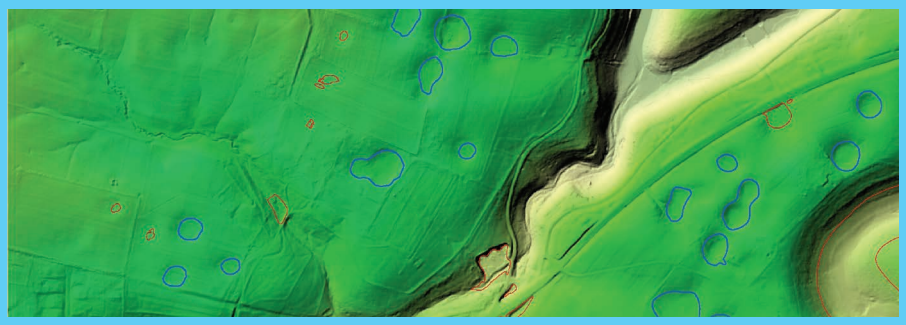
KENTUCKY INTERAGENCY GROUNDWATER MONITORING NETWORK

ANNUAL REPORT 2018–2019



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November 2019

Kentucky Interagency Groundwater Monitoring Network

Annual Report

July 2018–June 2019

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Introduction

Groundwater is a vital natural resource used extensively throughout Kentucky for domestic, public, agricultural, commercial, and industrial purposes. Because of its connection with rivers, lakes, and wetlands, groundwater is also essential for surface-water resources and the health of their ecosystems. Systematic monitoring of groundwater quality and quantity is therefore of paramount importance to the health and well-being of the commonwealth and its citizens.

In 1998, the Kentucky General Assembly enacted KRS 151.625, directing the Kentucky Geological Survey at the University of Kentucky to establish a long-term groundwater monitoring network for the state. That same year, the General Assembly also established, through KRS 151.629, the Interagency Technical Advisory Committee on Groundwater, to advise and assist KGS in the development, coordination, and implementation of the groundwater monitoring network. The following agencies and organizations were asked to appoint a representative to the Interagency Technical Advisory Committee:

- Kentucky Department for Environmental Protection
- Kentucky Department for Natural Resources
- Kentucky Department of Agriculture, Division of Environmental Services
- Kentucky Division of Conservation
- Kentucky Division of Forestry
- Kentucky Division of Public Health Protection and Safety
- Kentucky Division of Waste Management
- Kentucky Division of Water
- University of Kentucky, College of Agriculture, Food and Environment
- University of Kentucky, Kentucky Geological Survey
- University of Kentucky, Kentucky Water Resources Research Institute
- U.S. Geological Survey, Ohio-Kentucky-Indiana Water Science Center.

Working cooperatively with the Kentucky Geological Survey, these participating agencies have made, and continue to make, significant contributions to the collection of groundwater data, and the understanding and assessment of the state's water and related environmental resources throughout the 20 years of the Network's existence. Annual reports summarizing these activities since 1999 are available on the Network website at www.uky.edu/KGS/water/gnet.

The following sections summarize projects related primarily to groundwater that were conducted by ITAC member agencies during the 2018-19 fiscal year. Surface-water projects are listed in the "Other Activities" section of this report. Additional information about any of these projects can be obtained by contacting the reporting agency.

Groundwater Data Collection

Groundwater data are generated through many avenues. Drilling wells, collecting and analyzing water samples, measuring water levels in wells, and mapping recharge and discharge areas of karst systems provide the fundamental data needed to determine current groundwater quality, detect changes over time, and evaluate hydrogeologic hazards.

Kentucky Division of Water, Watershed Management Branch, Groundwater Section

The Groundwater Section of the Kentucky Division of Water's Watershed Management Branch carries out an active groundwater sampling and analysis program, and conducts research to address issues related to groundwater quantity, quality, and use. These studies range in scope from statewide to basin management unit (BMU) scale (Fig. 1). Table 1 lists the number of sites by physiographic region and basin management unit and Figure 2 shows the locations of the sites within physiographic regions. Table 2 lists the AKGWA numbers (Assembled Kentucky Ground Water)—a Kentucky Division of Water identification number—map numbers, and sampling frequency of the Network sites shown in Figure 2.

The DOW also addresses and protects groundwater through the certification of water-well and monitoring-well drillers, through education and outreach, and by providing assistance with citizen complaints and requests for technical assistance. The following information characterizes program activities that have been conducted during fiscal year 2018-19.

Ambient Groundwater Monitoring Network. Regularly scheduled sampling continued for the statewide Ambient Groundwater Monitoring Network. This fiscal year, 129 samples were collected from 52 permanent sites (25 wells and 27 springs)

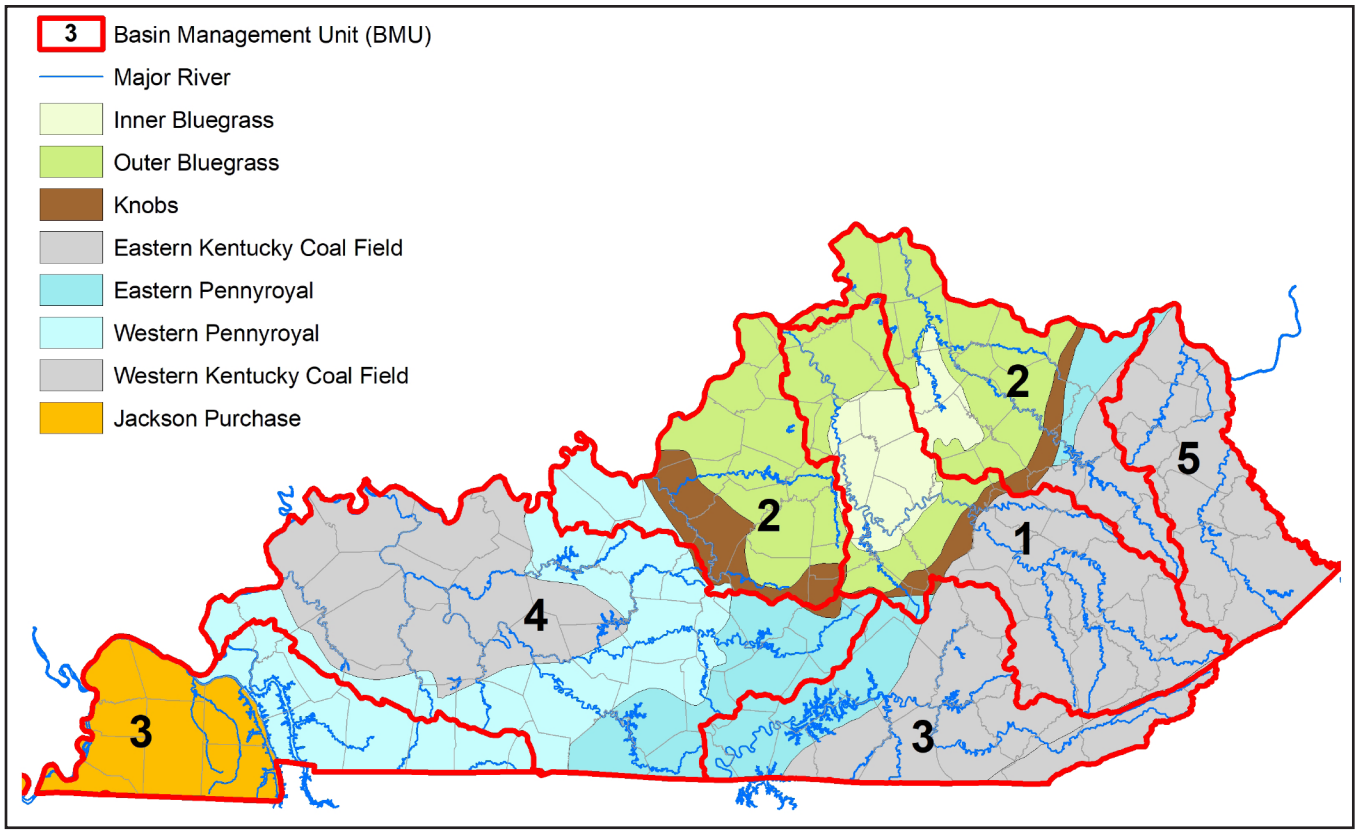

Figure 1. Major rivers, basin management units, and physiographic regions in Kentucky.

Table 1. Spatial distribution of permanent groundwater monitoring sites.			
Region	*Number of Sites*	*Basin Management Unit*	*Number of Sites*
Bluegrass	11	1—Kentucky River	11
Eastern Kentucky Coal Field	8	2—Salt and Licking Rivers	7
Ohio River alluvium	10	3—Four Rivers, Upper and Lower Cumberland	22
Mississippian Plateau	23	4—Green and Tradewater Rivers	15
Western Kentucky Coal Field	2	5—Big and Little Sandy Rivers and Tygarts Creek	5
Jackson Purchase	6		

across the state, of which 47 are water wells and 82 are springs (Fig. 3). Nineteen of these sites (14 water wells and five springs) are public water suppliers. All groundwater-quality data are uploaded to the Groundwater Data Repository and made available to the public. Groundwater-quality data were also provided to numerous persons through information requests, and used in-house for statistical analyses for regional and watershed-based groundwater assessments.

The Groundwater Section works with the Kentucky Geological Survey on developing a water-level monitoring and flow-measurement network. A joint endeavor between KGS, Hardin County District No. 1, and the DOW to collect groundwater-flow data from the Head of Rough Spring in Hardin County continues to provide essential data for this public drinking-water source.

The Kentucky Division of Water considers strategies for expanding the Ambient Groundwater

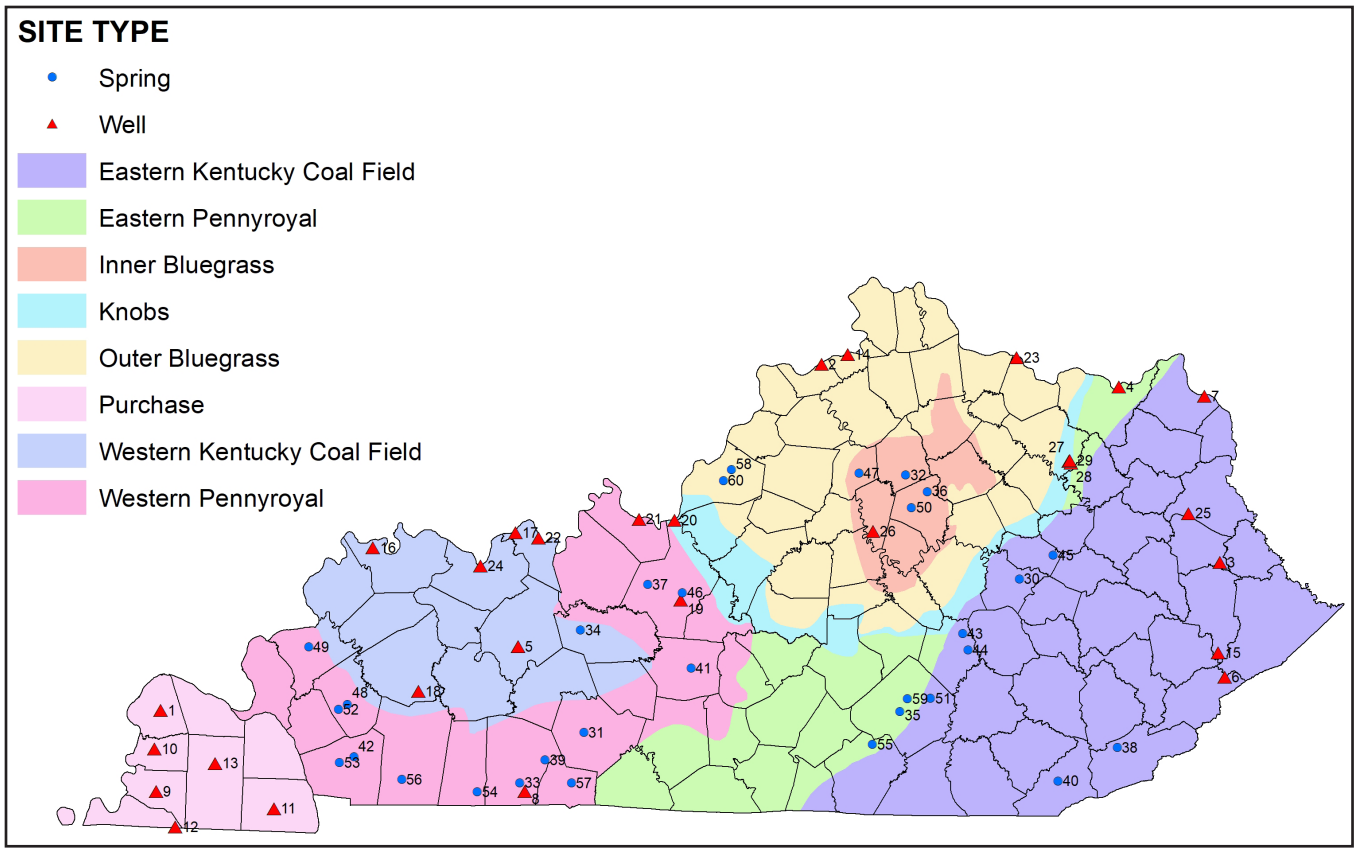

Figure 2. Kentucky Interagency Groundwater Monitoring Network sites maintained by the Kentucky Division of Water. Table 2 gives map numbers, AKGWA numbers, and sampling frequency for these sites.

Table 2. AKGWA numbers and sampling frequency for the Network sites shown in Figure 2. Sites corresponding to the AKGWA numbers can be located using the Kentucky Groundwater Data Repository website. Q = quarterly. M = monthly. 5Q = every fifth quarter. 2Q = every second quarter. Pest. MOA = Pesticides Memorandum of Agreement. AKGWA numbers starting with "0" are water wells, starting with "8" are monitoring wells, and starting with "9" are springs. Sample times vary.

Map No.	*AKGWA No.*	*Sample Frequency*	*Map No.*	*AKGWA No.*	*Sample Frequency*	*Map No.*	*AKGWA No.*	*Sample Frequency*
1	00000811	5Q	21	00061854	Q	41	90000798	M
2	00007133	5Q	22	00061858	Q	42	90000854	2Q
3	00012311	Q	23	00065002	Q	43	90001020	Q
4	00014293	2Q	24	00065149	Q	44	90001051	5Q
5	00019489	5Q	25	00068511	Q	45	90001134	Q
6	00028100	5Q	26	00069574	Q	46	90001137	Q
7	00029505	2Q	27	80046811	2Q	47	90001143	M
8	00029983	Pest. MOA	28	80046812	2Q	48	90001145	2Q
9	00033887	5Q	29	80046813	2Q	49	90001149	2Q
10	00033904	5Q	30	90000045	Q	50	90001161	Q
11	00033965	5Q	31	90000054	Q	51	90001254	5Q
12	00033972	5Q	32	90000055	M	52	90001343	2Q
13	00037330	5Q	33	90000315	Pest. MOA	53	90001344	2Q
14	00037376	5Q	34	90000456	5Q	54	90001475	Pest. MOA
15	00039374	5Q	35	90000544	5Q	55	90001822	Q
16	00040944	Q	36	90000552	Q	56	90001857	Q
17	00041471	Q	37	90000702	Q	57	90002823	Pest. MOA
18	00042984	Q	38	90000703	Q	58	90002934	Q
19	00043253	5Q	39	90000705	M	59	90003064	5Q
20	00055957	Q	40	90000710	5Q	60	90003355	Q

Figure 3. Groundwater Section personnel record pH, conductivity, and temperature at the Robey Farms monitoring network site in Logan County.

Monitoring Network in order to further characterize groundwater for the state of Kentucky.

A new site was added to the Northwest sampling run, in order to replace the loss of the West Point well monitoring site. The new site is the Fort Knox well no. 13. Located near the Ohio River in Hardin County, this well is part of a series of large, turbine-pumped wells that supply water to the Fort Knox area. The system uses a barrier pumping method to control hydrocarbon migration from an identified plume within the aquifer. The well is operated by both the Hardin County Water District and the Louisville Water Co. Our contacts for this site are Jim Smith from the Louisville Water Co. and Brett Pyles from Hardin County Water District No. 1. Additional wells may be sampled in the future.

Pesticides Memorandum of Agreement Project (Pest MOA). The Pest MOA with the Kentucky

Department of Agriculture was renewed for fiscal year 2018-19. The MOA funds four permanent sampling sites (three springs and one well) in the Mississippian Plateau Region of western Kentucky. Each site was sampled quarterly for a total of 16 samples during the fiscal year. Pesticide data from these sites are submitted to the Department of Agriculture annually.

Complaint and Technical Assistance Sampling. Groundwater Section personnel respond to complaints and requests for technical assistance concerning groundwater, and perform investigations as requested by the public, industry, and other government agencies (Fig. 4). In fiscal year 2018-19, the Groundwater Section responded to 30 complaints and requests for technical assistance. This resulted in 10 samples being collected from eight wells and two springs. In cases where samples are not collected, recipients receive on-site technical assistance or their domestic water source is inspected.

Nonpoint-Source Groundwater Assessments. The Groundwater Section is currently involved in three nonpoint-source studies. These projects are in various stages, from review of the final report to area reconnaissance and site selection. Retirement of research personnel and the loss of staff through attrition have resulted in much of this work being put on hold for most of the 2018-19 reporting period. With the addition of three new staff members, however, work is expected to resume.

The *Statewide Pathogens Study* determines the occurrence of pathogens in groundwater, particu-

Figure 4. Groundwater Section personnel collect a sample from a domestic water well in Bullitt County in response to the homeowner's request for technical assistance.

larly in wells and springs providing domestic water supplies. A total of 210 sites—202 wells and eight springs—across Kentucky were sampled for total coliform, *E. coli,* iron-related, sulfate-reducing, and slime-forming bacteria, as well as caffeine. Results indicate that the presence of bacteria correlates with the type of well construction and maintenance practices. A secondary goal during sample collection is to educate well owners about proper maintenance and disinfection practices. A report on the results of this study is under administrative review and is expected to be completed by Dec. 30, 2019.

The *South-Central Karst Study* has expanded karst groundwater mapping south of Lake Cumberland. The study area covers parts of Pulaski, Clinton, Wayne, and McCreary Counties. Current work focuses on groundwater dye tracing and delineation of karst basins. Thus far, 48 tracer tests have been recovered at 40 springs. Further delineation of spring basins is needed, as well as selection of large-spring monitoring sites. The project will use an integrated surface-water and groundwater assessment approach. Field work is expected to resume during fiscal year 2019-20.

The study on *Onsite Sewage Disposal Systems and Their Potential Effects on Groundwater* will evaluate potential impacts of home septic systems on groundwater. The study has passed the literature-review stage, and site selection and evaluation are ongoing. Seven sites have already been evaluated, and some initial water-quality sampling has been conducted. Field work is expected to resume during fiscal year 2019-20.

Special Projects

Burgin Sinkhole Flooding. The City of Burgin in Mercer County requested technical assistance concerning sinkhole flooding issues (Fig. 5). The mayor and city council were concerned that the recent installation of a new sanitary sewer system had somehow exacerbated sinkhole flooding at several locations throughout the community. Burgin is located in the Inner Bluegrass physiographic region, and local geology there consists of the Ordovician Tanglewood and Grier Members of the Lexington Limestone. A preliminary investigation indicated that sinkhole flooding in Burgin occurs in a dry tributary valley that drains to Burgin Spring (Fig. 6). This tributary valley is underlain predominantly by the Grier Limestone Member of the Lexington Limestone and is characterized by numerous sinkholes and other karst features. Surface water in the valley has been pirated underground through the development of the karst landscape.

Sinkhole flooding occurs when surface-water inflow, predominantly from rainfall, overwhelms the subsurface groundwater aquifer system. This results in a reverse-flow phenomenon in which groundwater wells up from the subsurface via sinkholes and other karst features, reactivating the old surface-water flow system in response to the lack of storage within the aquifer.

Groundwater data collected for Burgin Spring from May 3, 2018, through Sept. 29, 2018, indicate that groundwater discharge from the spring is intimately tied to the amount of precipitation that falls within the Burgin Spring groundwater basin. An evaluation of rainfall, discharge rates at Burgin Spring, and sinkhole flooding in the area indicates that when rainfall over consecutive days is equal to or greater than 3 inches, sinkhole flooding occurs. When rainfall over consecutive days is equal to or greater than 5 inches, catastrophic flooding of the entire area of interest occurs.

Based upon the results of the preliminary investigation, Groundwater Section personnel were unable to determine if construction of the city sewer system, especially construction of the pump station at Peach and East Water Streets, had in any way affected groundwater flow to Burgin Spring, or was contributing to sinkhole flooding within the area of interest. This was mainly because subsurface data and as-built construction plans for the pump station were not available. Lack of access to the subsurface flow system that drains to Burgin Spring was also a factor. Groundwater Section personnel involved in the study recommended a quantitative study of the relationship of sinkhole flooding to precipitation events.

Water Well Abandonment, Scott County, Kentucky. Groundwater Section personnel responded to a complaint from a homeowner that for approximately one year, dark, foul-smelling water had been accumulating in the backyard of his property. A mix of residential and agricultural activities take place in the area. The local water and wastewater utilities had been contacted about the discharge

Figure 5. Sinkhole flooding in Burgin, Ky.

of water from the seep, and both utilities determined that the discharge was not related to their infrastructure. A bacterial analysis of a sample from the seep indicated a most probable number of 809 colonies of *E. coli* per 100 milliliters of water. A reconnaissance of the area identified a small farm of less than 10 acres located upgradient of the groundwater seep. An inspection of the farm identified several things that could be contributing to the discharge of contaminated water on the neighboring property, such as abandoning an in-ground swimming pool by filling it with construction demolition debris and household waste, and a hand-dug water well at the farm in which offal and animal carcasses had been disposed of.

An order to cease and desist was issued to the farm owner, and the homeowner met with representatives of the DOW's Division of Waste Management and the Kentucky Department of Agriculture to develop a plan, which was agreed upon by all parties involved. The plan mandated the proper abandonment of the in-ground swimming pool, removal and reburial of the offal and animal carcasses from the well, and the proper abandonment of the water well per Kentucky's well abandonment regulations.

Groundwater Protection Plan Program. The Groundwater Protection Plan Program focuses on public outreach and education regarding activities that can threaten groundwater. This program requires that best management practices for defined activities be implemented to protect groundwater. Emphasis has been placed on offering on-site technical assistance to facilities and the public to identify best management practices needed to protect the groundwater from activities that have the

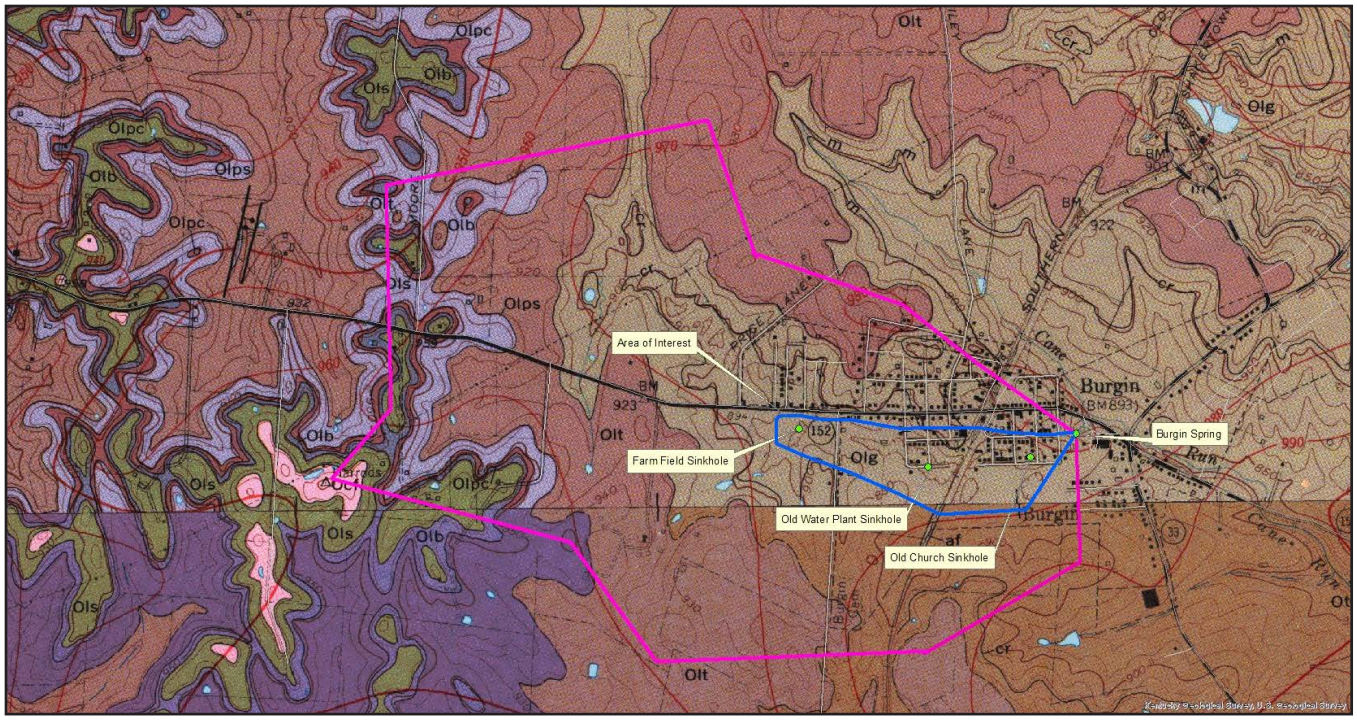

Figure 6. Burgin Spring and associated sinkholes. The area of interest (outlined in blue) is located in the estimated recharge area of Burgin Spring.

potential to contaminate groundwater at homes or facilities. A wide variety of activities conducted by individuals and companies throughout Kentucky require groundwater protection plans. These activities are defined in 401 KAR 5:037. Table 3 provides data on groundwater protection plans received, reviewed, and approved, and the number of field reviews completed for fiscal year 2018-19. Numbers are somewhat down from previous years, but the position of the program coordinator was vacant from August 2018 until August 2019, when a new employee was hired.

Certified Well Drillers Program. Use of domestic wells remains consistent throughout Kentucky. The Eastern Kentucky Coal Field and Jackson Purchase Region have the greatest percentage of households that rely on domestic wells as their primary source for drinking water. In the 2018-19 fiscal year, 507 wells were drilled and reported to DOW. Plugging records were submitted for 494 decommissioned wells during this same period.

The Groundwater Section issued licenses to 155 certified drillers: 38 water-well, 61 monitoring-well, and 57 dual licenses. The official licensing renewal period began July 1, 2018, and ended Aug. 31, 2018, but drillers are allowed to continue to submit new and renewal applications beyond the end of the official reporting period without penalty.

Groundwater Section personnel assist the Kentucky Groundwater Association with their annual Drillers' Tradeshow and Workshop. Information on accessing and navigating the Energy and Environment Cabinet's redesigned website was provided at this year's tradeshow, including how to access the eForm for well-records submissions

Table 3. Statistics for the Groundwater Protection Plan Program during fiscal year 2018-19.

Month and Year	July 2018	Aug. 2018	Sept. 2018	Oct. 2018	Nov. 2018	Dec. 2018	Jan. 2019	Feb. 2019	March 2019	April 2019	May 2019	June 2019	*Totals*
Number Received	2	1	1	1	0	0	10	4	11	1	1	2	33
Number Reviewed	2	1	1	0	0	0	0	1	0	1	0	0	6
Number Approved	2	0	0	0	0	0	0	0	0	1	0	0	1
Field Reviews	0	0	0	0	0	0	1	0	0	0	0	0	1

and how to use the new paper forms now required by approved changes to Chapter 6 regulations. The new certified driller web application has been a rousing success; it allows users to find a certified driller at the click of a mouse. Approximately 80 drillers received their annually required continuing education credits at the tradeshow; these credits are needed to meet licensure requirements.

KRS Chapter 223 was amended during this year's legislative session to include certification of water- and monitoring-well driller assistants. The new requirements became effective July 1, 2019. This change to the law has necessitated changes to 401 KAR 6:001, 6:310, 6:320, and 6:350; the changes have been filed with the Legislative Research Commission and are currently undergoing a public comment period. Barring unforeseen circumstances, the amended regulations will become effective in November of 2019.

Public Outreach. The Groundwater Section explores new ways of reaching the public to increase groundwater awareness and to educate the public on groundwater issues that may affect them. Groundwater Awareness Week and Protect Your Groundwater Day are two occasions during which the citizens of the commonwealth receive information about maintenance and protection of their private drinking-water wells, as well as protection of the groundwater resource. During fiscal year 2018-19, Groundwater Section personnel participated in regional Envirothon training for students by providing information on Kentucky's geology and hydrogeology. They also staffed a booth at Wolf Creek Dam during Eco–Day to discuss the interconnectivity of groundwater and surface water, and they participated in this year's UK College of Agriculture 4H Environmental Camp in Laurel County, where they discussed geology and hydrogeology concepts with 4H campers ages 9 to 14.

U.S. Geological Survey, Ohio-Kentucky-Indiana Water Science Center

USGS Climate Response Network. The U.S. Geological Survey, as directed by Congress, is establishing a national climate-response network of groundwater wells. Each climate division in the country is to have at least one real-time monitoring well in a climate-responsive aquifer that is not affected by groundwater withdrawals or interactions with nearby surface water. Kentucky has one climate-response network well in each of its four climate divisions. The wells are in Graves, Larue, Fayette, and Bell Counties. Data from these wells, compiled by the USGS's Ohio-Kentucky-Indiana Water Science Center, describe the natural variability in groundwater levels attributable to weather and climate. These data are available to the public through websites operated by the USGS (waterdata.usgs.gov/ky/nwis/current/?type=gw) and the USGS Climate Response Network (groundwaterwatch.usgs.gov).

Monitoring of Groundwater Resources of the Northeast Portion of the Ohio River Alluvial Aquifer, Near Louisville, Jefferson County. The USGS, in cooperation with the Louisville Water Co., monitors groundwater levels in the northeastern part of the alluvial aquifer near Louisville, in Jefferson County. Tasks and field activities are designed to improve understanding of the various aspects of groundwater and surface-water interaction, especially riverbank infiltration. The USGS collects groundwater-level data and infiltration rates for the water company's riverbank filtration system, monitors groundwater quality to ensure proper wellhead protection planning, evaluates groundwater-level data to estimate the contributing areas to the riverbank filtration system, measures streambed permeability, and develops groundwater flow-modeling capabilities.

West Point Well Field Monitoring, Hardin and Meade Counties. Water treatment facilities at Fort Knox receive source water from drinking-water supply wells located along the Ohio River near West Point. The alluvial deposits in this area are typically 100 feet thick and are underlain by bedrock formations known to contain natural gas and high chloride concentrations. Previous investigations by the USGS and the U.S. Army have determined that improperly abandoned gas wells have provided a means for brines, under pressure within the underlying bedrock, to migrate upward and affect the groundwater in the alluvial deposits. The USGS is collecting data in the well field to monitor groundwater conditions. These activities include measuring groundwater levels

and chloride concentrations, providing surveillance of active and abandoned gas wells, collecting geophysical information to monitor chloride movement, and simulating groundwater flow for wellhead-protection management strategies.

Monitoring Groundwater Levels for a U.S. Army Corps of Engineers Earthen Dam Restoration Project at Rough River Lake, Breckinridge and Grayson Counties. The Louisville District of the U.S. Army Corps of Engineers is rehabilitating a large-scale earthen dam at Rough River Lake in Breckinridge and Grayson Counties. As part of the effort to track the progress of the restoration, the USGS monitors groundwater levels in 60 piezometers equipped with continuously recording pressure transducers. Changes in pressure are also monitored with vibrating-wire transducers grouted in place at 60 sites throughout the dam. The Corps uses these data to determine priorities for repair and to monitor groundwater-level changes related to construction activities.

Kentucky Department of Agriculture

The Kentucky Department of Agriculture, Technical Support Branch, receives monitoring data from the Division of Water under a memorandum of agreement. The memorandum covers 16 samples yearly from four sites. This sampling is supplemented by the DOW's Ambient Groundwater Monitoring Network.

Kentucky Geological Survey

During 2018-19, Water Resources Section staff worked on projects to characterize groundwater and surface water, started the previous year, and began several new projects in collaboration with the University of Kentucky Department of Earth and Environmental Sciences and the Kentucky Division of Water.

Aquifer Designation Project. A project to identify and characterize the aquifers used by permitted water-supply wells will conclude at the end of 2019. This cooperative project between KGS and the Division of Water is funded by the U.S. Geological Survey's Water-Use Data and Research Program. Included in this project are wells that withdraw some of the largest amounts of groundwater in the state. An online map will provide locations and construction details for permitted water-supply wells in Kentucky and information about their associated aquifers. A webpage will allow, for the first time, a seamless interactive format containing detailed data about aquifer and water-well characteristics in the Ohio River alluvium, one of the most productive and heavily used aquifers in Kentucky; these data were published previously in the U.S. Geological Survey's Hydrologic Atlas map series. Making these data more accessible and easily understood will help state and local water-resource managers better develop and protect Kentucky's groundwater resources. The project was funded through June of 2019.

Karst Spring Investigation at The Homeplace on Green River, Campbellsville. By the end of 2019, an investigation of sinkhole drainage characteristics and the karst hydrogeology at The Homeplace on Green River farm near Campbellsville will be completed. The project was funded by a Conservation Innovation Grant from the Natural Resources Conservation Service. The Kentucky Geological Survey collected spring discharge data and conducted hydrogeologic mapping using dye-tracer tests to delineate groundwater flow paths and basin boundaries for karst springs on The Homeplace property (Figs. 7–8). The Crawford Hydrology Laboratory of Western Kentucky University analyzed the dye-tracer tests. A detailed statistical analysis of the spring's discharge characteristics, including variability in flow, water temperature, specific conductance, and other parameters, and their relation to precipitation, is being conducted and will be the subject of further investigation. The data collected during this project will help with planning for possible future water-quality sampling to evaluate the effects of agricultural best management practices at the farm. The results of this project should also help inform agricultural resource managers, scientists, and others how edge-of-field monitoring techniques for assessing water quality and soil health at Kentucky farms must be modified where karst is present or surface runoff from cropped fields is controlled by sinkholes.

Machine Learning in LiDAR-Based Sinkhole Mapping. Junfeng Zhu and Adam Nolte are using high-resolution LiDAR topographic data to improve sinkhole mapping. To learn how to pro-

Figure 7. Weir installed to measure flow rate at a karst spring at The Homeplace on Green River as part of a project to characterize the karst hydrogeology of the area.

Figure 8. Kentucky Geological Survey Water Resources Section staff Steve Webb, Ben Tobin, and Adam Nolte prepare to inject fluorescent dye into a sinkhole at The Homeplace on Green River near Campbellsville.

cess LiDAR data more efficiently, they worked in collaboration with Nathan Jacobs, an associate professor of computer science at the University of Kentucky. They explored different machine-learning methods and developed a neural network model to automatically identify sinkholes. The model expedited the LiDAR data processing, and they were able to map approximately 15,000 sinkholes in Anderson, Clark, Franklin, Garrard, Harrison, Mercer, Montgomery, Owen, Scott, Shelby, and Trimble Counties during the 2018-19 fiscal year; most of these counties are in the Bluegrass Region.

The collaboration with Jacobs also benefited his fall 2018 machine-learning class: Zhu provided LiDAR data from four central Kentucky counties to the class, and the students were challenged to use any machine-learning tools to identify sinkholes (Figs. 9–10).

Understanding Spatial Variability of Methane in Groundwater in Eastern Kentucky. Steve Webb and Marty Parris are collaborating with Dr. Andrea Erhardt and graduate student Cristopher Alvarez of the University of Kentucky Department of Earth and Environmental Sciences on an investigation to improve characterization and understanding of the spatial variability of methane in groundwater in eastern Kentucky. The Cambrian Rogersville Shale in eastern Kentucky has the potential to become a major shale-gas play, and a better understanding of the occurrence of methane in groundwater is critical to evaluating potential impacts of shale-gas development on the shallow groundwater in the region. Funded by the U.S. Geological Survey through the Kentucky Water Resources Research Institute, this study is part of a continuing effort by KGS to characterize and understand baseline groundwater conditions in an area of increasing unconventional oil and gas development. During April and May 2019, Alvarez and Webb, assisted by Adam Nolte, sampled 18 wells in Floyd, Knott, and Magoffin Counties. The samples were analyzed at the KGS analytical laboratory and Earth

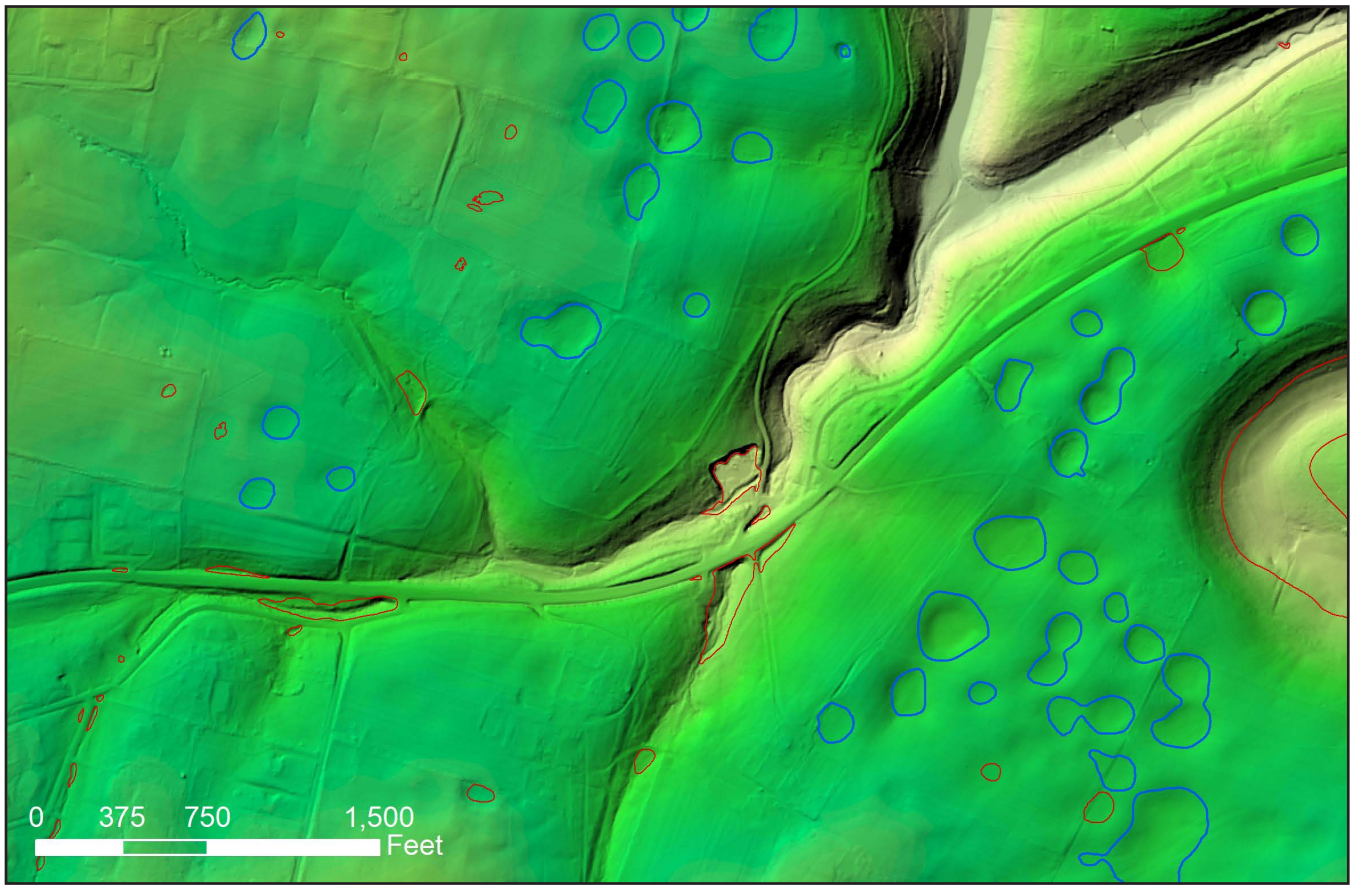

Figure 9. Shaded-relief map showing surface depressions that are either sinkholes (blue) or not sinkholes (red).

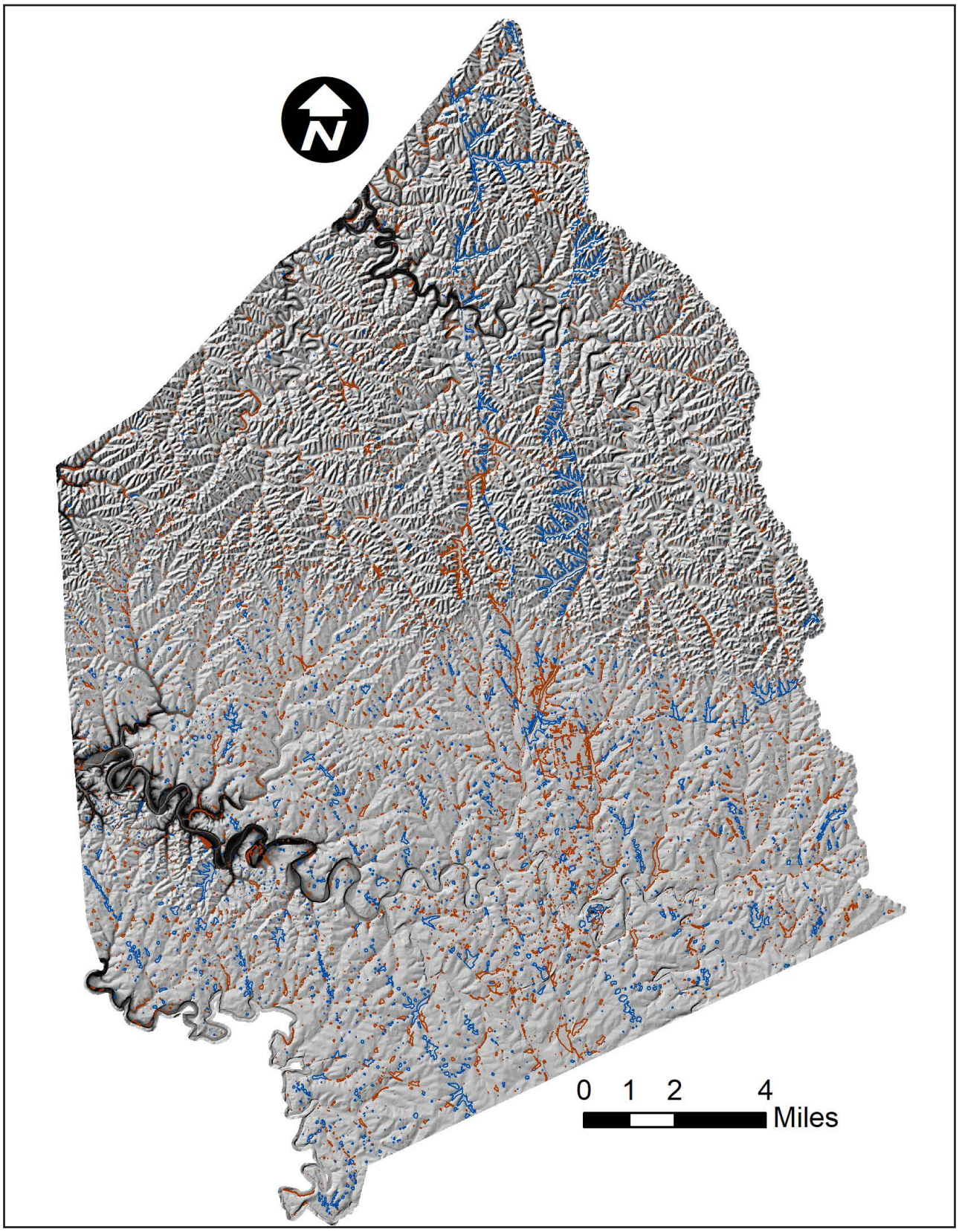

Figure 10. Classification results by a neural network model for Scott County. The neural network model automatically classifies topographic features as either sinkholes (blue) or not sinkholes (red).

and Environmental Sciences' Stable Isotope Geochemistry Laboratory for major and minor ions, dissolved gases, and isotopic composition. The team planned to sample eight more wells during the summer of 2019.

Groundwater Modeling Activities for Paducah Gaseous Diffusion Plant Site. Hydrogeologist Junfeng Zhu is providing scientific technical assistance on a project funded by the U.S. Department of Energy through the Kentucky Research Consortium for Energy and Environment to assess groundwater remediation plans at the Paducah Gaseous Diffusion Plant. Zhu is providing an independent review of computer-simulated groundwater models created by private contractors to assist in removal and treatment of groundwater contaminated by radionuclides and chlorinated solvents. The most recent version of the model incorporates new field data, but only simulates groundwater flow. Zhu will evaluate the model's capability of replicating the migration history of groundwater contaminant plumes at the site.

Kentucky Groundwater Data Repository and Monitoring Mandates. The Kentucky Geological Survey is legislatively mandated to serve as the state's official repository for groundwater information (KRS 151.035) and oversee establishment of a long-term groundwater-monitoring network (KRS 151.625).

KGS works with colleagues at the Kentucky Division of Water to periodically update the data in the Kentucky Groundwater Data Repository. One of KGS's two water-related legislative mandates, the Repository is a web-accessible digital database containing data for 106,078 sites across Kentucky, comprising 43,361 domestic wells, 1,468 public wells, 882 industrial wells, 4,453 agricultural wells, 36,307 monitoring wells, and 5,419 springs. Most data are derived from water-well construction records required under the Kentucky Water Well Drillers Certification Program and from water-quality analyses conducted by various departments of the Kentucky Energy and Environment Cabinet; data are also contributed from other sources, including KGS, researchers from UK and other universities, and environmental and geotechnical consultants. The Division of Water also routinely forwards scanned documents relating to public and private water wells or karst springs being used for drinking-water supplies, irrigation, or other purposes. Approximately 80,000 scanned records are stored and available from the Repository (www.uky. edu/KGS/water/research/gwreposit.htm).

A grant from the U.S. Geological Survey's National Geological and Geophysical Data Preservation Program is providing funding to add lithologic data from scanned water-well construction records to the Repository. Such lithologic data from more than 33,000 wells were entered into the database prior to 2002, but data entry was discontinued then because of funding cuts. Student interns will be hired during the 2019-20 fiscal year to resume entering these data, under the supervision of the new manager of the Repository, Sarah Arpin.

Activities in the KGS Analytical Chemistry Laboratory. The Kentucky Geological Survey analytical laboratory supports the research of KGS geologists, faculty and graduate students from the University of Kentucky, and students from other Kentucky universities by providing analytical expertise, as well as training on and access to analytical instruments.

Lab personnel assisted 31 users of the University of Kentucky's shared-use X-ray diffractometer, and trained a postdoctoral scholar and several students and provided instrument time on the lab's carbon analyzer and inorganic coulometer. Two graduate students in the UK Department of Earth and Environmental Sciences used the wavelength X-ray fluorimeter this year for their research projects.

The lab added a portable gas chromatograph this year, and two methods for its use have been developed: a low-level soil-gas method that allows low-molecular-weight hydrocarbons to be measured (in parts per million) and a higher-concentration gas method that will be used to determine natural-gas levels for a project to analyze the impacts of abandoned wells. A student in the Department of Earth and Environmental Sciences used both methods this spring to quantify methane, ethane, and propane concentrations for his thesis project.

The lab provides analysis for several KGS water-monitoring projects, three projects by the UK Department of Civil Engineering that focus on

water chemistry from Cane Run, and water monitoring and testing for Kentucky River Watershed Watch. The lab analyzes coal and coal-ash samples for rare earth elements, analyzing more than 1,500 digested and leached samples for that project in the last 12 months. Lab personnel also measured radon levels at many sites in eastern Kentucky.

Ten unique groups and individuals toured the labs this year, and a student from Lexington Catholic High School was mentored, which allowed her to gain lab experience for her senior project.

Watershed Pour-Point Elevations to Evaluate Depth of Fresh Groundwater. Research by Ethan Davis, Marty Parris, and Jerrad Grider reexamined distribution of deep fresh groundwater in the Cumberland Plateau of Eastern Kentucky. In 1966, the U.S. Geological Survey and Kentucky Geological Survey published the "Fresh-Saline Water Interface Map of Kentucky," by H.T. Hopkins. The map has been used by oil and gas drillers to determine how deep casing should be set to protect groundwater. To create this map, Hopkins used the total depth of domestic water wells to estimate the depth of the fresh-saline water interface. Because domestic water wells are rarely deep enough to penetrate saline water, however, Hopkins's map in most settings underestimates the depth of the fresh-saline water interface. Moreover, the number of wells available to Hopkins in 1966 was far less than what is currently available through the Kentucky Groundwater Data Repository (kgs.uky.edu/kgsweb/DataSearching/watersearch.asp).

Davis, Parris, and Grider recognized the need for a new, higher-resolution map, especially since horizontal drilling and hydraulic fracturing are being used now to develop shallow oil reservoirs in northeastern Kentucky. They defined a 14-county study area in eastern Kentucky where hydraulic fracturing was occurring or likely to occur in the future. They used a dataset of 4,824 wells compared with Hopkins's dataset of 50 wells. Davis and his co-researchers excluded wells in which total depths were less than the elevation of watershed pour points, as defined by 14- and 11-digit hydrologic unit codes, because, by definition, domestic water wells with total depths shallower than the pour point cannot represent the deepest fresh water in a drainage basin. Using this more robust and filtered dataset indicated that the deepest observed fresh water was, on average, 147 feet deeper than the 1966 estimate. In eastern Lawrence County alone the difference exceeded 500 feet (Fig. 11).

This research was published as KGS Report of Investigations 7 (series 13), "Using Watershed

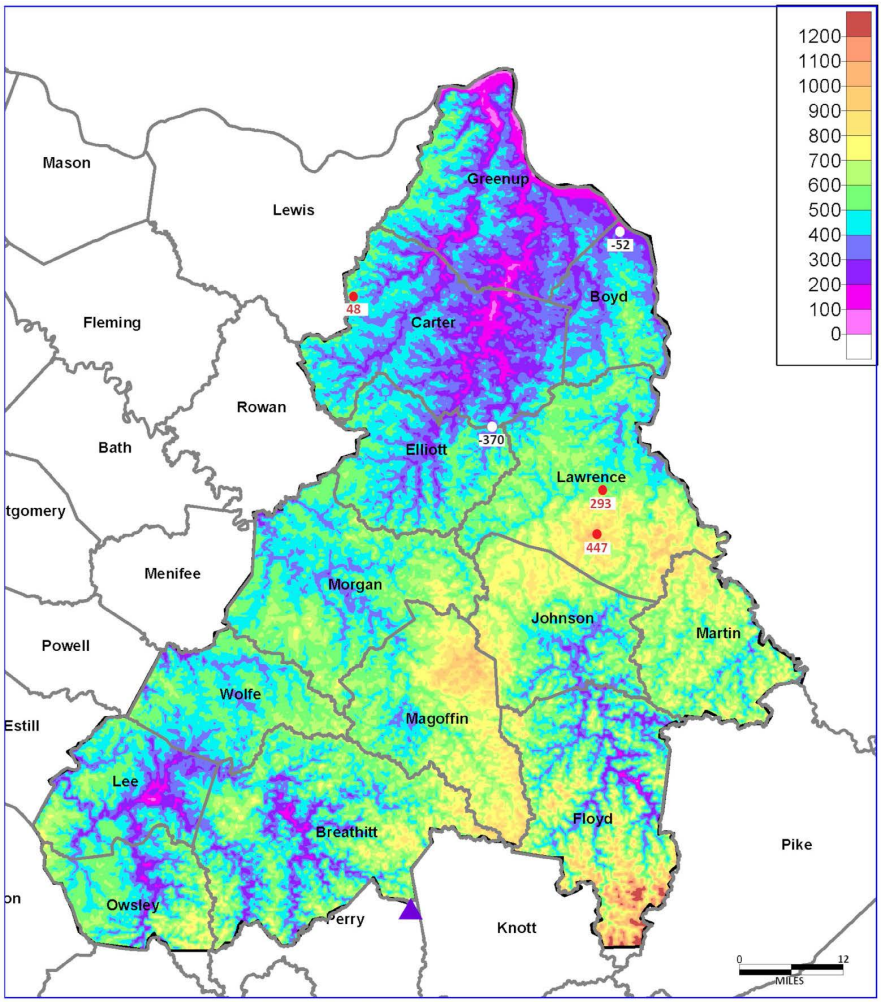

Figure 11. Estimated depth from the ground surface to the deepest observed fresh water as derived from a dataset of the deepest well in each 11-digit hydrologic unit in the study area.

Pour-Point Elevations to Evaluate the Base of Fresh Groundwater in the Cumberland Plateau of Eastern Kentucky" (kgs.uky.edu/kgsweb/olops/pub/kgs/RI07_13.pdf).

Invertebrates and Cave Systems. Ben Tobin, working with two UK Department of Biology undergraduate students who received credit for independent study, began quantifying relationships between karst groundwater resources and cave-adapted ecosystems during the fiscal year. One student assessed the relationship between land-use patterns and diversity of cave-adapted invertebrates throughout Kentucky. Although no statistically significant impact was found, the analysis will provide the foundation for future work in the state, including ongoing periodic monitoring in caves of Estill County. The other student assessed spatial patterns in cave-adapted invertebrates, using an existing dataset from Sequoia and Kings Canyon National Parks to quantify patterns in diversity and potential causal mechanisms for those patterns. The work has promise to provide a broader understanding of interconnectivity of karst groundwater basins. The mobility of species in the subsurface allows us to begin quantifying connections between groundwater basins that are not as easy to track using traditional methods, such as dye tracing. This work may improve our understanding of the potential for groundwater contamination under varying precipitation regimes and patterns. To further test these methods, Tobin, in collaboration with the UK Stable Isotope Geochemistry Laboratory and researchers from the U.S. Geological Survey and the University of Alabama-Huntsville, has been awarded funding from the U.S. Fish and Wildlife Service.

Kentucky Division of Mine Reclamation and Enforcement

The Field Support Section of the Division of Mine Reclamation and Enforcement investigates reports of diminished quality or quantity of groundwater at the request of citizens of the commonwealth. In addition, the Division investigates surface water in connection with diminished quality, stream loss, or flooding. Investigations are also conducted as a result of landslides, methane migration, or other problems related to coal mining in the Eastern and Western Kentucky Coal Fields.

Kentucky Water Resources Research Institute

The Kentucky Water Resources Research Institute, through Section 104B of the Water Resources Research Act of 1964, administered by the U.S. Geological Survey, sponsors a competitive annual grant in support of water-related research conducted by students at universities and colleges in Kentucky. Grant proposals are reviewed by the KWRRI Committee on Research and Policy to determine which projects best address Kentucky water-research needs, have potential meaningful impact, use sound science, and provide robust student training opportunities. Seven grants were awarded in 2018-19; two of these awards supported groundwater research.

Developing a Threat Assessment and Monitoring Framework for Urban Karst Groundwater Management. The Urban Karst Aquifer Resource Evaluation toolbox, developed by Dr. Jason Polk and master's student Rachel Kaiser of the Department of Geography and Geology at Western Kentucky University, is a universal and user-friendly tool for any urban karst system. It can be used to determine the most vulnerable, threatened, and suitable locations for monitoring urban karst groundwater and what should be monitored to protect groundwater quality.

Preexisting indices were evaluated and developed into toolboxes for threats (24 tools), vulnerability (nine tools), and monitoring (18 tools). The UKARE was then validated using data collected weekly from 10 karst sampling sites in Bowling Green for almost a year (Fig. 12). Sites (five prioritized and five controls for model validation) were chosen from 55 potential locations by applying the UKARE to a compiled karst inventory geodatabase.

Monitoring validated UKARE's scoring of priorities, and the health criteria for arsenic and lead was exceeded more frequently than other parameters in higher-risk drinking-water source areas. Lead, antimony, selenium, iron, thallium, nitrate, and *E. coli* were found throughout the entire aquifer, indicating a need for area-wide management. All sampling sites also routinely tested positive

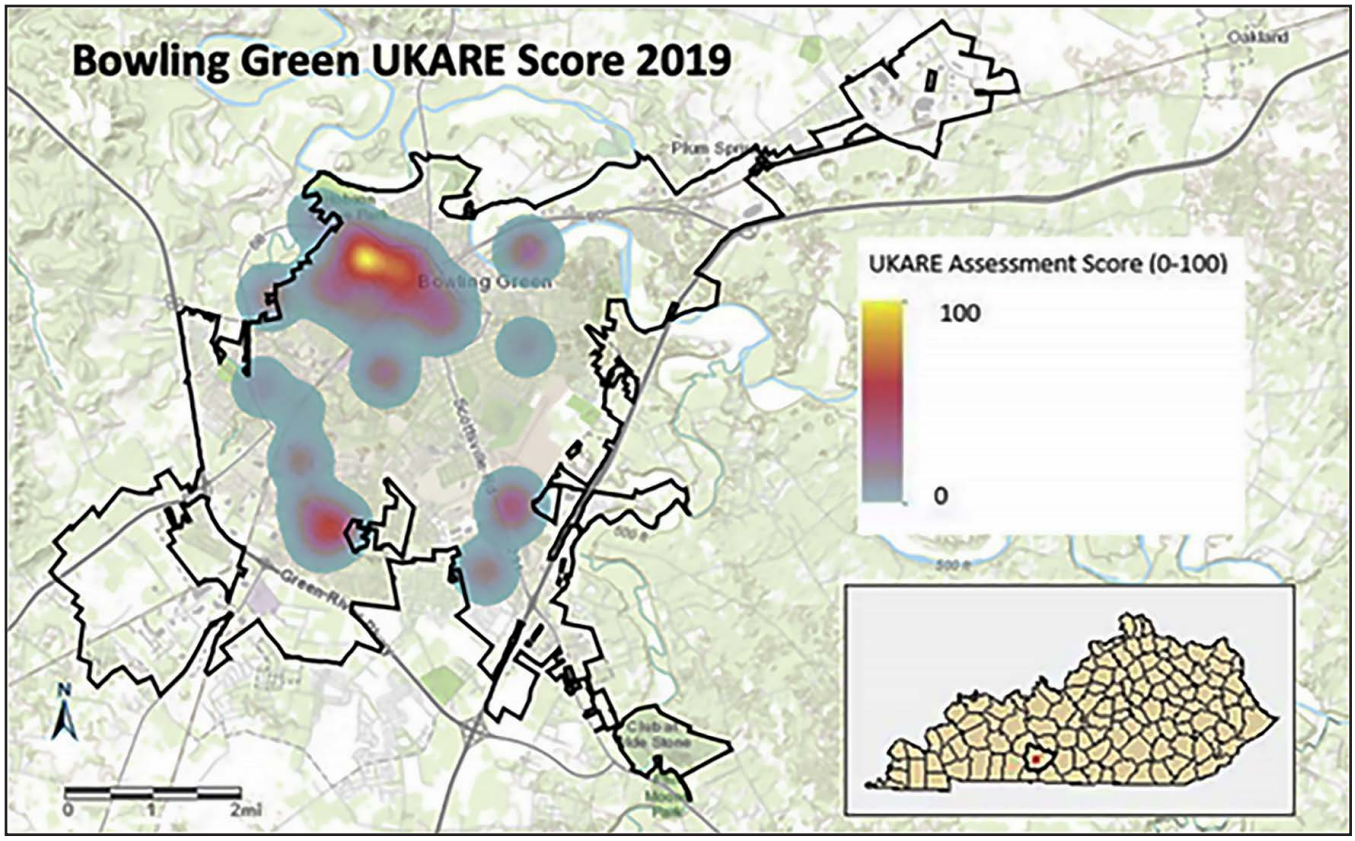

Figure 12. Results of the 2019 Urban Karst Aquifer Resource Evaluation for Bowling Green.

for bacteria resistant to Enterobacteriaceae (serious threat), *Klebsiella pneumoniae* Carbapenemase (urgent threat because they are resistant to nearly all antibiotics), and to generic antibiotic strengths. The bacteria resistance indicates that the disposal of personal care products and pharmaceuticals needs to be regulated and sewage infrastructure needs to be improved.

The study and resulting toolbox provide guidelines and a starting point for the development of groundwater management plans for urban karst areas and collection of primary data for effective groundwater management.

Distribution of Groundwater Information

One of the most important functions of the Interagency Technical Advisory Committee and the Groundwater Monitoring Network is translating analytical data from water-level measurements and groundwater analyses into readily available, useful information and presenting it to the public. During the 2018-19 fiscal year, groundwater information was communicated via short reports, oral and poster presentations at meetings and conferences, and posting on websites. Publications and presentations generated by ITAC agency members or affiliated personnel are listed below.

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Website Information

Statewide groundwater data in the Kentucky Groundwater Data Repository can be accessed at kgs.uky.edu/kgsweb/DataSearching/watersearch.asp. The Repository database contains water-well, spring, and groundwater-quality data. Several alternatives are available for viewing groundwater information on both interactive and static maps, and for creating graphic representations of groundwater-quality data.

The Kentucky Geological Survey also maintains a website for the Interagency Groundwater Monitoring Network (www.uky.edu/kgs/water/gnet), which contains links to current and previous annual reports of the Network and to the websites of the ITAC agencies and organizations.

The Kentucky Water-Well and Spring search engine was accessed 10,777 times during fiscal year 2018-19, resulting in 602 downloads. This search engine remains the second-most popular on the KGS website, after the one for oil and gas records. Users can search for wells or springs by county, 7.5-minute quadrangle, or a radius from a latitude/longitude location. Resulting data can be displayed on maps or downloaded for use in GIS packages. The website also contains documents scanned by the Kentucky Division of Water, and these were downloaded 18,973 times. The associated Water Wells and Springs map service was accessed 5,155 times during the fiscal year, and the Karst Potential Map layout on the KGS Geologic Map Service was accessed 2,476 times.

The Kentucky Groundwater-Quality Data search engine was accessed 1,167 times during fiscal year 2018-19, resulting in 312 downloads. Users can select from hundreds of parameters in 14 major categories, some of which are herbicides, pesticides, inorganics, metals, nutrients, volatile organic compounds, and petroleum hydrocarbons. Resulting data can be downloaded, displayed on maps, or used to generate graphs comparing groundwater-quality data by physiographic region or watershed basin. The water-quality map was accessed 449 times, and the groundwater-quality data plotting service was accessed 56 times.

In addition to the Repository data, information about hydrology, geology, topography, water supply, and water quality has been compiled from maps, reports, and data collected from 1940 to the present and is available at www.uky.edu/kgs/water. For more information on groundwater-quality or water-well and spring data, contact the Kentucky Geological Survey at (859) 323-0523.

Interagency Coordination

Cooperation among agencies and research organizations that collect, analyze, and use groundwater data reduces monitoring costs, improves program efficiency, and promotes data sharing. The Interagency Technical Advisory Committee on Groundwater provides a forum for participating organizations to meet and discuss groundwater issues.

Many programs benefit from the Division of Water's willingness to collect and analyze groundwater samples to support various projects. The DOW also samples groundwater and surface water for nonpoint-source constituents in support of projects for the Division of Pesticide Regulation.

The DOW and the Kentucky Geological Survey regularly answer inquiries from the public and communicate with staff of the Kentucky Rural Water Association. Kentucky Geological Survey staff have been meeting with Cooperative Extension Service agents and Area Development District personnel throughout the commonwealth to promote awareness of hydrogeologic issues. Some ITAC agencies are also members of the Kentucky Agriculture Water Quality Authority or cooperate with the Authority and participate in its meetings. Staff of both the DOW and KGS regularly participate in meetings of state and federal agencies and citizens' groups that have interests in groundwater resources.

Groundwater Data Sharing

Sharing data is an essential function of the Interagency Groundwater Monitoring Network. Data transfers between agencies provide each group access to a larger dataset than any agency could develop independently, thereby improving evaluations of groundwater quality and suitability for various uses, dealing with threats to groundwater quality, and mitigating the effects of mining, logging, agricultural practices, urbanization, waste disposal, and oil and gas production. Sharing data also reduces the overall expense and increases the efficiency of monitoring efforts.

Data have been transferred electronically between the DOW's groundwater database and the Kentucky Groundwater Data Repository since 1992. During 2018-19, electronic files of water-well, spring, and groundwater-quality data were transferred from the DOW to KGS quarterly, and scanned drillers' logs twice a year. These data and scanned images were uploaded to the Kentucky Groundwater Data Repository, allowing end-users to access the most recent well and spring data available.

Change in Kentucky Groundwater Data Repository's Management

In December 2018, Bart Davidson retired from KGS after 32 years; much of that time was spent in the Water Resources Section. As the longtime manager of the Kentucky Groundwater Data Repository, Davidson worked diligently with colleagues at KGS, the Kentucky Division of Water, and other state agencies to improve access to groundwater data by helping to make thousands of records on water wells and springs available online. He also helped users with searches for groundwater data, and developed material to educate the public about the state's groundwater resources.

Following Davidson's retirement, Sarah Arpin (Fig. 13), an alumna of Western Kentucky University with a master's degree in hydrogeology, joined the KGS Water Resources Section in February 2019 as the new manager of the Repository. Arpin's experience includes working for the National Park Service at Mammoth Cave in Kentucky, Mesa Verde in Colorado, and Carlsbad Caverns in New Mexico, and being an active member of the Kentucky Speleological Survey, in which she serves as a board member and the chair of its Data Access Committee.

Figure 13. New manager of the Kentucky Groundwater Data Repository, Sarah Arpin.

Since joining the KGS team, Arpin has worked hard to familiarize herself with the Repository's database and begin developing new ideas on how to enhance the current data search and user interface. She is developing plans to enhance the searchability and accessibility of the database and the Water section of the KGS website in general. Ongoing quality assurance and quality control has corrected a number of small errors in the database, such as miskeyed values.

To make the downloaded data ready for use, units of water-quality results are being standardized, and a note added to the comments field to document the conversion. Though all data are publicly available, Arpin often works with users to fill specific needs and large requests. She also works with landowners to inventory springs and collect water-quality data for entry in the Repository. Feedback from Repository users and suggestions on how to improve the database is encouraged. To report a new spring or provide feedback, please contact Arpin at sarah.arpin@uky.edu.

Other Activities

ITAC agencies are involved in many activities concerning surface-water quality and public education about water resources. Although these projects do not directly address issues raised by the 1998 Kentucky General Assembly, they are important contributions because of the close interconnection of groundwater and surface-water systems in Kentucky. Some of these activities are listed below.

University of Kentucky Cooperative Extension Service, Agriculture and Natural Resources Extension Programs

The Agriculture and Natural Resources Extension Programs of the UK Cooperative Extension Service launched KYH2O, a podcast about water in Kentucky (kyh2o.podbean.com). So far, the podcast has released several episodes that are specific to groundwater resources (episodes 12 and 13), and all are related by surface water-groundwater interactions.

Kentucky Division of Forestry

Forested land provides important benefits to both groundwater and surface water in rural and urban landscapes. Forests absorb rain, trap and filter pollutants, recharge groundwater, slow storm runoff, sustain late-season flows, reduce flooding, maintain watershed stability and resilience, and provide critical habitat for fish and wildlife. Studies show that the percentage of forested land in a source-water area is one of the most important factors in determining water quality. The more forested land in a source area, the better the water quality and lower the treatment costs. Watersheds with less forested land have higher water temperatures and higher levels of fecal coliform bacteria, turbidity, and nutrients.

Reducing forest cover increases water yield, whereas establishing forest cover decreases water yield. Water yield is the amount of surface water and groundwater leaving a watershed. On average, removing 10 percent of forest cover increases water yield by 40 millimeters in conifers, 25 millimeters in deciduous hardwoods, and 10 millimeters in brush and grasslands. Although simply removing forest increases the water yield, placing an impervious barrier such as pavement, roofing, or exposed rocks from mining further increases these yields.

The Kentucky Statewide Assessment of Forest Resources and Strategy, known as the Kentucky Forest Action Plan, released in June 2010 by the Kentucky Division of Forestry, revealed that the citizens of the commonwealth consider water quality and quantity to be the second-most important concern about forests, according to a statewide survey of the most important issues affecting the state's forest resources. The Division, also using stakeholder input, delineated seven major forest priority areas across the commonwealth in which to focus a collaborative strategy to maintain sustainable forests and as a basis for improving water quality and quantity (Fig. 14).

The primary objective of the Division of Forestry's Timber Harvest Compliance Program is to ensure that commercial timber-harvesting operations use best management practices to protect water from nonpoint-source pollution. This program enforces the minimum performance standards of best management practices mandated by the Kentucky Agriculture Water Quality Plan.

For the 2018-19 fiscal year, 3,143 harvest inspections were performed, resulting in 373 enforcement actions.

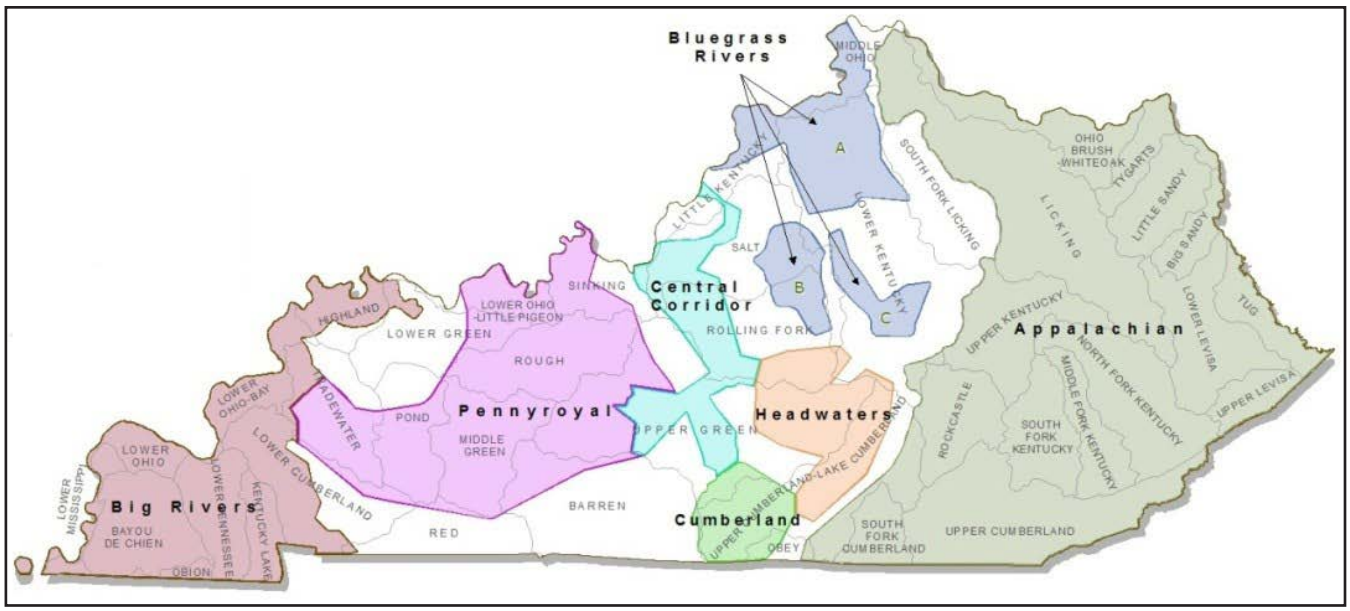

Figure 14. Forest priority areas and watersheds in Kentucky.

The Division's Forestry Stewardship Program proactively mitigates water-quality concerns by providing technical assistance in practice plans for riparian buffer development under the auspices of the U.S. Department of Agriculture–Natural Resources Conservation Service's Conservation Reserve Program.

The Division also addresses water quality by promoting the agroforestry concept of strategically incorporating trees into the agricultural landscape in order to protect water resources and meet landowner objectives. This integrated watershed approach is very effective in promoting good water quality, often proving economical to the landowner when implemented.

Mitigating stormwater issues is a component of the Division's Urban Forestry Program. The Division's urban forestry specialists educate community leaders about the many benefits of trees in the urban setting, one of which is phytoremediation, or the use of trees to decontaminate soils or water. Thirty-eight Kentucky communities were certified as a Tree City USA community, which is a national designation sponsored by the Arbor Day Foundation and administered locally by state forestry agencies. Five of these communities were also designated as a Growth Award community for significantly expanding their urban forestry programs. Eleven universities and colleges in Kentucky received Tree Campus USA certifications. This Arbor Day Foundation program recognizes college campuses that show a commitment to campus tree care through dedicated planning, funding, and collaboration with students, faculty, staff, and community organizations. Three utility companies in Kentucky received Tree Line USA designations; this Arbor Day Foundation program recognizes companies that use best management practices in public and private utility arboriculture.

Urban forestry specialists and foresters at the Division in fiscal year 2018-19 were involved in Lexington's Reforest the Bluegrass, in which more than 1,000 citizen volunteers planted more than 8,000 tree seedlings at Masterson Station Park. At the Reforest Northern Kentucky event at Morning View Heritage Area, nearly 200 volunteers planted 2,000 tree seedlings; and at Reforest Frankfort at Capitol View Park, 800 volunteers planted 1,500 tree seedlings. At all of these reforestation events, Kentucky Division of Forestry personnel assisted with planning, coordination, layout, and technical recommendations, as well as serving as crew leaders.

County judge-executives from 116 Kentucky counties signed Arbor Day proclamations for their respective counties, designating a specific day to celebrate Arbor Day. The Division sold or gave away 112,300 tree seedlings for use in a variety of Arbor Day activities.

Crawford Hydrology Laboratory, Western Kentucky University

The Crawford Hydrology Laboratory within Western Kentucky University's Applied Research Technology Program is a nationally leading laboratory for groundwater-flow investigations with an emphasis on karst landscape/aquifer systems. Established in 1979, CHL provides a range of technical, field, and laboratory services to a diverse national and international clientele, including federal, state, and local agencies; environmental consulting firms; and individuals. CHL has extensive experience with a variety of fluorescent dye-tracing applications, including groundwater basin delineation, sewage leaks, dam safety and remediation, contamination-source determination, and spring protection. Past clients and partners include the National Park Service, Bureau of Land Management, U.S. Forest Service, and U.S. Army Corps of Engineers. In the past few years, the Laboratory has provided services to clients in 23 states plus Brazil, Canada, Italy, Jamaica, Mexico, New Zealand, and Peru.

Natural Resource Condition Assessment for Mammoth Cave National Park. The common feature of all national parks in America is that they protect natural, and often cultural, resources. The National Park Service's Natural Resource Condition Program (www.nps.gov/orgs/1439/nrca.htm) provides a framework to evaluate the conditions of a park's natural resources as a "snapshot in time" by using credible science to report on conditions and trends, critical data gaps, and threats for a broad subset of a particular park's resources. In 2018, CHL, along with others at Western Kentucky University, reported the results of such an analysis in the "Natural Resource Condition Assessment for Mammoth Cave National Park" (Fig. 15).

Established in 1941 with an area of 21,380 hectares, this national park protects a globally significant karst landscape—a landscape that forms on soluble rocks such as limestone and in which caves, underground rivers, sinkholes, and large springs are common. The centerpiece is the Mammoth Cave System, which has a current known length of more than 660 kilometers, by far the world's most extensive known cave system. Although Mammoth Cave served as the principal motivation for the establishment of the park, the national park also serves to protect many other important resources on the surface and underground. The Green River, which bisects the park, flowing from east to west, has among the highest biodiversity of North American river systems, with a range of diverse habitats that support at least 150 species of fish and 70 mussels. There are at least 43 endemic species in the park—those not found anywhere else in the world. The park is home to at least 1,925 species, a number of which are threatened or endangered.

Based on scoping meetings and close communication with the staff of Mammoth Cave National Park's Division of Science and Resource Management and the National Park Service's Cumberland Piedmont Inventory and Monitoring Network, 13 focal natural resources were selected to form the framework of the report: four physical/landscape topics (surface air, cave air, geology and soils, and hydrology/water resources), six biological topics (bats, birds, herpetofauna, native communities, surface aquatic communities, and cave communities), and three that evaluate human influences on the resources (fire management, night skies, and human impacts).

We found a range of conditions and trends, and although many of the park's resources are in good condition and adequately protected, there are challenges. A major threat posed to many species of cave-dwelling bats in the park and elsewhere is the deadly fungal disease known as White-nose syndrome. Since discovery of the disease in the United States in 2006, and documentation in the park as of 2013, the syndrome has been an important issue related to cave and bat management at Mammoth Cave National Park. Multiple bat species, including the federally protected Indiana bat and northern long-eared bat, have declined substantially in response to White-nose syndrome. The decline observed in some winter-roosting species is as high as 93 percent (little brown bats at Colossal Cave since 2013). For now, there are no treatments or intervention other than monitoring, but active research is underway by a variety of laboratories.

Other major challenges include the threats to native plant communities, which are very diverse because of the range of habitats in the park, from invasive plants and exotic pests and diseases. There are at least 174 species of non-native plants in the

Figure 15. Crawford Hydrology Laboratory Director Chris Groves guides geology students through the large passages of Mammoth Cave as he discusses the geologic, natural, and cultural resources found at Mammoth Cave National Park.

park, including 31 each of species designated as severe and significant by the Kentucky Invasive Plant Council. The emerald ash borer *(Agrilus planipennis),* which has killed millions of ash trees since being accidentally introduced into the U.S. in 2002 (www.aphis.usda.gov/aphis/ourfocus/planthealth/plant-pest-and-disease-programs/pests-and-diseases/emerald-ash-borer), was confirmed at Mammoth Cave National Park just prior to our assessment.

There are also bright spots: Some resources are in good condition or even improving. Although the park continues to have significant air-pollution problems, the situation has improved in the last 10 years in some parameters, including rainfall acidity, sulfate, visibility, ozone, and wet deposition with amelioration of the impacts of regional coal combustion. Related to this, and also getting better as visibility improves, are the park's night skies. This is another special feature of the park, increasingly rare for the eastern U.S., and an example of how our assessments are based on quantitative data: Most of the park has a Class 4 rating on the Bortle scale as well as consistent Unihedron Sky Quality Meter readings over 21.0, which qualifies it for Silver Tier status from the International Dark Skies Association for "exemplary nighttime landscapes."

In general, we found that Mammoth Cave National Park is a well understood, well cared for, and carefully protected national park. In cycles of waxing and waning resources, we more fully than

ever appreciate and laud the scientists, administrators, support staff, and partners who have made this happen over more than seven decades as a national park.

Evaluation of Untreated Karst Groundwater as Community Water Sources, Barren County, Kentucky. Concerned for some time about the potential for karst groundwater used as a community water source to become contaminated, but lacking any clear data to define or even identify whether there is indeed such a problem, CHL very recently developed a relationship with members of a rural Barren County family who had reached out to ask questions about their water supply—a karst spring on their farm. Through conversations with the concerned community members, we discovered that numerous families in that area of south-central Kentucky are relying on karst springs, and in some cases with no water treatment at all (Fig. 16). Informal but highly credible discussions have made it clear that due to a complex weave of local social norms, rural residents in this part of Kentucky are drinking untreated water that is likely to be contaminated with fecal bacteria, and perhaps agricultural chemicals as well. There are several reasons for this: An important notion seems to be a sense that such "natural" water is healthier than treated city water, and indeed there are tangible fears related to possible harmful consequences of chlorine and fluoride. There also may be more

Figure 16. Western Kentucky University graduate student Cayla Baughn samples water from an untreated karst spring in Barren County. Prior to the Crawford Hydrology Laboratory study, an Amish family of 10 hand-carried all drinking water from this spring and drank it with no treatment. After the study showed that the water was contaminated with fecal bacterial, the family stopped using the spring.

practical concerns about cost, and indeed some farms in remote locations are not connected to the local water-supply infrastructure.

This project represents the first phase of a new research program for CHL, whose long-term goals are to use this part of south-central Kentucky as a demonstration site to (1) evaluate the nature and extent of contaminated, untreated karst water supplies, (2) develop a participatory, combined educational/technical approach to raise awareness of water quality and risks, and (3) evaluate a range of potential water-resource protection strategies.

The study sites were sampled in a synoptic, nonconditional program based on the U.S. Geological Survey's National Water Quality Assessment (water.usgs.gov/nawqa; accessed 08/01/2019). The sampling program was synoptic in that it provides a general summary, and nonconditional in that the samples were collected on preselected days, with 13 rounds on a 28-day cycle. We sampled for fecal bacteria including total coliforms and *E. coli,* turbidity, nitrate, and ammonium. Specific conductance, temperature, and pH were measured in the field. We analyzed ammonium and nitrate using ion chromatography and turbidity by nephelometry at the WKU Advanced Materials Institute. The Science and Resource Management Water Quality lab at Mammoth Cave National Park used Colilert reagent to detect the presence and most probable number of total coliform and *E. coli.*

Risk of fecal water contamination was interpreted following the guidelines of the World Health Organization (whqlibdoc.who.int/publications/2011/9789241548151_eng.pdf; accessed 08/01/2019) and U.S. Centers for Disease Control and Prevention (www.cdc.gov/healthywater/drinking/private/wells/testing.html; accessed 08/01/2019), which evaluate water based on the presence of total coliforms, which may contain *E. coli.* Samples are scored by water quality, and are considered to be potable when total coliforms are absent and polluted when one or more are detected, as well as a gastrointestinal health risk. No risk is present where no coliform or *E. coli* are present, there is low risk when total coliforms are present but not *E. coli,* and there is high risk when at least one *E. coli* is present. Analysis showed that all untreated water from the study site was positive for both total coliforms (ranging from 436 colonies per 100 milliliters to more than 2,419—the largest number that can be quantified without dilution) and *E. coli* (ranging from 2 to 920 colonies).[1] This indicates that, according to World Health Organization guidelines, every sample of nontreated water was polluted with respect to water quality and had high gastrointestinal health risk.

Nitrate was also present in all samples, ranging from about 12 milligrams per liter (reported as nitrate) to about 42 milligrams per liter in raw spring water, and levels at the family's source-water spring were reduced by the filter system by about 50 percent to more than 80 percent. No samples were above the U.S. Environmental Protection Agency's maximum contaminant level of 62 parts per million when reported as nitrate.[2]

We also made good progress in learning about these communities, and met members of another nearby community in which several homes and a church are supplied by a karst spring. There is a cleverly designed primary screen filtering system at the spring mouth itself, and each of the spring's users has an on-site treatment system. We were able to sample the raw and treated water at one home for fecal bacteria, and although the raw water was positive both for total coliforms and *E. coli* (132 and 2 colonies per 100 milliliters, respectively), the in-home filter system worked well and water there was negative for both. A manuscript detailing all results of this study is under preparation to be submitted to a peer-reviewed journal.

Refining Groundwater Basins at Mammoth Cave National Park. Mammoth Cave National Park in south-central Kentucky is home to the world's longest cave and is a World Heritage Site and core area of an International Biosphere Reserve. Mammoth Cave may also be one of the most studied caves in

[1]Environmental Protection Agency, 2017, Revised total coliform rule—Webinar: water.epa.gov/lawsregs/rulesregs/sdwa/tcr/upload/rtcrwebinar41013-1-2.pdf [accessed 08/01/2019].

[2]Environmental Protection Agency, 2017, Water: Basic information about regulated drinking water contaminants: water.epa.gov/drink/contaminants/basicinformation/pathogens.cfm [accessed 08/01/2019].

Figure 17. Western Kentucky University graduate student Charlie O'Connell exchanges dye receptors at Pike Spring in Mammoth Cave National Park.

the world. There is still much to be learned from investigating the complex karst aquifer system found there, however. In 2017, CHL began conducting a series of dye-tracer tests to better define the Great Onyx Spring Basin (Fig. 17). The Great Onyx basin has been selected as a long-term study site because of limited land use and minimal human impact, therefore representing a relatively pristine groundwater basin for carbon cycling and climate change research. This project will follow the framework of a Critical Zone Observatory, though at a micro-scale. For proper site characterization and accurate geochemical interpretation, the groundwater basin must be well-defined spatially. Much work[3] has been done to identify drainage basin boundaries south of the Green River, yet some of these divisions are based on limited data. Results from 2017 and early 2019 indicate that the Great Onyx Spring basin boundary, as acknowledged currently, is not wholly correct and appears to be more dynamic than considered previously. Additional fluorescent

[3]Meiman, J., Groves C., and Herstein, S., 2001, In-cave dye tracing and drainage basin divides in the Mammoth Cave karst aquifer, Kentucky, *in* Kuniansky, E.L., ed., Karst Interest Group proceedings, St. Petersburg, Florida, February 13–16, 2001: U.S. Geological Survey Water-Resources Investigations Report 01-4011, p. 99–105.

Quinlan, J.F., and Ray, J.A., 1981, Groundwater basins in the Mammoth Cave region, Kentucky, showing springs, major caves, flow routes and potentiometric surface: Friends of Karst Occasional Publication 1, scale 1:138,000.

Quinlan, J.F., and Ray, 1989, Groundwater basins in the Mammoth Cave region, Kentucky, showing springs, major caves, flow routes and potentiometric surface: Friends of Karst Occasional Publication 2, scale 1:138,000.

dye tracing, water-quality sampling, and other hydrologic monitoring continues at Great Onyx.

Karst Education and Outreach. In addition to groundwater research and environmental investigations, CHL provides formal and informal educational opportunities to all age groups and supports public outreach efforts pertaining to water resources as well as cave and karst science. The Laboratory is also committed to distributing scientific information via professional presentations and publications. Here's a few highlights from 2018-19:

- CHL welcomed Lost River Cave STEM Camp participants, Boy Scouts of America, Girls in Engineering, Math and Science Club, and local grade school classes for tours or traveled off campus to chat about caves and clean water.
- Numerous groups of students, scientists, and researchers visited WKU's Crumps Cave Education and Research Preserve, a Kentucky Land Heritage Conservation property. This "underground laboratory" provides the perfect setting in which to discuss the connection of land use and groundwater quality (Fig. 18).
- CHL conducted multiple hydrogeology field trips for various academic, professional, and conservation groups to nearby Mammoth Cave National Park. World-class karst = world-class "classroom" (Fig. 15).
- CHL personnel led a water-quality field trip for homeschooled students in Larue County, volunteered at the annual household hazardous waste drop-off day, and participated in exotic plant removal at Lost River Cave.
- CHL personnel made presentations to local organizations such as the Barren River Area Development District Water Management Council and the Mammoth Cave Area Biosphere Reserve Advisory Council, as well as at campus events at WKU and public events such as Science Café and departmental seminars.

Figure 18. Crawford Hydrology Laboratory Director Chris Groves (far right) and Assistant Director Lee Anne Bledsoe (front center) host students of all ages during Western Kentucky University's Bring Your Son and Daughter to Work Day at Crumps Cave Education and Research Preserve.

- CHL works with international partners via UNESCO and other academic and research programs on understanding, managing, and protecting fragile karst areas, with a focus on groundwater resources.
- CHL hosted Dr. Yang Pingheng from Southwest University in Chongqing, China, for a yearlong research scholar exchange focused on karst hydrogeology and intensive training in dye-tracing techniques.
- CHL is planning a karst resources workshop, "Conservation of Fragile Karst Resources," as part of UNESCO Karst 2020, and will offer a course in karst hydrogeology as part of WKU's karst field studies program in 2020.

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