Tetrachloride) are detected as well. The spatial and temporal distributions of CVOCs seem to be highly dependent upon the monitoring scheme and objectives, indicating that the data does not adequately capture the contamination plumes. Targeted remedial action using pump and treat (air stripping) and soil vapor extraction in two superfund sites has reduced concentrations over time, but the spatial and temporal extent of the contamination reflect inability to completely capture the heterogeneous plumes.

Thursday, October 8th
1:30pm-4:30pm
Track A: Geophysical Exploration of Karst

The Million Dollar Question: Which Geophysical Methods Locate Caves Best Over the Edwards Aquifer? A Potpourri of Case Studies from San Antonio and Austin, Texas, USA

Mustafa Saribudak, Environmental Geophysics Associates

The existence of caves represents a hazard for urban areas. Therefore it is important to know the size, position and depth of caves before building or reconstruction. Cavity imaging using geophysical surveys has become common in the San Antonio area since early 2000 although their use has been going on in other parts of country for the last 25 years. It appears from these studies that the resistivity imaging method has been the primary technique among others, such as gravity, ground penetrating radar (GPR), magnetic, conductivity, and self-potential(natural potential). This study mainly describes resistivity imaging and natural potential data (NP), and some other geophysical data collected over several known and unknown caves during the study between the years of 2000 and 2015. All caves but one was encountered through drilling and/or excavation for building and utility lines or power pole reconstructions. The study area falls into the part of the Recharge Zone of the Edwards Aquifer region and it represents a well- developed karstified and faulted limestone in the Austin and San Antonio areas. 2D resistivity imaging data is presented as a colored 2-D electrical image of subsurface (i.e. a vertical cross section of the distribution of subsurface resistivity). Such a display section indicates low, medium, and high resistivity areas and the structural configuration of the subsurface geology. Based on our 15 years of experience working with resistivity data, we like to indicate that all range of resistivity values (low to high) can cause caves and voids. However, purely air-filled cavities cause high resistivity anomalies whereas clay-filled caves are the source of low resistivity anomalies. But it is rarely that caves are purely filled with air. A variety of sediments accumulates in caves and can be preserved more or less intact for long periods of time.

Presence of sand and gravel and clay deposits, mineralization, faults and fractures, perched water in caves are the rules rather than the exception. It is clear from this body of work over the 15 years that the resistivity method does not always successfully delineate the location of caves and other karstic features. However, it provides significant information on the near-surface geology and geological structure. The NP data, on the other hand, notably defines the location of karstic features. This study thus demonstrates that the resistivity method is not always a reliable predictive technique, but is useful in karst terrains to cover large areas quickly and, the merits of integrating natural potential method, in order to reduce the ambiguity in the interpretation, are quite evident from the case studies.

Rollalong Resistivity Surveys Reveal Karstic Paleotopography Developed on Near-Surface Gypsum Bedrock

Lewis Land, National Cave and karst Research Institute; Lasha Asanidze, Tbilisi State University

Following flooding in September 2013, several areas in northern Eddy County, New Mexico were damaged by multiple sinkhole collapses. We conducted rollalong electrical resistivity (ER) surveys for subsurface cavities parallel to roads within and near the community of Lakewood, NM to guide road repairs. The rollalong method allowed us to generate exceptionally long, continuous ER profiles of the survey area. ER surveys attained a maximum exploration depth of 55 to 62 meters over a lateral extent of ~1000 meters, revealing an unconformable surface developed on gypsum bedrock, punctuated by shallow depressions. Subsurface stratigraphy, including clay-rich valley fill sediments, and mudstone and gypsum of the underlying Seven Rivers Formation, can be identified by vertical and lateral variations in electrical resistivity. The irregular bedrock surface of the Seven Rivers Formation reflects paleotopography developed on that surface prior to its burial by floodplain sediment. Some of the negative paleotopographic features are probably filled sinkholes, which may be associated with shallower karstic features not imaged on the profiles.

Integration and Delivery of Interferometric Synthetic Aperture Radar (InSAR) Data Into Stormwater Planning Within Karst Terranes

Brian Bruckno, Virginia Department of Transportation
Andrea Vaccari, University of Virginia
Edward Hoppe, Virginia Cntr for Trans. Innovation & Research
Scott T. Acton, University of Virginia
Elizabeth Campbell, Virginia Department of Transportation

As part of a USDOT-funded study focused on the implementation of satellite-based Interferometric Synthetic Aperture Radar (InSAR) technology, the researchers integrated InSAR-derived point cloud data into the transportation design process within karst terrain. The group's workflow included initial validation of InSAR data by acquiring over 1.67 million InSAR data points (various "scatterers") which were then brought into a GIS dataframe and georeferenced to locations of mapped sinkholes. The technique was then applied to the evaluation of karst hazard of within a 40x40 km data frame located in the Valley and Ridge Province of Virginia. The group identified systematic kinematic differences in scatterer behavior with respect to their proximity to mapped karst geohazards, and used this method to screen for and identify unknown karst features, revealing numerous previously unidentified sinkholes. After validating the data with quantitative field correlations, the group then integrated the InSAR data into a traditional, CADD-developed design ported into a GIS dataframe. This integrated data was then applied to a traditionally-developed roadway project and used to optimize the location of stormwater management assets. In so doing, the group was able to develop open-source data delivery method that allows greater flexibility, efficiency, and optimization of the infrastructure design and planning process, which can be developed collaboratively over geospatial platforms. This data integration offers lifecycle cost benefits, improvements to the safety of the traveling public, and protection of the environment, particularly in groundwater-sensitive karst terranes.

Disclaimer: The views, opinions, findings and conclusions reflected in this presentation are the responsibility of the authors only and do not represent the official policy or position of the US Department of Transportation/Office of the Assistant Secretary for Research and Technology, or any state or other entity.

Detection of Voids in Karst Terrain with Full Waveform Tomography

Khiem T. Tran, Clarkson University
Michael McVay, University of Florida
Trung Dung Nguyen, Clarkson University

The paper presents an application of time-domain surface-based waveform tomography for detection of voids in karst terrain. The measured seismic surface wave fields were inverted using a full waveform inversion (FWI) technique, based on a finite-difference solution of 2-D elastic wave equations and Gauss-Newton inversion method. The FWI was applied to real experimental data sets collected from twelve test lines at a karst site in Florida. Two of the test lines were located next to open chimneys to image their extents. Ten other test lines were located in an open and flat area without any void indication from the ground surface to detect an unknown void. The inversion results show that the waveform analysis was able to delineate embedded low-velocity anomalies, the void, and highly variable bedrock both laterally and vertically. Locations of the low-velocity anomalies were consistent to the known open chimneys observed from the ground surface. The identified void was confirmed by an independent invasive test (standard penetration test, SPT).

Characterization of Karst Terrain Using Geophysical Methods Based on Sinkhole Analysis: A Case Study of the Anina Karstic Region (Banat Mountains, Romania)

Laurentiu Artugyan, West University of Timisoara
Adrian C. Ardelean, West University of Timisoara
Petru Urdea, West University of Timisoara

To understand karst topography, we must determine both the nature and the factors that are defining dissolution processes in soluble rocks, as well as the drainage network resulting from these processes. The goal of this paper is to understand the underground drainage direction configuration and, also, the factors that are involved in surface water drainage of the Anina karstic region.

In this study we used two complementary geophysical methods, spontaneous potential (SP) and ground penetrating radar (GPR), applied in 5 sinkholes with a funnel shaped aspect. Four of these sinkholes are circular and one of them is elongated NW-SE direction. Three of the studied sinkholes are representing a chain of sinkholes orientated west-east.

SP data describe the surface drainage, indicating drainage direction and/or moisture accumulation points. The GPR investigation utilizes electromagnetic pulses for the investigation of subsurface dielectric properties. GPR offers an image of the underground, showing possible bedding planes, in this case mostly along north-south orientations. Besides, in two GPR profiles, we could identify an object that could be a cavity, in that point were on SP grid the values indicate small values, pointing out a link between those two geophysical results. Using SP and GPR methods we were able to show that the bottoms of these depressions are retaining more humidity and soil. In addition, the GPR profiles outlined several subsurface "objects", at a depth ranging between 20 and 40 meters, which need a more thorough analysis.

Our future work is intended to enrich our field data using SP and GPR methods, to compare with our first results. Also, we intend to integrate electrical resistivity tomography measurements in our analysis for better subsurface characterization.

Thursday, October 8th 3:30pm-5:30pm Track A: Karst Management, Regulations and Education

The Cost of Karst Subsidence and Sinkhole Collapse in the United States Compared with Other Natural Hazards

David Weary, US Geological Survey

Rocks with potential for karst formation are found in all 50 states. Damage due to karst subsidence and sinkhole collapse is a natural hazard of national scope. Repair of damage to buildings, highways, and other infrastructure represents a significant national cost. Sparse and incomplete data show that the average cost of karst-related damages in the United States over the last 15 years is estimated to be at least $300,000,000 per year and the actual total is probably much higher. This estimate is lower than the estimated annual costs for other natural hazards; flooding, hurricanes and cyclonic storms, tornadoes, landslides, earthquakes, or wildfires, all of which average over $1 billion per year. Very few state organizations track karst subsidence and sinkhole damage mitigation costs; none occurs at the Federal level. Many states discuss the karst hazard in their State hazard mitigation plans, but seldom include detailed reports of subsidence incidents or their mitigation costs. Most State highway departments do not differentiate karst subsidence or sinkhole collapse from other road repair costs. Amassing of these data would raise the

estimated annual cost considerably. Information from insurance organizations about sinkhole damage claims and payouts is also not readily available. Currently there is no agency with a mandate for developing such data. If a more realistic estimate could be made, it would illuminate the national scope of this hazard and make comparison with costs of other natural hazards more realistic.

Hazard of Sinkhole Flooding to a Cave Hominin Site and its Control Countermeasures in a Tower Karst Area, South China

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Guanghui Jiang, Institue of Karst Geology, CAGS
Kwong Fai, Chinese Culture University
Andrew Lo, Chinese Culture University
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Yongli Guo, Institue of Karst Geology, CAGS
Shaohua Liu, Institue of Karst Geology, CAGS

Zengpiyan Cave, one of the most important cave hominin sites of the Neolithic in the South of China, was listed on the national register of cultural preservation sites in 2001. Large quantities of precious material in the Zengpiyan site were unearthed since the beginning of the trial excavation in 1973. These materials include hominin skeletal remains, fire pits, human burials, stone implements, tools fashioned from mollusk shells and animal or plant fossils. According to the historical record, ancient people lived in caves in the karst plain of Guilin. They moved out of the caves approximately 7000 years ago. These cave hominin sites provide important material for understanding ancient environmental change and human prehistory. However, the exploratory shaft of Zengpiyan had no appropriate treatment after the initial excavation. Groundwater flooded the exploratory shaft due to frequent rises in the water table, resulting in collapse of the exploratory shaft shoring as well as some other serious damages. Even though some rescue and protection measures were taken, for example, slope supporting and backfill treatment, they failed to eliminate the hidden trouble caused by rapid fluctuation of groundwater levels during the rainy season. Rapid urbanization is also affecting this region. Infrastructure construction of the city changes the hydrogeological conditions of the karst, increasing the area of impervious surface and risks of urban flooding. Moreover, an increase of extreme climate events may lead to frequent flooding of the site by groundwater. Therefore, a focused hydrogeological investigation was carried out to study the status of the site and karst development, and the mechanism of groundwater movement at local and regional scales. These surveys include borehole drilling, electrical resistivity surveys, computed tomography (CT) scanning technology, dye tracer tests, groundwater monitoring, and hydrochemistry analysis. The results show that the site is located in the seasonal fluctuation zone of the groundwater. Water level in the karst aquifer is sensitive to rainfall. Continuous rainstorms lead to synchronous rising of the groundwater level in both the cave and the aquifer. In addition, surface runoff and urban sewers cannot discharge smoothly, resulting in surface water backflooding into the cave entrance. Therefore, controlling the recharge of groundwater and the influx of surface runoff, and dredging a groundwater discharge channel are all important in order to reduce the damage of flooding to the archaeological sites. Based on these detailed investigations and research results, countermeasures for flood control and archaeological site protection were put forward. We recommend that the engineering measures should combine curtain grouting, drain construction, and effective water resources management for the entire basin. Even though the measures are feasible, we can't promise a perfect damage control of the ruins by water due to the complex hydrogeological conditions in the covered karst area.

Case Studies of Animal Feedlots on Karst in Olmsted County, Minnesota

Martin Larsen, Olmsted County Soil and Water Consv. District

A unique area of Olmsted County is located a few miles southeast of Rochester by the small community of Predmore. Surface geology within the Orion Sinkhole Plain is dominated by a large array of sinkholes and limited soil cover over carbonate bedrock of the Ordovician Stewartville and Prosser Formations. Dye trace studies completed by Eagle and Alexander (2007) have demonstrated that a large portion of the plain's groundwater discharges into springs that feed two local trout streams. Land-use in the area is mixed. For generations, local farmers have relied on livestock for stable income and profit. To put the 8,000 acre region into perspective, there are approximately 3,600 animal units located at 12 facilities which produce an estimated 74 million pounds of manure per year (United States Department of Agriculture / Natural Resources Conservation Service, 1995) and 10 million gallons of manure contaminated runoff. (Larsen et. al., 2014) 349 known karst features exist of which 316 are sinkholes. (Alexander, et. al., 1988). Following snowmelt and rain in March of 2013; an incident occurred where an area well was potentially impacted. Investigation revealed manure contaminated runoff was entering groundwater in a newly discovered sinkhole (Larsen, 2013). Local citizen concern grew for groundwater quality. Developing relationships with landowners and livestock producers became necessary for protection of water resources and has facilitated research, education and action. A newly formed sinkhole which seasonally receives feedlot runoff was studied with ground penetrating radar for repair. Two producers in the region are implementing manure management techniques

that are more stringent then regulation. The Wiskow dye trace was completed in spring of 2014. The study identified discharge springs that discharge into the Mill Creek trout stream from two vulnerable sinkholes (Johnson et al., 2014). Four springs and four previously unknown sinkholes were identified and mapped. A manure contaminated runoff storage area was constructed in the fall of 2014 by a livestock producer located at a headwater spring of Mill Creek. A filter strip and large manure contaminated runoff system is being designed for construction in 2015. Building great relationships with producers has been successful in Olmsted County. Livestock producers are making investments and taking action. Producers are an essential component of the mid-western economy and assistance with information, funding and resources will help protect the environment and keep farms profitable for future generations.

Evaporite Geo-Hazard in the Sauris Area (Friuli Venezia Giulia Region - NE Italy)

Chiara Calligaris, Trieste University
Stefano Devoto, Trieste University
Luca Zini, Trieste University
Franco Cucchi, Trieste University

Evaporite sinkholes represent a severe threat to many European countries, including Italy. Among the Italian regions, of the area most affected is the northern sector of Friuli Venezia Giulia Region (NE Italy). Here chalks had two main depositional periods first in the Late Permian and then during the Late Carnian (Late Triassic). Evaporites outcrop mainly in the Alpine valleys or are partially mantled by Quaternary deposits, as occur along the Tagliamento River Valley. Furthermore, evaporites make up some portions of mountains and Alpine slopes, generating hundreds of karst depressions.

This paper presents the preliminary results of the research activities carried out in Sauris Municipality where sinkhole phenomena related to the presence of gypsum are very common.

Field investigations were devoted to recognition, mapping and classification of evaporite sinkholes. To recognize sinkhole phenomena, the preliminary steps included the analysis of historical documents collected in archives, the analysis of aerial photos and Airborne Laser Scanning (ALS) surveys. The integration of the above-cited activities allowed a preliminary identification of the phenomena, which were later validated by detailed field surveys.

All the collected data populate a geo-database implemented for a project funded by the Geological Survey of Friuli Venezia Giulia Region. The objective of this project is to inventory and classify the sinkholes associated to evaporite rocks.

Building Codes to Minimize Cover-Collapses in Sinkhole-Prone Areas

George Veni, National Cave and Karst Research Institute
Connie Campbell Brashear, Bracken Engineering, Inc.
Andrew Glasbrenner, Bracken Engineering, Inc.

Cover-collapse sinkholes are forming with increasing frequency under buildings. Analyses of sinkhole distribution in Beacon Woods, Florida, preliminarily indicate their occurrence is an order of magnitude greater in urban versus undeveloped areas, suggesting the structures themselves are enhancing the collapse process. The most likely causes are induced recharge via at least one of two sources. First, runoff and drainage from roads, structures, and impoundments that is not adequately dispersed will promote sinkhole development. Second, leaking water, sewer, and septic systems beneath or adjacent to a structure will also promote collapse. The process of cover-collapse from induced recharge is well understood. However, building codes generally do not require drainage and structural engineering practices that would reduce induced recharge and thus reduce the risk of collapse. This paper proposes engineering practices that measurably restrict the accidental discharge of municipal water through leaking subgrade drainage systems or the deliberate discharge of stormwater runoff, induced shallow groundwater recharge from retention ponds and septic drainfields, or heavily-irrigated land use. We recommend these practices be incorporated into building codes and ordinances to reduce induced sinkhole development in areas prone to cover-collapse.

Cars and Karst: Investigating the National Corvette Museum Sinkhole

Jason S. Polk, Western Kentucky University
Leslie A. North, Western Kentucky University
Ric Federico, EnSafe
Brian Ham, EnSafe
Dan Nedvidek, EnSafe
Kegan McClanahan, Western Kentucky University
Pat Kambesis, Western Kentucky University
Michael J. Marasa, Hayward Baker

On February 12th, 2014, a sinkhole occurred at the National Corvette Museum in Bowling Green, Kentucky. The collapse happened inside part of the building known as the Skydome and eight Corvettes on display were lost into the void that opened in the concrete floor. In this region of Kentucky, known as the Pennyroyal sinkhole plain, subsidence and cover collapse sinkholes are commonly found throughout the landscape. This iconic karst region in the United States is also home to

Mammoth Cave, the longest cave in the world, and thousands of other caves and karst features. Investigation of the sinkhole collapse began immediately while the Corvettes were extracted from the debris cone inside the void. Techniques used for investigation included water jet drilling, downhole cameras and drone footage, a microgravity surface survey, and mapping of the void and accompanying cave. After exploration of the sinkhole by karst researchers and compilation of the data, the cause of the sinkhole was determined to be a cave roof collapse in a breakout dome. The cave underlying the collapse is about 220 feet (67 m) long and 39 feet (12 m) wide on average with an average depth of 65-85 feet (20-25 m). The structural integrity of the bedrock (thinly interbedded limestone and chert located at a contact between two major limestone units) is lacking in the area. Talus and breakdown are abundant in the cave in which the sinkhole formed. The progression of the roof failure likely occurred over a long span of time, eventually giving way due to a variety of conditions, including speleogenetic and climatic factors. Current remediation is underway and involves filling the sinkhole with gravel and sand, then installing a micropile supported concrete slab floor under the building. Future changes to the structure will be monitored to detect any activity.

Thursday, October 8th 3:30pm-4:30pm Track B: Geophysical Exploration of Karst

Investigation of a Sinkhole in Ogle County, Northwestern Illinois, Using Near-Surface Geophysical Techniques

Philip J. Carpenter, Northern Illinois University
Lauren M. Schroeder, Northern Illinois University

A sinkhole measuring 40 m in diameter and up to 6.5 m deep occurs within the Nachusa Grasslands, near the town of Franklin Grove, northwestern Illinois. This area, dedicated to prairie conservation and restoration, is owned and operated by The Nature Conservancy. Several meters of unconsolidated sand, gravel, and clay overlie the St. Peter sandstone, beneath which lies karstic Prairie du Chien dolomite. Investigations included EM conductivity profiles, resistivity soundings, 2D resistivity, and ground- penetrating radar (GPR), supplemented by conductivity logs, soil cores, and tree core studies. These data indicate the sandstone averages about 5 m deep near the sinkhole rim and the sinkhole is about 120 years old. Nearby residential wells indicate an average static water level of 11 m below the surface, so the water table currently lies well below the sinkhole floor. GPR sections show abrupt termination of the bedrock reflector near the sinkhole rim, suggesting formation by collapse. Geophysical investigations also identified possible hydraulic conduits associated with the sinkhole. Specifically, GPR profiles, at 50 and 100 MHz, provide the highest resolution images of the subsurface and indicate possible conduits (soil pipes) near the sinkhole rim as diffraction hyperbolas 2-3 m below the surface. GeoProbeTM conductivity logs showing unusually low conductivity, and sudden probe drops, also suggest the presence of shallow soil cavities around the sinkhole. However, dye poured into various low spots on the sinkhole floor was never recovered, despite numerous sampling locations.

Study on Monitoring and Early Warning of Karst Collapse Based on BOTDR Technique

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X. Z. Jiang, Inst. of Karst Geology, China Univ. of Geoscience
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Brilliouin Optical Time Domain Reflectometer (BOTDR) is a newly developed measurement and monitoring technique, which utilizes Brilliouin spectroscopy and Optical Time Domain Reflectometer (Jiang et al., 2006; Zhang et al., 2009; Xu et al., 2011) to measure strain generated in optical fibers as distributed in the longitudinal direction. This paper introduces the principle and characters of BOTDR technique firstly, and makes an example of karst collapse monitoring at section K14 of highway from Guilin to Yangshuo. And we talk about how to use this technique in underlying karst collapse monitoring in karst highway, discuss environmental factors, like temperature and vehicle dynamic load, how to affect the monitoring results and how to choose optical fiber type and paving region. At last, we compare the results between using BOTDR and geological radar, and conduct the safety diagnosis on the experimental road. The application achievements demonstrate that BOTDR is a viable technique for the karst collapse monitoring.

Pre-Event and Post-Formation Ground Movement Associated with the Bayou Corne Sinkhole

Cathleen E. Jones, Jet Prop. Lab., California Inst. of Tech.
Ronald G. Blom, Jet Prop. Lab., California Inst. of Tech.

We discuss measurements of the precursory and post-formation ground displacement in the vicinity of the Bayou Corne, Louisiana, sinkhole made using interferometric synthetic aperture radar (InSAR) and data from the L-band UAVSAR instrument. Large precursory movement was observed at the sinkhole site and shown to be predominantly horizontal in direction, in contrast to sinkhole precursors previously detected with InSAR, all of which indicated vertical deformation. Here we discuss how two opposing imaging directions were used to determine the precursory horizontal movement, and use the same technique to look at the progression of post-formation ground displacement around the expanding sinkhole during the interval 2012-2014. We find that the Bayou Corne sinkhole has expanded asymmetrically about the initial location, and show that expansion has tracked ground movement observed with InSAR along the margins of the water-filled central subsided area. This work shows that InSAR applied to images acquired from multiple directions can be used to image incipient sinkhole formation over large areas and to track the expected direction of expansion. We discuss how geologists can best use the InSAR technique to quantitatively monitor ground movement associated with sinkholes, particularly in areas where radar rapidly decorrelates, e.g., in Florida or Louisiana. These results demonstrate that InSAR could be used in sinkhole warning systems across a much broader geographical area than previously demonstrated, and for identifying both precursory and post-formation surface movement.

Thursday, October 8th
4:30pm-5:30pm
Track B: Modeling of Karst Systems

Numerical Simulation of Karst Soil Cave Evolution

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Yan Meng, Institute of Karst Geology
Zhen-de Guan, Institute of Karst Geology
Li-peng Liu, China Inst. of Water Resources and Hydropower

This study is focused on numerical simulation of the formation and development of karst soil caves related to cover-collapse sinkholes. The so-called "karst soil cave" refers to the caves formed in the soil layers above bedrock of sinkhole regions. Because the soil caves are formed and developed under groundwater seepage, studying groundwater level changes can help understand soil cave development and collapse. Based on the improved Terzaghi loosening pressure theory and using excess pore water pressure, two kinds of critical groundwater level decline are discussed. The first, denoted as $\Delta H0$, is the critical groundwater level decline related to soil cave formation and evolution; the other one, denoted as ΔHT, is the critical groundwater decline related to cave roof collapse. After a soil cave is formed, its evolution can cause uneven displacement and stress redistribution in the overlying soil layer. The process of soil cave expansion can be understood by investigating the change in displacement and stress. Numerical simulation of the vertical displacement using FLAC3D shows that the maximum vertical displacement occurs at the arch roof of the soil cave and that the displacement can cause tensile failure of the arch roof. The simulated soil layer displacement is used to determine the soil depth disturbed by the cave by delineating the planes of equal settlement. Analyzing the simulated shear stress shows that the maximum shear stress occurs at the arch toes and causes shear failure. On the other hand, the zones of low shear stress can be used to evaluate existence of arching effect in the overlying soil layer. By analyzing the plastic zone of the soil layer, it was found that, in rigid clay, arch roof collapse and tensile failure are the major events that lead eventually to the barrel-shaped or bottle-shaped forms of collapsed pits. In loose soil, shear failure of the arch toe is the major event that eventually leads to the taper-shaped or bowl-shaped form of collapsed pits. Generally speaking, stability and size of soil caves can be determined using the three variables of low shear stress area, equal settlement plane, and plastic zone discussed above. The numerical simulation of this study is valuable to the monitoring and assessment of sinkhole occurrence.

Experimental and Numerical Investigation of Cover-Collapse Sinkhole Development and Collapse in Central Florida

Xiaohu Tao, Florida State University
Ming Ye, Florida State University
Dangliang Wang, Florida State University
Roger Pacheco Castro, Florida State University
Xiaoming Wang, Florida State University
Jian Zhao, Hohai University

The mechanisms of sinkhole formation, development, and collapse are investigated in this study using experimental and numerical methods. Sandbox experiments are conducted to understand how excessive groundwater pumping triggers sinkholes formation. The experimental results indicate that the change of hydrologic conditions is critical to sinkhole development. When seepage force increases due to increase of hydraulic gradient, clay and sand particles start moving downward to form a cavity. The confining unit is of particular importance because the cavity is first formed in this layer. Based on the conceptual model developed from the sandbox experiments, the Fast Lagrangian Analysis of Continua (FLAC) code and Particle Flow Code (PFC) are coupled to simulate the sandbox experiments. PFC was used to simulate particle movement in the sinkhole area, and FLAC is used for other areas. While the current numerical simulation can simulate the experiment results such as the sizes of the cavity and the sinkhole, the simulation capability is limited by the computing cost of PFC. More effort of model development is necessary in the future study.

Accounting for Anomalous Hydraulic Responses During Constant-Rate Pumping Tests in the Prairie Du Chien-Jordan Aquifer System - Towards a More Accurate Assessment of Leakage

Justin L. Blum, Minnesota Department of Health

The Prairie du Chien-Jordan Aquifer system is an important source of drinking water for residents of southeastern Minnesota. Assessment of the hydraulic properties of this aquifer continues to be of interest for wellhead protection and resource evaluation efforts. When performing constant-rate pumping tests on wells constructed in the karsted Prairie du Chien Aquifer, anomalous hydraulic responses resulting from cavernous flow are frequently observed. Hydraulic response in the adjacent Jordan Sandstone Aquifer is also commonly distorted because of bedding-plane fractures and well development techniques such as blasting and bailing. Resolution of these anomalous responses is important for accurate estimates of leakage through adjacent resistive layers. Examples are presented with a rational for the analysis process.

Thursday, October 8th
6:30pm
Banquet & Guest Speaker

Hales Bar and the Pitfalls of Constructing Dams on Karst

David J. Rogers, Missouri University of Science and Technology

Hales Bar Dam was built on the Tennessee River 33 miles downstream of Chattanooga by a private company to generate power in 1905-1913. The dam site was selected because it was the narrowest reach in the downstream end of the Walden Ridge Gorge. The site is underlain by Mississippian Bangor Limestone on the southeast flank of the Sequatchie Anticline. Three different contracts failed to complete the dam because of difficult foundation conditions. From 1910-1913 diamond drill core holes were used to explore the site and a series of reinforced concrete caissons 40x45 ft on upstream side and 30x32 ft on the downstream side were installed. Excessive leakage soon appeared near the eastern abutment, and gradually increased. Soundings were made in 1914 to ascertain the areas of gross leakage thereafter rags were placed over suction holes on the river bed and concrete pumped over these. Once a leak was stemmed, leakage would resume at other, adjacent locations. The owners tried to stem the leaks by inserting hay bales, old mattresses, chicken wire, and even corsets! In 1919 the owners began drilling grout holes from the inspection gallery within the dam and pumping hot asphalt into the voids. This was followed by the injection of 78,324 cubic feet of hot asphalt grout into the dam foundation, using 6,266 lineal feet of boreholes with average hole depth of 92 ft. By 1922 the problem appeared solved, but leakage gradually resumed between 1922-1929, rising to the same level as had been observed previously.

In 1930-1931 a new program of exploration was undertaken, using dyes and oils to identify conduits under the dam. Leakage was found to vary between 100 and 1200 cubic feet per second (cfs). When the dam was acquired by the Tennessee Valley Authority (TVA) in 1939 they employed fluorescein dyes to track the under-seepage. Dye tests revealed that the leakage varied between 1720 and 1650 cfs; about 10% of the river's normal flow. They also noted seepage boils forming in the gravel bars, which increased each year. The TVA began constructing the most expensive cutoff wall ever

built, drilling 750 18-inch diameter holes along the dam's centerline and backfilling this with concrete to a maximum depth of 163 feet, extending 25 to 103 feet below the river bed. In April 1963 the TVA announced it was abandoning Hales Bar Dam, due to increasing leakage.

Friday, October 9th 8:30am-11:10pm Engineering and Geotechnical Investigations in Karst

Concepts for Geotechnical Investigation in Karst

Joseph A. Fischer, Geoscience Services
Joseph J. Fischer, Geoscience Services

There seems to be a lack of recognition in the literature that addresses the variety of karst in the United States of America and some of its offshore territories. For example, there are the well-known solutioned carbonates of Florida and the Caribbean, but there are also the somewhat older, harder carbonates of St. Croix, U.S.V.I. Even Florida's recently deposited karst varies from region to region. There are also the ancient, flat-lying carbonates of the interior craton that often have semi-horizontal cavities resulting from variations in ground water levels affecting bedding and the contorted rocks of the Appalachians with its apparently chaotic variations in solutioning found across-strike and in relation to folds, faults and fracturing. In addition, there are various salt and gypsum deposits in the south and southwest that pose their own problems to man's works.

As the geology differs, so does, to some extent, the investigation requirements, investigation techniques and engineering solutions. There is no single set of investigative tools that fit all karst sites. Geophysical investigations are apparently far less suitable for the broken and twisted Appalachian karst than in the flat-lying mid-continent carbonates or the less contorted "karst" of Florida.

Specific procedures developed for geotechnical investigation in true karst have been documented for many years now. However, it appears that many practitioners are not aware of them or choose not to use them because of the possibility of increased costs; or too often, a lack of geotechnical understanding of the work of others in karstic areas outside their sphere of experience.

This paper will attempt to provide a rational geotechnical approach to carbonate rock investigations in the United States while recognizing the inherent variabilities of the targets and the economics of pre-construction investigations; with the understanding that one size does not fit all.

Sinkhole Physical Models to Simulate and Investigate Sinkhole Collapses

Mohamed Alrowaimi, University of Central Florida
Hae-Bum Yun , University of Central Florida
Manoj Chopra, University of Central Florida

Florida is one of the most susceptible states for sinkhole collapses due to its karst geology. In Florida, sinkholes are mainly classified as cover subsidence sinkholes that result in a gradual collapse with possible surface signs, and cover collapse sinkholes, which collapse in a sudden and often catastrophic manner. The future development of a reliable sinkhole prediction system will have the potential to minimize the risk to life, and reduce delays in construction due to the need for post-collapse remediation. In this study, different versions of small-scale sinkhole physical models experimentally used to monitor the water levels in a network of wells. This information is then used in a spatial-temporal analysis model to study the behavior of the system until the sinkhole collapses. The ultimate goal is to use this process in a reverse manner to monitor an existing network of installed groundwater wells to study the fluctuations in the water levels and use the spatial-temporal analysis to predict potential sinkhole collapses. The groundwater levels are monitored using sensors that are hooked up to a high-resolution data acquisition system. The results of a series of tests conducted using this sinkhole physical model showed that there is a very distinguishable groundwater cone of depression that forms underground before the sinkhole collapses. This cone of depression was studied in its early stages and as it progressed with time. This analysis is used to then investigate the growth of the sinkhole before the surface eventually collapses. The spatial-temporal model showed the development of the groundwater cone of depression with time during the development of the cavities within the sediments can be used as a potential 'signal' to identify and isolate the sinkhole location.

Monitoring the Threat of Sinkhole Formation Under a Portion of US 18 in Cerro Gordo County, Iowa Using TDR Measurements

Kevin M. O'Connor, GeoTDR, Inc
Matthew Trainum, Iowa Department of Transportation

Sinkhole formation is a common occurrence in northeast Iowa, and U.S. 18 in Cerro Gordo County was constructed over an area where sinkhole formation had only been locally known. It had not been recorded or identified in the Iowa DNR database at the time. Since 2004, sinkholes have developed along the right of way. Geophysical surveys contributed very little in the identifying the cause. However a Soil Survey (drilling program) identified numerous voids within carbonate bedrock. The soil borings indicated that shale overlying the carbonate rock has been removed/eroded, and resulted in the development of a karst subsurface through the dissolution of the carbonate rock. Without removing the structural fill and site soils to expose the rock, it will not be possible to impede the natural processes occurring. An alternative approach was adopted and consisted of: (a) removing the existing pavement, (b) installing coaxial cables in trenches excavated within the subgrade, (c) replacing the pavement as double reinforced pavement (including shoulders), and (d) monitoring the cables using Time Domain Reflectometry (TDR). The cables are interrogated several times a day and data is transmitted via cellular modem to Iowa DOT facilities. Among the data transmitted is a log file of deformation activity along each of the cables which is evaluated and an action plan is initiated based on: (a) information in the activity file, and (b) updated plots for each cable. Unexpected behavior has been observed, with activity occurring annually between the months of September and March. Although several explanations have been proposed, there is no definitive correlation between locations of the activity detected by TDR, sinkhole locations, or geophysical anomaly locations. In spite of this uncertainty, real time remote monitoring for ground movement is continuing.

Predicting Compaction Grout Quantities in Sinkhole Remediation

Edward D. Zisman, Cardno ATC

Predicting the required quantity of grout needed to remediate a sinkhole-damaged home is a challenging task that involves significant amounts of uncertainty. The difficulty arises from the limited amount of subsurface information that is available to make subsurface predictions particularly in complex karst environments. In typical sinkhole investigations, our understanding of the subsurface is limited by the three to four data points (borings) that provide a small window into actual subsurface conditions. This information is normally obtained from borings and from information inferred by geophysical surveys. In many cases, the information is not sufficient to make accurate predictions of grout quantities. This paper will discuss the uncertainties in analyzing the many factors that influence grout prediction; it will provide a method of calculating grout quantities and discuss how one may moderate the difficulties in prediction of grout quantities. Examples of case studies are given showing pre-grout and post-grout information and the lessons learned from these comparisons.

A Feasibility Study of the Implementation of a Flowable Fill Material to Prevent Sinkhole Occurrence at the I&W Brine Well Site in Carlsbad, New Mexico

Chase L. Kicker, New Mexico Inst. of Mining and Technology

Solution mining at the I&W Brine Well Site in Carlsbad, New Mexico has produced a large underground cavity that could result in a catastrophic sinkhole-inducing collapse. A church, feed store, residences, a highway, and an irrigation canal are potentially in the sinkhole area. The purpose of this research is to demonstrate the feasibility of a solution to stabilize the underground cavity and prevent sinkhole occurrence. With extensive use of relatively inexpensive fillers in a cement-based grout, a flowable fill material was developed and tested. The application of this fill material was studied by injecting the flowable fill into several types of underground cavities to determine if the material can be effectively implemented as a stabilizing agent. A range of test configurations was created to simulate various cavity scenarios, and the fill material was injected into each cavity to assess how the material responds and evaluate ground stability in each case. This research has shown that maintaining a pressure balance while pumping the flowable fill material into a brine-filled cavity and discharging the brine at the surface is a feasible method to stabilize the cavity. The flowable fill solidifies in place to prevent sinkhole occurrence. The flowable fill material is recommended for use at the I&W Site. This research has application for stabilizing underground mines to prevent collapse and reduce subsidence. The flowable fill can also be used to stabilize foundations in areas of naturally occurring dissolution cavities that cause sinkholes.

Pre-Construction Rock Treatment and Soil Modification Program Using Low Mobility Grout to Mitigate Future Sinkhole Development in a 2,787.1 Square Meter (30,000 SF) Maintenance Facility

Steven W. Shifflett, US Army Corps of Engineers

The US Army required construction of a 2,787.1 square meter (30,000 sq. ft) maintenance facility supported on shallow foundations at the Fort Campbell Military Installation. During the subsurface investigation a seven foot air-filled void was encountered in the bedrock within the building footprint. Electrical Resistivity Imaging (ERI) was conducted in an attempt to determine the lateral extent of the encountered void and to establish the general prevalence of karst features at the site. Due to uncertainty in the subsurface conditions, a rock treatment and soil modification program was developed which consisted of a series of targeted exploratory grout holes advanced in 126 locations in the structural areas of the building footprint. The intent of the program was not to prevent the development of a soil dropout, but to improve the foundation support of the structure so that the facility would perform acceptably if a future soil dropout were to occur during the design life of the facility. This was achieved by targeting each footing with 3 exploratory grout holes. The intent of each grout injection was 1) to identify the top of rock elevation, 2) determine if a karst feature existed, 3) cap the karst bedrock below the footing and treat defects in the rock, and 4) provide localized improvement of soft soils through the use of low mobility grout columns under each footing. Drilling refusal elevations were obtained for every grout hole and were assumed to represent the top of bedrock. Each exploratory hole was closely monitored for pressure and volume in 0.61 meter (2-foot) stages. Zones where the bedrock had lower elevations or took excessive grout at low pressures were targeted with additional tertiary holes. The tertiary holes were verified with additional SPT sampling. Documented ground improvement was achieved, evident by increased SPT blow counts ranging between 25 to 50+ post treatment. Based on results from this program, lower grouting pressures could have been utilized as part of the refusal criteria to successfully identify and treat karst features.

Successful Foundation Preparations in Karst Bedrock of the Masonry Section of Wolf Creek Dam

David M. Robison, U.S. Army Corps of Engineers

Extensive foundation preparations during construction of the Wolf Creek Dam concrete masonry section precluded the need for additional rehabilitation to mitigate seepage through karstic limestone bedrock. Wolf Creek Dam on the Cumberland River in southern Kentucky has become well known for karst related seepage issues underneath the embankment section, and yet has had little to no seepage issues associated with the concrete masonry portion of the dam. Post-construction efforts to control seepage underneath the embankment began in 1967 and 1968. Emergency grouting commenced and continued through 1970. Between 1975 and 1979 a more permanent solution of a concrete diaphragm cut-off wall was constructed through the centerline of the left portion of the embankment section down to competent bedrock. The wall interrupted the progression of foundation erosion, but post construction monitoring, instrumentation readings, and persistent wet areas downstream showed that seepage paths under or around the wall continued. A second cut-off wall upstream of the first was constructed between 2007 and 2013, extending nearly the entire length of the embankment and up to 75 feet (22.9 m) deeper than the original wall. Cost of the second wall and other concurrent rehabilitation efforts reached nearly $600 million. Exploratory grouting beneath the concrete masonry section of the dam in 2012 resulted in low grout volume takes, so no further remediation efforts below the masonry dam were conducted. The original construction photographs and foundation reports for the concrete masonry section of Wolf Creek Dam instill confidence that the designers and builders of the monoliths took adequate, if not excessive measures to ensure that all the monoliths were founded on competent bedrock. These measures included extensive borehole investigations both prior to and during excavation, efforts to locate, delineate, remove, and clean all karst solution channels, the removal of all loose rock, grouting in the foundation and side vertical faces, large stair-step faces on the left abutment, extended excavations to remove soft beds, final manual cleaning of rock surfaces, and the careful documentation of foundation preparations. These measures do not guarantee that seepage issues will not develop under the concrete dam over time, but they do show with reasonable certainty that the monoliths were originally founded on competent bedrock, and that future seepage issues are either unlikely or will be significantly inhibited by the preparation made to the foundation prior to the construction of the concrete monoliths.