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Introduction

Crumps Cave is located about one kilometer northeast of Smiths Grove, Kentucky (Figures 1, 2, and 3). The only known entrance was purchased by Western Kentucky University (WKU) in 2009 through a grant from the Kentucky Heritage Land Conservation Fund and the cave is managed as the focal point of a research and education preserve to study a wide range of environmental conditions and dynamics, and their interactions, using high-resolution electronic monitoring along with geochemical sampling, analysis and modeling. Crews from WKU's Hoffman Environmental Research Institute visit the cave weekly for sampling, data downloading, and equipment maintenance, with a major emphasis on high quality data collection and management. Groups of scientists and students from around the country and world visit the cave on a regular basis for educational activities. The purpose of this extended abstract is to summarize the major data collection programs underway at the cave.

Figure 1. *Pennyroyal Plateau sinkhole plain, south central Kentucky, typical of the area near Crumps Cave (photo by Chris Groves).*

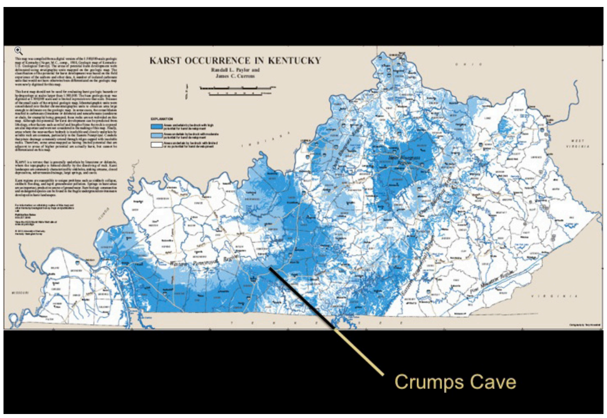

Figure 2. *Map of Kentucky's karst regions, and location of Crumps Cave. The Pennyroyal Plateau is the ring-shaped blue area in the western part of the state (map from Paylor and Currens, 2002).*

Figure 3. *Crumps Cave Preserve covers the ~one hectare area of the wooded sinkhole (image from Google Earth).*

The site is located at latitude 37.1oN with a surface altitude of 194 m above sea level. The climate here is humid subtropical (Köppen-Geiger Cfa) (Peel et al., 2007). Five long-term weather observation stations located with 35 km of the Preserve and all within less than 50 m elevation have a mean annual precipitation of 1,300 mm and temperature of 14.7oC (Kentucky Climate Center, 2012). Precipitation is spread approximately evenly across the year, though late spring tends to be a bit wetter, and fall a bit drier, than other times of the year. Hess (1974) estimated that mean-annual potential evaporation is 800 mm, varying from near zero to over 100 mm/mo.

The Preserve includes a roughly one hectare collapse sinkhole that contains the entrance to Crumps Cave (Figure 3), which from the entrance consists of a large, nearly horizontal passage typically 12 m tall by 18 m wide formed within the upper part of the St. Louis Limestone, which at this site dips about 2o towards the west. About 3 m of Baxter silt-loam soils overlie the bedrock on the flat surface surrounding the sink, with an additional 18 m of rock to the cave ceiling. The Lost River Chert, an interbedded, silicified limestone, lies between the surface and cave ceiling.

Water from epikarst drains form waterfalls that fall about 4 m from the cave ceiling at several locations, offering an opportunity to evaluate epikarst hydrology and hydrochemistry. Work here focuses on high-resolution data from measurement of the epikarst drain at Waterfall One (Figure 3), in a side alcove about 30 m from the cave entrance. As it falls from the cave ceiling and disappears into the cave floor making its way downward through the vadose zone, the water has entered the main body of the karst aquifer, where it reaches the water table about 40 meters below (during low flow conditions), then flows through large conduits to reach the Barren River at Wilkins Bluehole, 18 km to the southwest. Wilkins Bluehole is the second largest spring in Kentucky, with a minimum discharge of 0.56 m^3/s (Ray and Blair, 2005).

Monitoring Efforts

There are a number of interrelated efforts to collect high-resolution data, which include measurement of more than 20 parameters, most with ten-minute resolution using data loggers. These include 1) surface weather conditions above the cave, 2) measurement of water levels through wells into the epikarstic zone and the main water table,

3) measurement of flow and chemical conditions at the epikarst drain at Waterfall One, 4) collection of water in various parts of the system for evaluation of both carbonate and isotope geochemistry, and 5) monitoring of bat activity at several locations as they enter and leave the cave. These data support an ongoing series of experiments including study of epikarst groundwater flow with introduced tracers including fluorescent dyes and agricultural compounds from actual field-scale farming at the site, including both bacteria from animal waste and herbicides. Surface and cave biological and archeological surveys have also been completed at the preserve. Several of these efforts are described in more detail below.

Surface Monitoring

Weather/climate conditions are measured with an automated weather station above the cave (Figure 4) with ten-minute resolution, including rainfall, air temperature, relative humidity, solar radiation, wind speed and direction, and barometric pressure. Water leaving the rain gage is collected in a device that inhibits evaporation for weekly analysis of hydrogen and oxygen isotopes that provide information of precipitation source areas as well serving as a tracer that helps us to better understand mixing processes in the epikarstic zone, where they are also collected weekly in the cave.

Soil temperature data for 5, 10, 25, 50 and 100 cm depths are measured with 30 minute resolution at two nearby research-grade climate monitoring stations that make up part of the Kentucky Mesonet network, including the Warren County and Barren County stations that lie about 18 km west south west and 18 km east south east of the Preserve, respectively. Comparison of the data from the two sites indicates that over the one year of 30-minute resolution data the average difference between the 87,600 readings comparing paired measurements taken at the same depths and times was less than 1^{o}C. Comparison of these data thus suggest that seasonal and diurnal variations between the two sites, and thus those in the soil at the preserve, are nearly identical, though timing of temperature variations on the scale of minutes to hours can be larger due to local conditions. Local differences between soil moisture conditions at the two Mesonet stations are greater, and our use of these data herein is limited to interpretation of relative changes (whether soil moisture is increasing or decreasing over some period, for example) when both stations are in agreement.

Figure 4. *Weather station above Crumps Cave (photo by Chris Groves).*

Soil water is collected weekly (when it is present) from two lysimeters above the cave.

Hydrologic Monitoring

In fall 2011, the City of Bowling Green very generously used its air-rotary drilling rig to drill two wells at the site just to the west the main trunk passage of Crumps Cave that allow us to monitor water levels (now with ten-minute resolution) in the main water table, which under dry conditions is down about 40 meters below the ground surface, and the top of the saturated part of the epikarstic zone, about 15 meters down, but above the cave. This is very instructive to see for folks who are just learning about concepts of how epikarst systems behave, with water table in two wells only about 20 m apart laterally, with a 25 meter difference in their elevations!

Below at Waterfall One, water leaving the epikarst drain on its way on to the main part of the aquifer (Figures 5 and 6) is directed into a large funnel-shaped tarp and into a 200-liter barrel-shaped compound weir with four circular, vertically arranged drainage holes, larger in ascending order to accommodate larger flows. Water

Figure 5. *Epikarst monitoring site at Crumps Cave (photo by Jason Polk).*

level is measured every ten minutes with a pressure transducer, and appropriate relationships are used to calculate discharge in liters per second as a function of water level. Water exiting the weir flows past duplicate temperature and specific conductance (spC) probes and triplicate pH electrodes. These observations are recorded every ten minutes on duplicate Campbell Scientific multichannel data loggers (that is, each logger records temperature, spC and a pH; one logger has a second pH probe and one has the weir pressure transducer). Multiple equipment design is used for three reasons: 1) redundancy minimizes data loss in case of any component failure, 2) comparison of independent, multiple readings provides a measure of data quality, and 3) in cases of potentially unexpected behavior of any parameter, multiple probes behaving in the same way ensure that the signals reflect actual flow system behavior rather than electronic artifacts. Water samples for lab analysis are taken by duplicate automatic water samplers each with 24 bottles, which when utilized are programmed with eight-hour resolution but staggered so one or the other sampler takes a one liter sample every four hours. This allows for four-hour resolution but lets the samplers run for eight days before filling all bottles, and also provides redundancy in case any component of the samplers malfunctions.

The site is visited every seven days for data measurement and downloads, probe maintenance and cleaning, and for lower flows discharge is also measured directly by timing flow into a bucket of fixed volume. The pH probe data are recorded as millivolts on the loggers during normal operation; each week the three pH probes were calibrated in pH 4, 7, and 10 buffers to develop current linear relations between voltage and pH, and these relations are later applied in the spreadsheets during data processing. During site visits pH, temperature and spC are also measured with a hand-held YSI multiparameter meter.

Water samples have been collected under a variety of flow conditions, and stored on ice until return to the laboratory and analyzed for alkalinity within 24 hours using the inflection point titration method. Species contributing to alkalinity other than bicarbonate are assumed to be negligible. Samples for cation analysis (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are filtered and acidified and analyzed using Inductively Coupled Plasma-Optical Emissions Spectroscopy. Anions (Cl^{-}, PO_4^{3-}, NO_3^{-}) are measured by Ion Chromatography. Charge balance errors for all samples used in our analyses fall within 6%.

We have used least-squares regression analysis to relate specific conductivity data to calcium, magnesium,

Figure 6. *Barrel-shaped weir at Waterfall One in Crumps Cave for discharge measurements. Water level is measured with a pressure transducer in the barrel and the temperature, pH and spC probes are in the bucket below (photo by Jason Polk).*

and bicarbonate concentrations, respectively. These relationships, along with direct temperature and pH measurements, then allow calculation of several important components of carbonate system behavior with high resolution, including CO_2 pressures, saturation indices, dissolution rates, and total inorganic carbon (*TIC*) concentrations at the point where the water drains from the bottom of the epikarstic zone.

Bat Monitoring

One of the most critical cave management concerns at Crumps Cave is focused on the presence of a group of federally endangered Gray Bats (Myotis grisescens) that inhabit a large chamber of the cave about 400 meters from the entrance. To monitor their activity in a minimally invasive way, we have installed to BatLogger II ultrasound bat detectors, one near a constriction through which they must fly coming in or out of the cave, and one close to the entrance. Our data so far show both seasonal and diurnal changes in the activity of the bats, apparently related to air temperature.

Data and Interrelationships

Someone who has not thought a lot about caves, or else is not paying very close attention, could be excused for thinking that Crumps Cave is a rather static entity. Upon casual inspection, a few waterfalls notwithstanding, it is a large, rather dry trunk passage within which there does not seem to be all that much going on.

With very high-resolution, however, we are learning that the cave and the hydrologic/ecologic/atmospheric/biogeochemical systems of the environment within which it exists are tremendously dynamic, and the more we learn here the more it is revealed to us what the interesting questions really are.

This is especially so when the interrelationships become apparent. When various outside temperature thresholds are experienced, for example, not only do the bats seem to take notice, but we see in some cases that air temperature warming on a cool fall morning can cause (as we are starting to understand it) activity in the soil to change such that soil CO_2 concentrations quickly rise, which makes water entering the epikarst more acidic, the combination of these which results within a few hours at the epikarst drains that calcium and bicarbonate concentrations have significantly increased (from enhanced dissolution), dissolved CO_2 concentrations have jumped from 5 to more than 80 times atmospheric background, and the pH has dropped by more than a whole unit. That evening as it cools the whole processes is reversed!

What does this, in turn and for example, do to the microbial ecology of the epikarstic zone? We will see!

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