Shannon R. Trimboli and Rick S. Toomey. Temperature and reverse-flow patterns of the River Styx, Mammoth Cave, Kentucky. *Journal of Cave and Karst Studies*, v. 81, no. 3, p. 174-187. DOI:10.4311/2017ES0106

TEMPERATURE AND REVERSE-FLOW PATTERNS OF THE RIVER STYX, MAMMOTH CAVE, KENTUCKY

Shannon R. Trimboli[1,C] and Rick S. Toomey[2]

Abstract

River Styx and Echo River are two, closely-associated underground rivers located in the Mammoth Cave System. Both rivers are home to a variety of aquatic cave life, including the endangered Kentucky cave shrimp (*Palaemonias ganteri*). Typically, both underground rivers emerge at their respective springs and flow into the Green River. During flooding conditions, the Green River can back up into its subterranean tributaries, including the River Styx and Echo River. In addition, the hydraulic gradient in the River Styx can reverse under non-flood conditions of the Green River and create a stable, reverse-flow pattern. This phenomenon was identified at least as early as the 1920s, when a dye trace study noted that, after a rain event, Green River water was flowing into River Styx Spring and coming out at Echo River Spring. However, detailed studies on the River Styx's stable, reverse-flow patterns were not conducted until the 1950s, and little additional research has been conducted. Water temperature data were collected between October 2009 and October 2012 on the River Styx, Echo River, and Green River. During the study period, the Green River had a mean water temperature of 15.5 ± 7.2 °C, while River Styx and Echo River had cooler and more stable mean water temperatures of 13.5 ± 2.7 °C and 13.4 ± 0.6 °C, respectively. Water temperature was used as a proxy for determining whether the River Styx was flowing forward (out of the cave) or backward (into the cave). Periods of time when the River Styx was flowing into the cave were classified as being due to back-flooding or a stable reverse-flow. During the times when data were available for all three rivers, the River Styx flowed out of the cave 77 % of the time, was in a stable reverse-flow 17 % of the time, and it was back-flooding 3 % of the time. These results differ from the original studies' results that identified the River Styx's stable, reverse-flow pattern. The different results could be due to anthropogenic influences on the Green River and/or due to differences in precipitation patterns, possibly as a result of climate change.

Introduction

Karst topography can be found throughout most of south-central Kentucky. As in other karst landscapes, much of the precipitation that falls in south-central Kentucky quickly infiltrates into caves and smaller subterranean passages. The meteoric waters then join cave streams and rivers that flow underground until they emerge at springs located on, or near, one of a relatively small number of perennial streams or rivers. Each spring is the outlet of a karst basin, encompassing the karst catchment area that feeds the associated cave streams during times of normal, low karst flow. During periods of high karst flow, water from one karst basin can spill over into a neighboring karst basin if upper-level connecting passages are available.

Mammoth Cave National Park (Fig. 1) is located in south-central Kentucky and is home to the longest known cave in the world, the Mammoth Cave System. The park is bisected by the Green River (Fig. 2), which is the master stream for south-central Kentucky and is approximately 618 km long. Six modern underground rivers flow through the Mammoth Cave System and are subterranean tributaries of the Green River. Two of Mammoth Cave's underground rivers are the River Styx and Echo River. Both underground rivers are home to many cave-adapted, aquatic organisms including: cave crayfish (*Orconectes pellucidus*), two species of eyeless cavefish (*Typhlichthys subterraneus* and *Amblyopsis spelaea*), and the endangered Kentucky cave shrimp (*Palaemonias ganteri*), which is endemic to the Mammoth Cave region.

Under base-flow conditions, the Echo River karst basin (21.7 km^2) and the River Styx karst basin (2.2 km^2) are almost completely within the park's boundaries (Mammoth Cave data, 2017). However, during periods of high karst flow, waters from the Turnhole Bend karst basin (254.4 km^2) can overflow into the neighboring Echo River karst basin (Meiman, 2006). When this occurs, water from the primarily agricultural lands surrounding the park enters the Echo River karst basin and brings with it potential contaminants from outside of the park. Under flood conditions, water from the Green River backs up into all of its tributaries, including Echo River and River Styx. These back-flooding events can bring contaminants that entered the Green River upstream of the park into the cave system.

Greensburg, Ky. (Fig. 2) is more than 100 river-kilometers upstream on the Green River from Mammoth Cave National Park. In 1958, oil-drilling operations increased near Greensburg. The drilling operations caused a significant increase in the chloride concentration of the Green River (Brown, 1966). These concentrations could still be detected when

[1] Mammoth Cave National Park Citizen Science Coordinator, Western Kentucky University, Bowling Green, KY 42101
[2] Research Coordinator, Mammoth Cave National Park, Mammoth Cave, KY 42259
[C] Corresponding Author: shannon.trimboli699@topper.wku.edu

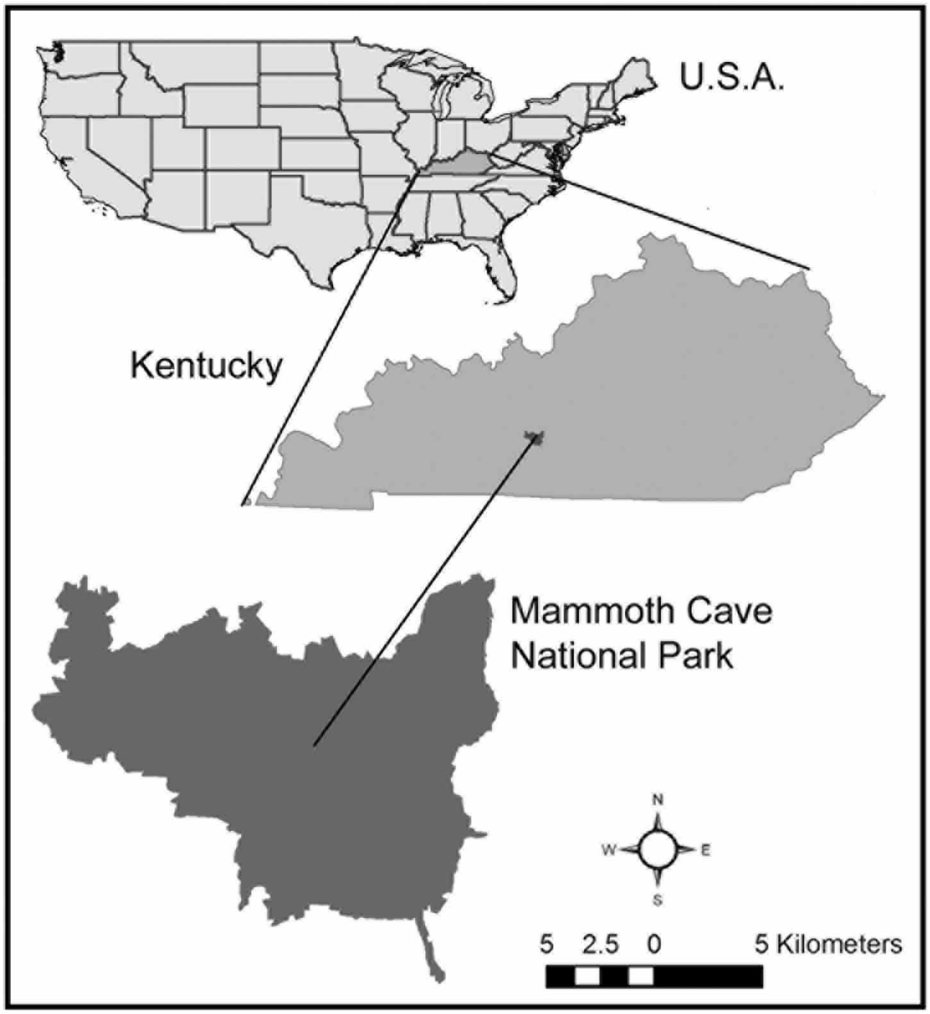

Figure 1. Location of Mammoth Cave National Park within Kentucky and the United States of America.

the Green River reached Mammoth Cave. Between 1958 and 1959, the USGS conducted an extensive hydrological study of the Mammoth Cave area, using the increased chloride content of the Green River as a tracer (Hendrickson, 1961; Brown, 1966). The USGS study found that the River Styx frequently flows backward, even when the Green River is not flooding (Hendrickson, 1961; Brown, 1966). When the River Styx flows backward, Green River surface water flows into the cave through the River Styx Spring. The backward flow of the River Styx forces it to reverse the direction of its flow, cross into the Echo River karst basin, and flow out of Echo River Spring (Figs. 3 and 4).

The River Styx's reverse-flow events can be due to Green River flooding or they can be a stable, relatively long-term, divergent-flow pattern that occurs even when the Green River is not under flood conditions. For the purposes of this paper, reverse-flow events, due to Green River flooding, are referred to as back-flooding events, while reverse-flow events that occur when the Green River is not flooding, are referred to as stable, reverse-flow events. The more general phrase, reverse flow, is used when no distinction is being made between back-flooding events and stable, reverse-flow events.

Stable, reverse-flow events typically take place when the Green River is at a higher stage than the River Styx and when the karst basin is at low flow (Hendrickson, 1961; Brown, 1966; Meiman, 2006). These conditions are more common in the winter. Thus, stable, reverse-flow events are more common during the winter. However, stable, reverse-flow events also occur in the summer when the necessary hydrological conditions are met.

Understanding the River Styx's reverse flow patterns is important because they can affect the biological, geological, cultural, and archeological resources in the cave. Meiman (2006) reported distinct changes in the water quality of the River Styx and Echo River during River Styx reverse flow events. During the River Styx's reverse-flow events, any chemical contaminants, found within the Green River, when it reaches the River Styx Spring, are circulated through the River Styx and the affected portion of Echo River. These contaminants have the potential to impact the aquatic ecosystems found within the two underground rivers; however, those potential impacts have not been quantified.

When Green River water enters the cave, it also carries non-troglobitic fish (Ruhl, 2005) and nutrients from the surface into the low-energy, cave aquatic ecosystem. In moderation, increased nutrients can be a boon to the ecosystem; however, too many nutrients can be a detriment to such a low-energy system. The overall impact of the non-troglobitic fish is unknown because they have the potential to provide additional nutrients when they die, or to consume or compete with troglobitic species, depending on how long the non-troglobitic species survive in the cave.

During the winter, reverse-flow events bring cold water from the surface into the cave. The cold surface water cools the River Styx and can create condensation or fog in the nearby passages. In the summer, reverse-flow events bring warm, surface water into the cave and can have impacts similar to those seen during winter reverse-flow conditions. However, the seasonal differences in the cave airflow patterns cause condensation to occur in different locations during summer and winter reversals. Anecdotal observations by park staff and partners suggest these micro-climate changes could be fairly significant and extend quite a distance away from the immediate River Styx area.

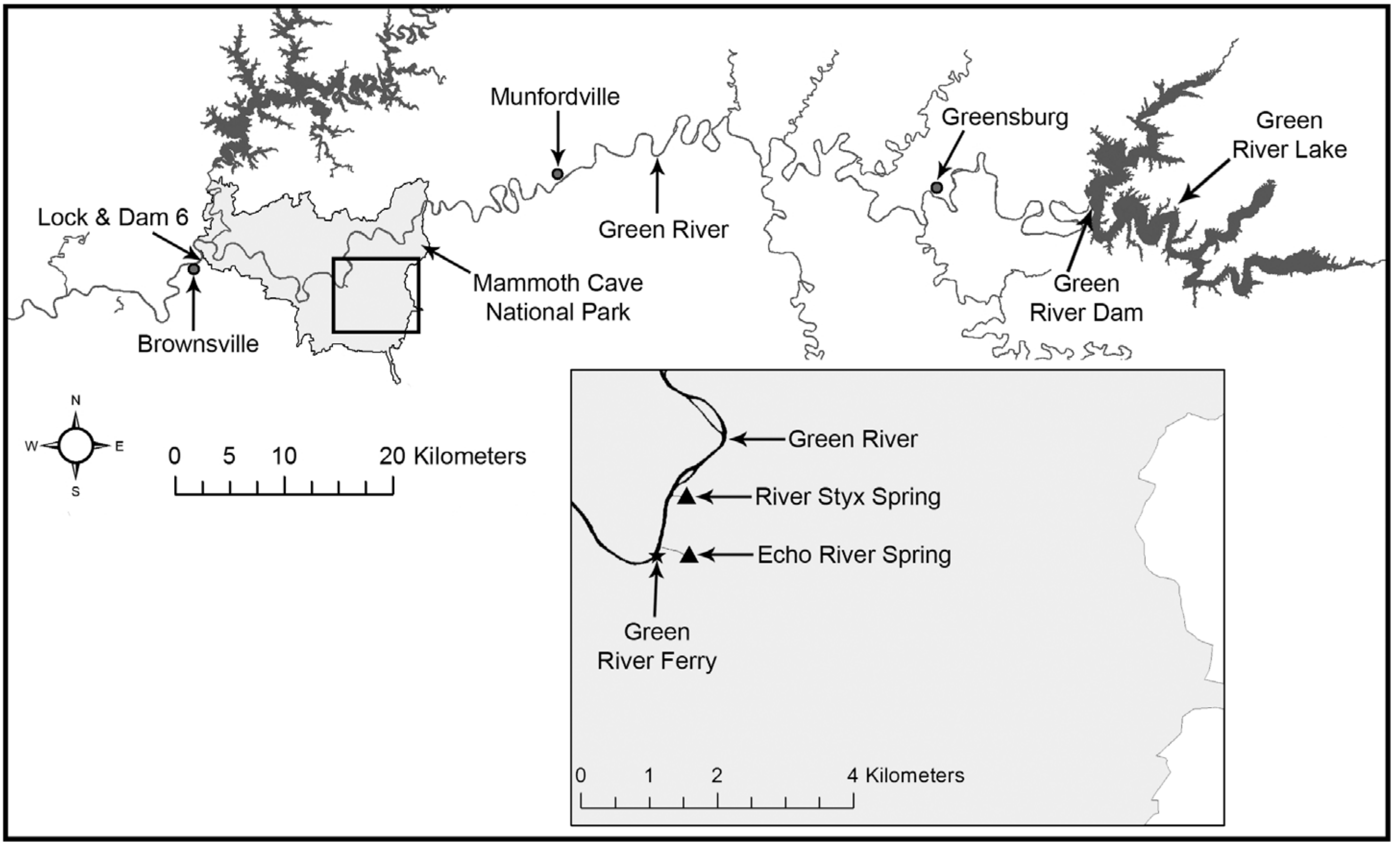

Figure 2. Regional overview with inset showing locations of River Styx Spring, Echo River Spring, and Green River Ferry in Mammoth Cave National Park.

Condensation due to seasonal weather patterns and anthropogenic changes to the Historic Entrance have resulted in increased fungal growth on archeological artifacts and cultural resources in Mammoth Cave's upper passages (Olson, 1996). We speculate that condensation and fog, resulting from reverse-flow events in the River Styx, may have similar effects on archeological and cultural resources in the lower passages of the cave. Research to quantify the micro-climatic changes in the lower passages, due to River Styx reverse-flow events, was recently begun (French and Trimboli, 2017).

The colder or warmer surface water, depending on the season, coming into the cave could also influence the behaviors of cave aquatic organisms that live in the affected portion of the underground rivers. For example, cave aquatic organisms could temporarily or permanently avoid areas of the underground rivers, where the temperature was too cold, too warm, or too variable. In fact, Edwards (2009) found temperature changes to be the most pronounced indication of reverse-flow events, when compared to turbidity, specific conductivity, and pH.

With the exception of the USGS (2015) study, there has been little research published on the River Styx's reverse-flow patterns. In 2008, a seventh-grade science teacher from T. K. Stone Middle School contacted the Mammoth Cave International Center for Science and Learning. She was interested in opportunities for her students to conduct research at Mammoth Cave National Park. In the fall of 2009, T. K. Stone Middle School and the Mammoth Cave International Center for Science and Learning partnered to study River Styx's reverse-flow patterns. Trimboli et al. (2011) provided details about the development of the project and lessons learned from conducting research with students. The current paper provides an in-depth analysis of the data collected through this research partnership.

Study Area

The Green River (Figs. 2, 3, and 5A) is the master stream for most of south-central Kentucky. It is heavily influenced by anthropogenic controls over much of its length. Green River Dam, located approximately 169 river kilometers upstream of the Green River Ferry (Fig. 2), is the primary anthropogenic control on the Green River. The U.S. Army Corps of Engineers completed the dam in 1969. Though the dam was built primarily for flood control, it also created the Green River Lake Reservoir, which has become a popular recreational spot. The timing of water releases and the amount of water released from the dam heavily influences the downstream level of the Green River, irrespective of local precipitation patterns.

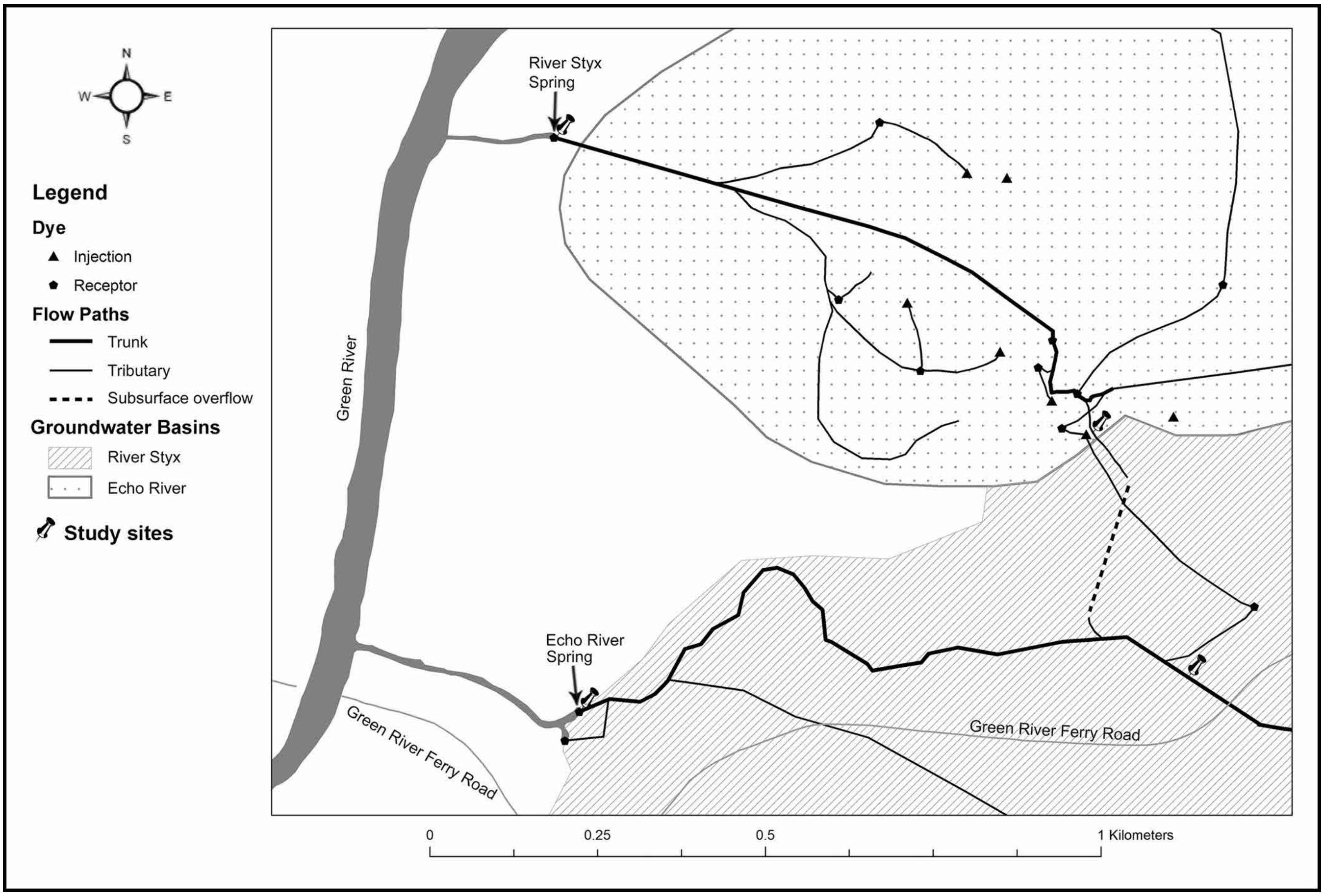

Figure 3. Close-up of the study area, showing a portion of the River Styx and Echo River drainage basins and the flow paths of each river, as determined by previous dye trace studies. When the River Styx flows backward, it flows into Echo River along the dashed subsurface overflow shown on the map. Pushpins show the study sites at River Styx, Echo River, and the two springs.

Another anthropogenic control of the Green River is a series of locks, built in the late 1800s and early 1900s to allow commercial river navigation. Lock and Dam 6 was completed in 1906, approximately 24 river kilometers downstream of Mammoth Cave National Park's Green River Ferry (Fig. 2). Behind Lock and Dam 6, the pool extended upriver beyond Echo River Spring and River Styx Spring. It artificially raised the level of the Green River and its tributaries located within the pooled area, including Echo River and the River Styx.

The River Styx and Echo River are two underground rivers located in Mammoth Cave, and they are subterranean tributaries to the Green River (Figs. 3 and 4). In cave, the Echo River and River Styx karst basins are separated by what is essentially a low, wide sandbar (Fig. 6). By a combination of walking and swimming, one could follow the same large cave passage to get from the River Styx site to the Echo River site (Figs. 4 and 6). However, because of the need to swim through a cave river, that is not the preferred route between sites. Echo River has several large tributaries (e.g. Roaring River, Mystic River, and Hanson's Lost River), while there are fewer River Styx tributaries, which tend to be much smaller. On the surface, the River Styx Spring (Figs. 2, 3 and 5B) is located approximately 1.6 river kilometers upstream from the Echo River Spring on the Green River (Figs. 2, 3 and 5C).

Study sites were located in River Styx, Echo River, the Green River, at River Styx Spring, and at Echo River Spring (Fig. 4). The River Styx sites were located in the areas of the river known as the Dead Sea and Lake Lethe. No differences were seen between the data at these two sites. Thus, the data were analyzed collectively as the River Styx data. The Echo River site was located in Echo River between Hanson's Lost River and the point where Roaring River enters Echo River. This location is not affected by the River Styx's stable, reverse-flow events.

The original Green River site was located at the Green River Ferry, immediately downstream of Echo River Spring. However, multiple early losses of the data loggers, due to flooding and vandalism, required the research team to abandon this location. Scouting from the ferry to shortly upstream of River Styx revealed no locations that: 1) the students could safely access, and 2) would not have the same potential for flooding and vandalism issues as the original location.

The USGS maintains a river station (#03308500) approximately 47-river kilometers upstream of the Green River Ferry at Munfordville, Ky. (Fig. 2). Relatively, little difference was seen between the original data collected at the Green

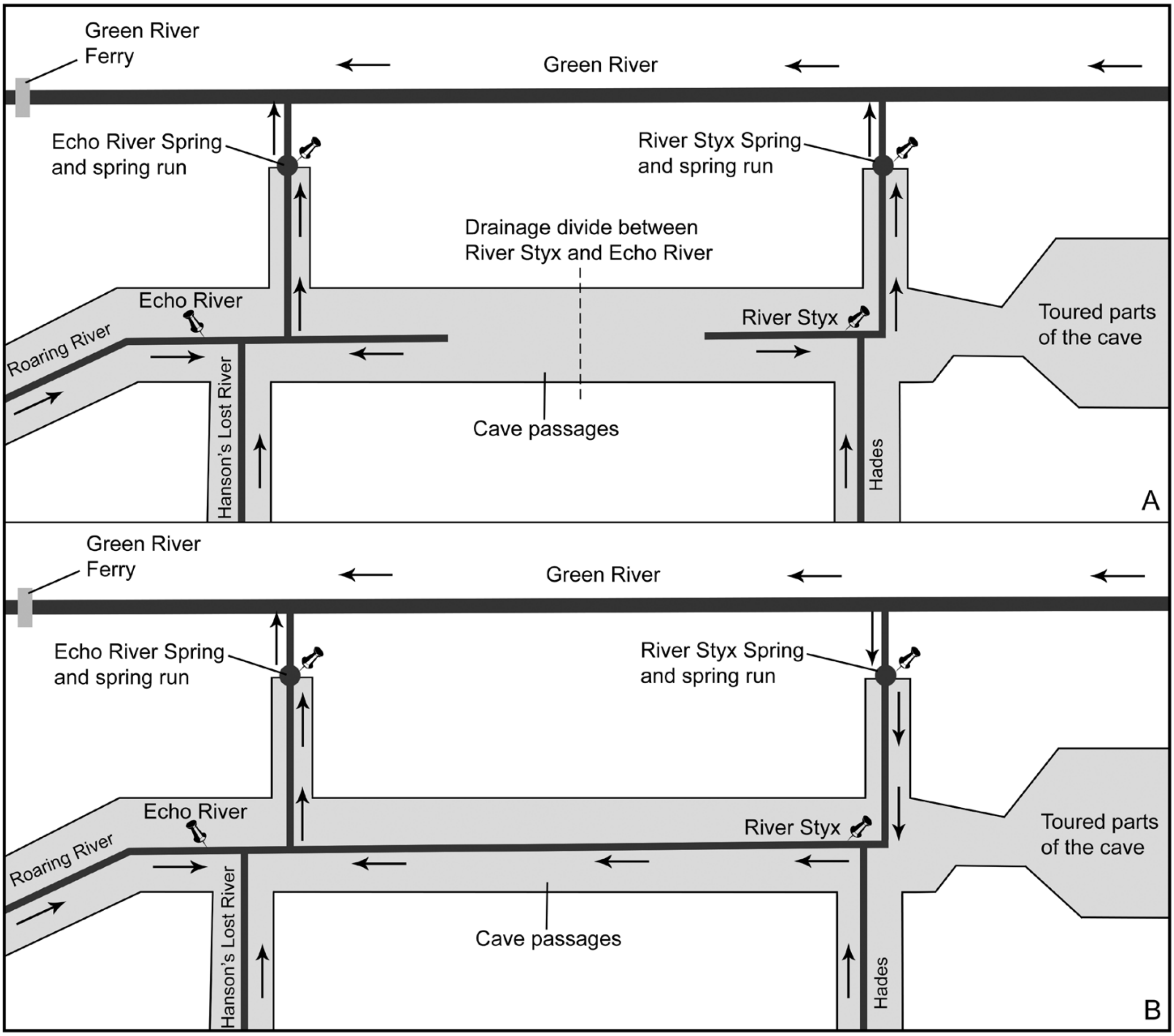

Figure 4. Schematic diagrams illustrating a) the normal flow pattern of River Styx out of the cave, and b) the reverse-flow pattern of River Styx into the cave. In diagram A, River Styx and Echo River are separated by a low, wide sandbar, which serves as a divide between the two karst drainage basins. When the River Styx reverses direction, it flows over the sandbar and into Echo River, as illustrated in diagram B. Pushpins show the study sites at River Styx, Echo River, and the two springs. Diagrams are highly simplified and not drawn to scale.

River Ferry and data collected by the USGS station in Munfordville for the same time period. The data trends for the two sites showed even less variation than the actual data points and, for this study, the patterns created by the data trends on the Green River were more important than the actual data points. Therefore, the decision was made to use data downloaded from the USGS station (USGS, 2015) as the Green River data during the remainder of the project. Earlier student analyses used a combination of data from the original site and the Munfordville station; however, only Green River data from the USGS station in Munfordville were used in this analysis.

Materials and Methods

Onset HOBO Pendant temperature/light data loggers (UA-002-64) were installed in late October 2009. The data loggers have an accuracy of ± 0.53 °C from 0 °C to 50 °C (Onset, 2017). The data loggers were programmed to record water temperature every two hours.

Two data loggers were initially installed to provide backup and quality assurance of the data in River Styx, in Echo River, and at River Styx Spring. During periods of high karst flow, Echo River Spring can issue forth large amounts

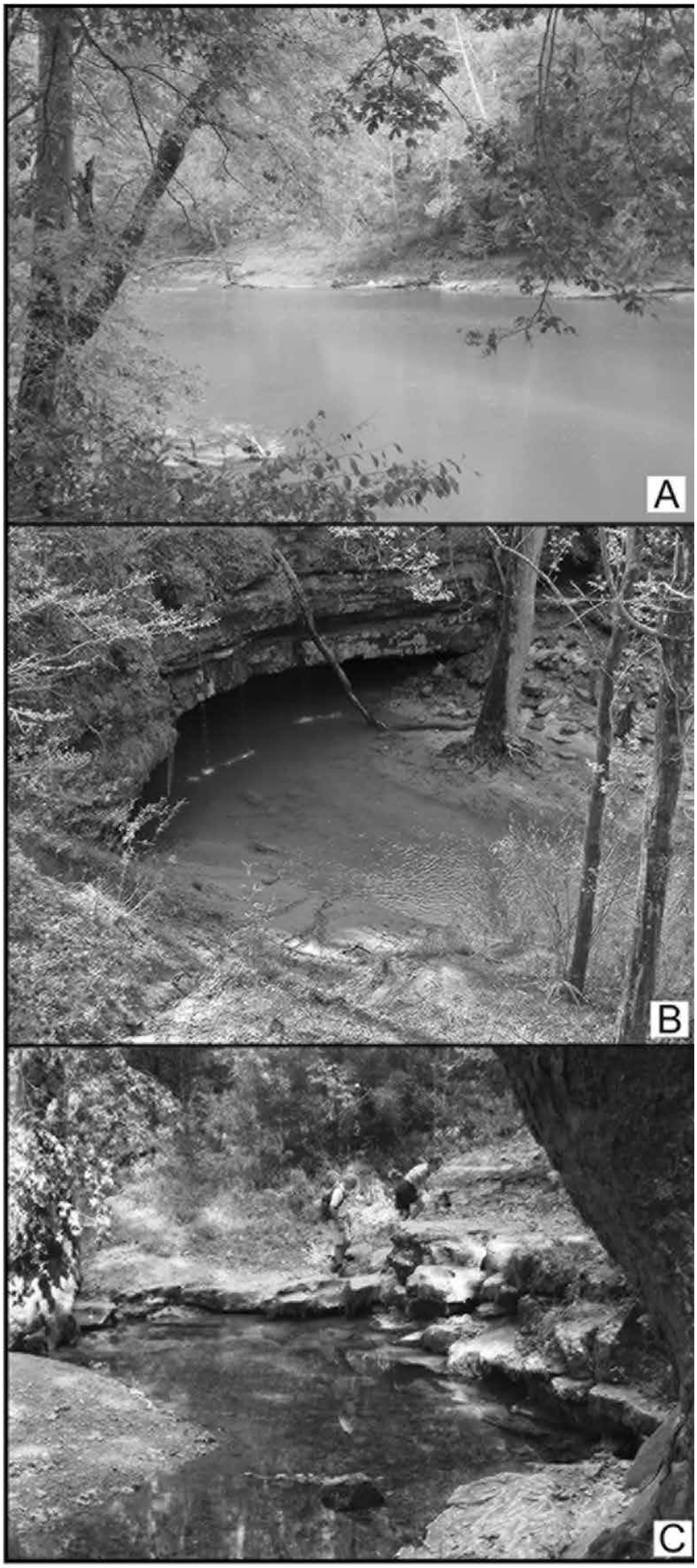

Figure 5. a) The Green River near the outflow of River Styx Spring, after the removal of Lock and Dam 6, looking downstream toward the River Styx Spring, b) River Styx Spring, and c) Echo River Spring.

of water at a rapid rate. This limited the locations where data loggers would: 1) remain in the water during low karst flow, 2) not be swept away during high karst flow events, 3) be easily accessible to the students, and 4) not be highly visible to the public. The best location that met all four requirements was a crevice that only had space for one data logger, thus only one data logger was installed at Echo River Spring. Even with backup data loggers in place, flooding and equipment failure resulted in occasional data gaps for all of the study sites. Lost data loggers were replaced as resources allowed.

This study analyzes the data collected between October 2009 and October 2012. Whenever a site had two data loggers simultaneously recording data, the mean temperature recorded for both data loggers was used. Overall, there was relatively little variance between the temperatures recorded by the two data loggers at a given site. When the data loggers differed by more than 1 °C, the data were inspected for quality control purposes. If it appeared one of the data loggers was out of the water, and thus, recording air temperature, or the data logger appeared to be malfunctioning, then those data points were removed from analysis.

Water temperature was graphed over time for each of the rivers for each week, where corresponding data were available from River Styx, Echo River, and the Green River. The graphs represented 103 weeks and more than 8,600 data points per river. Water temperature in the underground rivers is relatively constant year-round unless a reverse-flow event (from either back-flooding or a stable, reverse-flow) is occurring.

Temperature was used as a proxy for identifying the flow direction of the River Styx. Data were analyzed by comparing the River Styx temperatures to those of Echo River and the Green River. When the River Styx temperature was more similar to the Echo River temperature than to the Green River temperature, the River Styx was assumed to be flowing in its normal direction (out of the cave). If the River Styx temperature was more similar to the Green River temperature than to the Echo River temperature, then it was assumed to be in a stable, reverse-flow. The Green River was assumed to be back-flooding into both underground rivers if the temperatures for all three rivers were similar.

Occasionally, the river direction could not be determined because the Green River temperature was too close to the mean temperature of Echo River and River Styx (such as in the spring or fall), or because there was no clear pattern when comparing the graphs of the three rivers. The lack of a clear pattern occurred most often for short events, such as a possible, brief return to forward flow (out of the

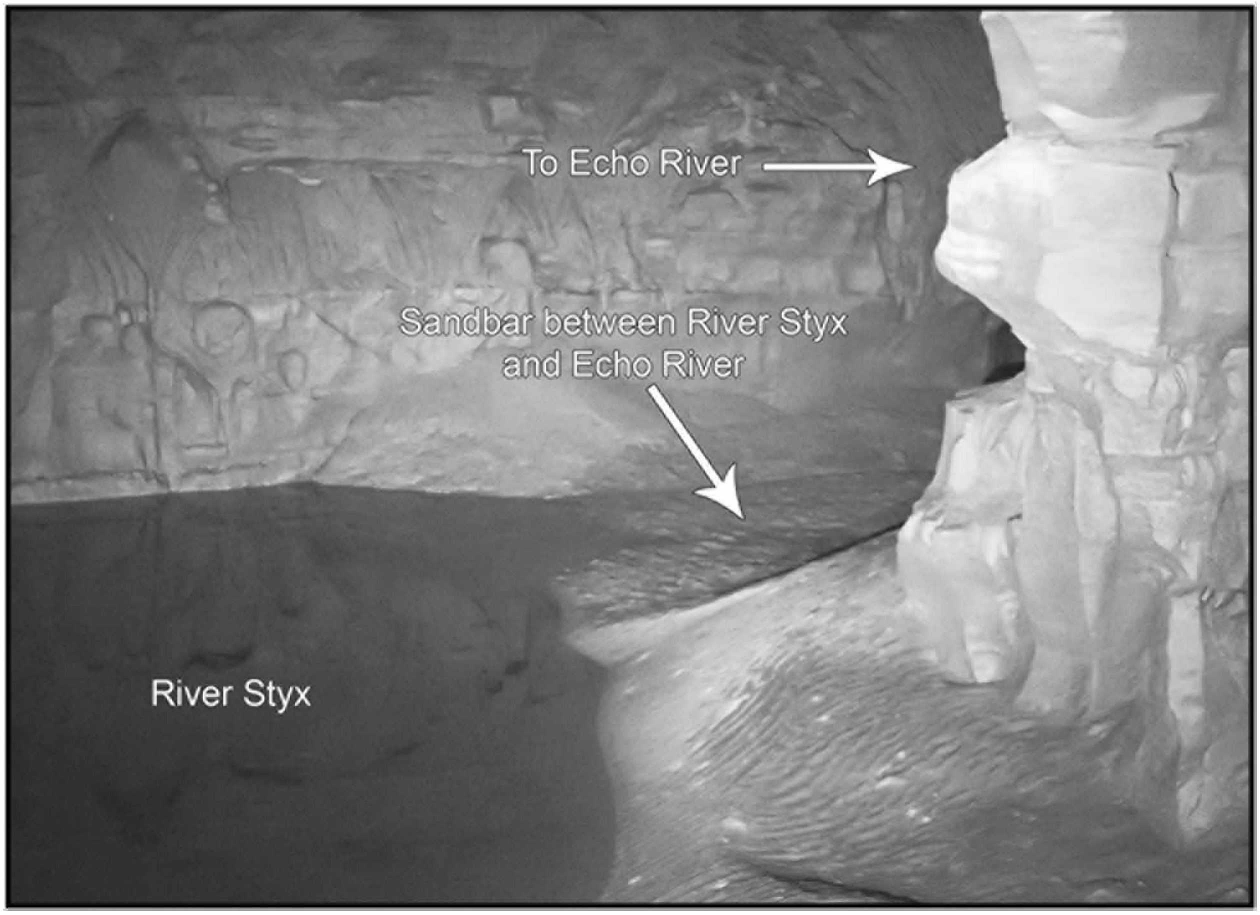

Figure 6. Under normal flow conditions, River Styx and Echo River are separated by the low, wide sandbar seen in this photo. River Styx is visible in the foreground. Continuing down the passage by walking across the sandbar would lead to Echo River. One could then wade or swim through Echo River to the Echo River study site. When the River Styx reverses, this sandbar is submerged, and River Styx flows freely into Echo River.

cave) between two reverse-flow events. There were also a few instances where it was obvious that the River Styx was reversed, but a determination could not be made as to whether it was a back-flooding event or a stable, reverse-flow event. This occurred most often during transition periods, as from back-flooding to stable, reverse-flow events.

Mammoth Cave National Park staff record the level of the Green River at the Green River Ferry twice a day, when the ferry is operating. River levels for each day of the study period were obtained from park records. The two data points for each day were averaged to give a mean, daily level of the Green River. Mean, daily precipitation from the three park weather stations was also obtained from park records. To analyze the influence of precipitation upstream of the park, daily precipitation totals from the NOAA climate station at Greensburg were downloaded from NOAA's website (NOAA, 2016). The station at Greensburg was chosen because it was located on the Green River, upstream of the park, and was well outside of the park boundary.

Each day of the study was coded as to whether River Styx was predominantly flowing forward (out of the cave) or was predominantly reversed (flowing into the cave). The reverse flows were also coded as either back-flooding or stable, reverse-flow events. Logistic regression, using XLStat 2017 software, was used to compare the flow direction of the River Styx (forward or reversed) to the level of the Green River, the local daily precipitation amounts, and the daily amount of precipitation at Greensburg, Ky. Logistic regressions allow the user to model the relationship between a binary, dependent variable (e.g., presence of a reverse flow) with one or more independent variables (e.g., river levels or daily precipitation) (XLSTAT, 2017).

Results

Water temperature

Between October 2009 and October 2012, the temperature in Echo River remained relatively constant with a mean temperature of 13.4 °C and a standard deviation of ± 0.6 °C (Table 1). The mean temperature in River Styx was similar

Table 1. Minimum, maximum, and mean temperatures recorded for each site between October 2009 and October 2012.

Temperature Range	Temperature, °C				
	River Styx (underground) *n* = 13,004	Echo River (underground) *n* = 8,602	Green River (surface) *n* = 12,581	River Styx Spring *n* = 13,002	Echo River Spring *n* = 7,571
Minimum	3.6	9.2	0.7	2.2	4.2
Maximum	23.8	14.4	29.5	26.3	18.4
Mean	13.5 ± 2.7	13.4 ± 0.6	15.5 ± 7.2	13.0 ± 3.5	13.0 ± 1.6

Table 2. Water temperature in each river and at both springs, when the lowest water temperature was recorded at each site between October 2009 and October 2012. The * indicates the lowest-recorded temperature at that site.

Date	Time	Temperature, ºC					Condition of River Styx Based on Graphs
		River Styx	Echo River	Green River	River Styx Spring	Echo River Spring	
02/01/2010	1600	3.6 *	13.1	3.5	3.5	6.4	Stable, reverse flow
12/08/2010	0200	8.2	9.2 *	7.9	7.8	8.5	Back-flooded
01/08/2010	0800	11.1	13.3	0.7 *	6.4	12.6	Normal flow direction
12/16/2010	0200	11.8	12.4	2.9	2.2 *	11.4	Normal flow direction
12/14/2010	0600	11.8	12.3	2.9	7.9	4.2 *	Normal flow direction

to that of Echo River, but it had a higher degree of variability (13.5 ± 2.7 °C, Table 1). The Green River had the highest mean temperature and the greatest degree of variability (15.5 ± 7.2 °C, Table 1).

The minimum temperature recorded at River Styx was 3.6 °C on February 1, 2010 (Table 2). River Styx remained at 3.6 °C for approximately four hours and was within 0.5 °C of the recorded low for approximately one day. Temperature at Echo River Spring at that time was 6.4 °C (Table 2). The temperature in Echo River at that time was 13.1 °C, indicating the River Styx was in a stable, reverse-flow pattern, and contributing a large percentage of the flow out of Echo River Spring. Analysis of the graph (Fig. 7) for this time period confirmed this interpretation.

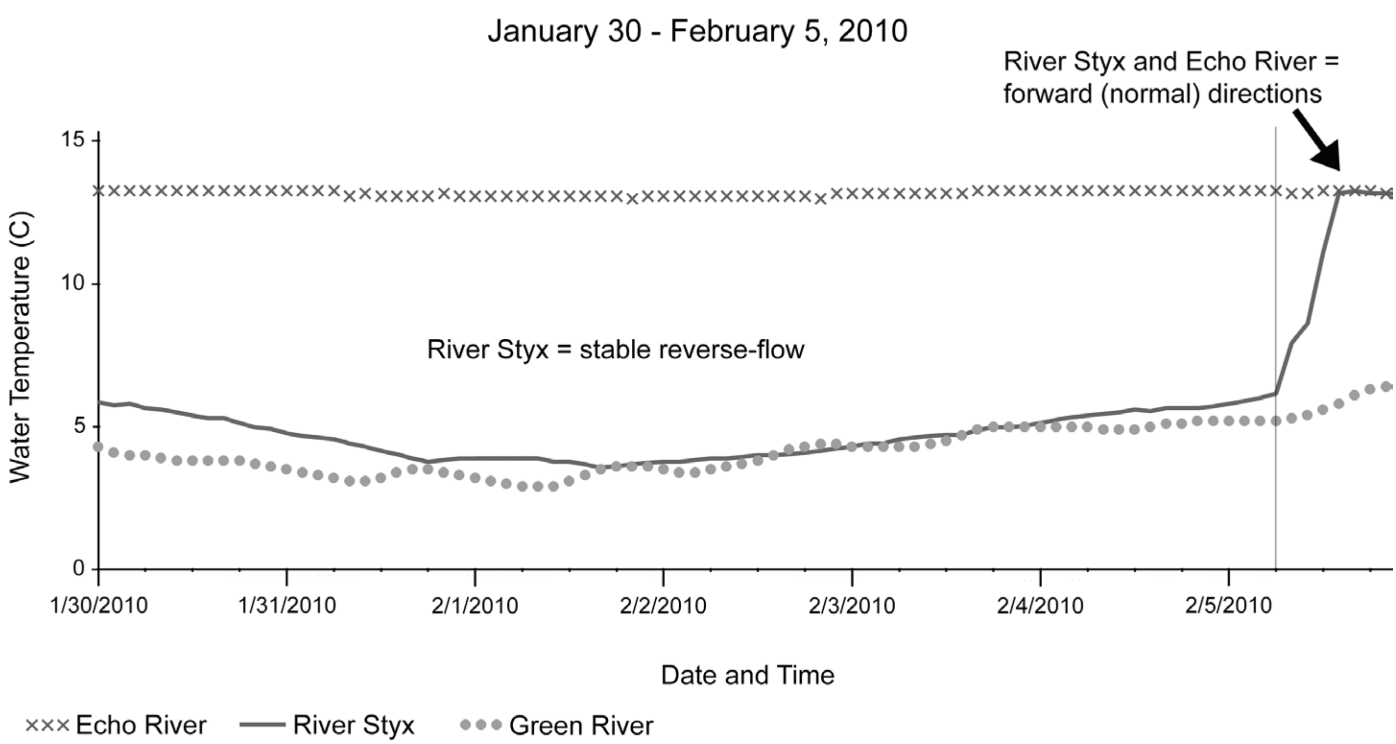

Figure 7. Time-series graph of water temperatures in River Styx, Echo River, and the Green River for the week of January 30 to February 5, 2010. Comparing the pattern of the River Styx water temperatures with those of the Green River and Echo River, confirms that River Styx was in a stable, reverse-flow pattern, when it reached its lowest recorded temperature of 3.6 ºC on February 1, 2010.

Minimum temperature recorded in Echo River was 9.2 °C on December 8, 2010 (Table 2). Echo River remained at 9.2 °C for approximately eight hours, and was within 0.5 °C of the recorded low for approximately 0.75 days. At the same time, River Styx was 8.2 °C and the Green River was 7.9 °C. Both springs also had similar temperatures. The similar water temperatures at all five sites indicate that the Green River was flooding and forcing water back into its tributaries. Based on the associated graph, shortly after the minimum temperature was recorded at Echo River, the back-flooding stopped and Echo River returned to a normal flow direction, while River Styx entered a stable, reverse-flow pattern (Fig. 8).

The maximum temperature recorded at Echo River was 14.4 °C on November 1, 2009 (Table 3), and the temperature remained at 14.4 °C for approximately 2.25 days. River Styx, Green River, and River Styx Spring all had similar temperatures (Table 3). Although the temperatures were similar and above Echo River's mean, the associated graph indicates that all three rivers were flowing in their normal directions during this time (Fig. 9). This interpretation makes sense, given the time of year, and illustrates why the patterns represented in the graphs were important to the analysis.

Maximum temperature recorded for River Styx was 23.8 °C on September 3, 2010 (Table 3), and lasted approximately two hours. The temperature was within 0.5 °C of 23.8 °C for approximately eight hours. Similar temperatures were recorded at the same time for Green River and River Styx Spring (Table 3). Whether the maximum temperature in River Styx was due to a stable, reverse-flow event or a back-flooding event cannot be determined because no data from the corresponding times are available from Echo River.

Reverse flows

The periods when data were recorded for all three rivers were October 23, 2009 to April 2, 2010, October 25, 2010 to May 15, 2011, and November 3, 2011 to October 24, 2012. Analysis of the graphs from these periods identified 34 times when the River Styx was in a stable, reverse-flow condition, five back-flooding events, when Green River water backed up into both cave rivers, and 10 times when the River Styx could not be classified as flowing forward (out of the cave), back-flooding, or in a stable, reverse-flow. Throughout the study, the River Styx flowed in its normal direction (out of the cave) approximately 77 % of the time and was either back-flooding or in a stable, reverse-flow approximately 20 % of the time. In each year, at least one stable, reverse-flow event was recorded every month from December through February. Two of the three years also showed stable, reverse-flow events in November and March.

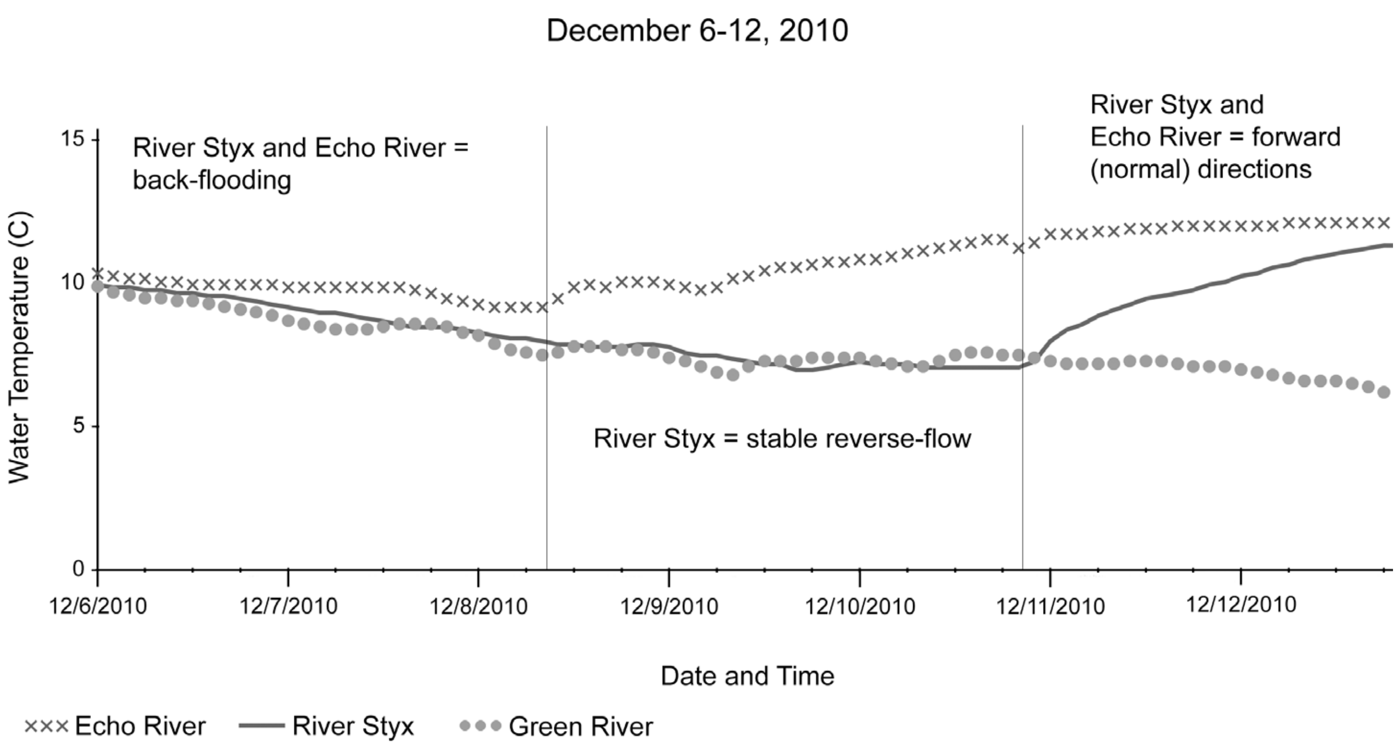

Figure 8. Time-series graph of water temperatures in River Styx, Echo River, and Green River for the week of December 6−12, 2010. Comparing the pattern of River Styx and Echo River's water temperatures with those of the Green River, confirms that River Styx and Echo River were back-flooding when Echo River reached its lowest-recorded temperature on December 8, 2010. The graph also shows that Echo River stopped back-flooding shortly after reaching its lowest-recorded temperature, while River Styx entered a stable, reverse-flow pattern.

Table 3. Water temperature in each river and at both springs, when the highest water temperature was recorded at each site between October 2009 and October 2012. The * indicates the highest-recorded temperature at that site. No graphs could be created for periods when there were no Echo River temperature data.

Date	Time	Temperature, °C					Condition of River Styx Based on Graphs
		River Styx	Echo River	Green River	River Styx Spring	Echo River Spring	
09/03/2010	0400	23.8 *	•••	22.1	22.5	•••	Unknown—no graph
11/01/2009	0400	14.3	14.4 *	14.3	14.3	•••	Normal flow direction
07/27/2012	1800	13.6	13.8	29.5 *	13.8	13.8	Normal flow direction
07/13/2011	1600	17.1	•••	24.6	26.3 *	14.2	Unknown—no graph
06/23/2011	0600	20.8	•••	19.6	20.2	18.4 *	Unknown—no graph

Duration of the stable, reverse-flow events varied greatly. Using temperature as a proxy for determining flow direction, some events appeared to last only a few hours, while others lasted for more than a week. Often, River Styx shifted flow direction multiple times in a week. The frequent switching of directions was most pronounced from mid-March 2011 through, at least mid-May 2011, when the data logger at Echo River stopped recording. During these two months, the River Styx switched 13 times between stable, reverse-flow events, periods of indeterminate flow direction, and normal flow patterns. Two approximately eight-day periods were the longest continuous periods when the River Styx was flowing forward (out of the cave) during this time. River depth at the Green River Ferry during this time ranged from a minimum of 1.6 m to a maximum of 10.2 m, with a mean of 4.7 m, and a standard deviation of 2.1 m.

Back-flooding events during the study period were rare compared to stable, reverse-flow events. However, there appears to be a relationship between back-flooding and stable, reverse-flow events. All five back-flooding events identified during this study were immediately preceded or followed by a stable, reverse-flow event. Two of the back-flooding events were sandwiched between two stable, reverse-flow events.

Logistic Regression

No significant relationship was found between local daily precipitation ($P = 0.66$) or daily precipitation at Greensburg ($P = 0.43$) and the flow direction of the River Styx. Logistic regression showed a strong relationship between the level of the Green River and the direction in which River Styx was flowing ($p < 0.0001$).

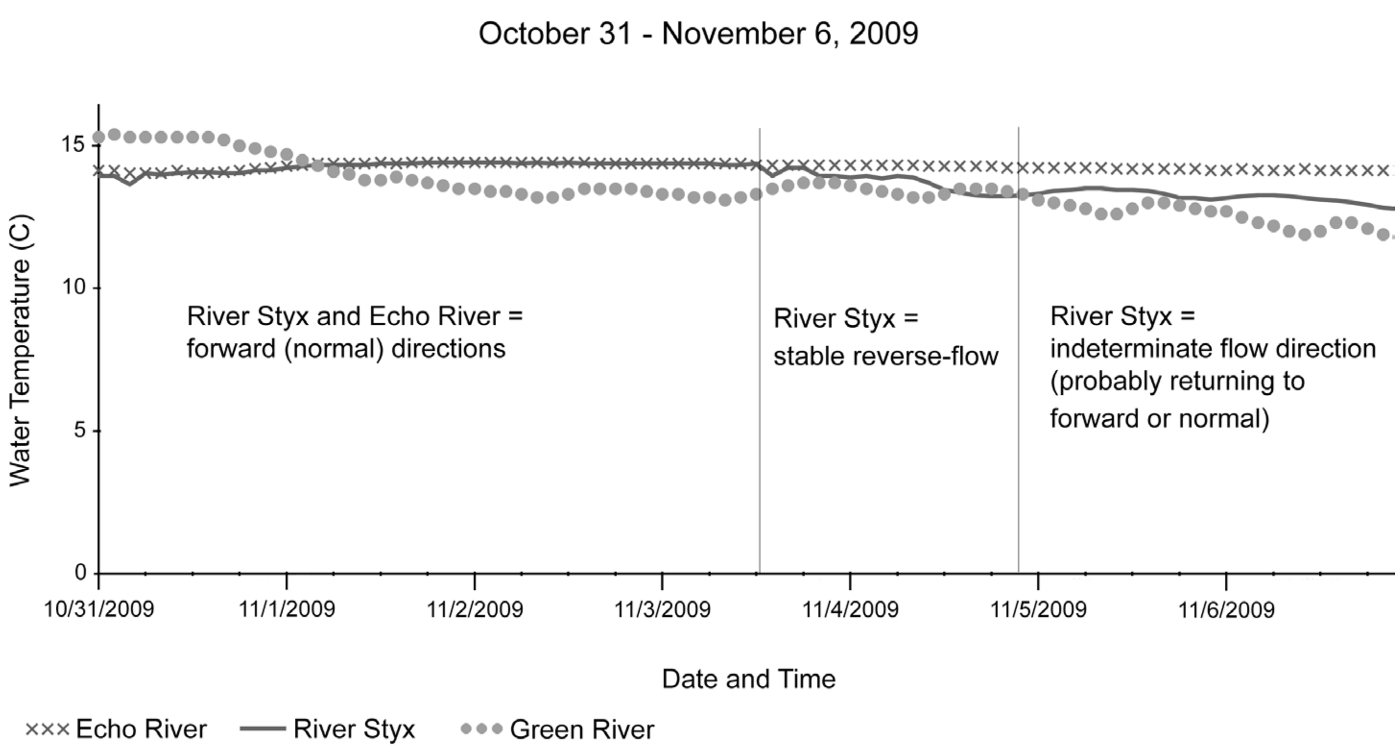

Figure 9. Time-series graph of water temperatures in River Styx, Echo River, and Green River for the week of October 31 to November 6, 2009. Comparing the pattern of River Styx and Echo River's water temperatures with those of the Green River, confirms that Echo River and River Styx were flowing forward (out of the cave), when the maximum temperature was recorded in Echo River on November 1, 2009. Both underground rivers remained relatively constant during this time, while the Green River was decreasing in temperature.

Table 4. Number of days and percentage of days when the River Styx was primarily flowing forward (out of the cave), backwards (into the cave, subdivided into stable reverse-flow or back-flooding), or the direction could not be determined.

River Styx	Periods of Examination and Days and Percent Days of Flow											
	Oct. 2009 to April 2010		Oct. 2010 to May 2011		Nov. 2011 to May 2012		June 2012 to Oct. 2012		Oct. to May 2009, 2010, 2011		All Four Seasons	
	Days	Percent	Days	Percent	Days	Percent	Days	Percent	Days	Percent	Days	Percent
Forward (out of the cave)	106	65	145	71	158	75	146	100	409	71	555	77
Backward (into the cave)	46	29	54	27	48	23	0	0	148	26	148	20
Stable, Reverse-Flow	45	28.4	48	24	36	17	0	0	129	23	129	17
Back-Flooding	1	0.6	6	3	12	6	0	0	19	3	19	3
Unknown	10	6	4	2	5	2	0	0	19	3	19	3

Discussion

Using Proxies

Edwards (2009) compared several proxies and found temperature changes to be the best indicator of reverse flow events in River Styx. However, relying on a proxy, such as water temperature to determine flow direction, presents inherent challenges to any study. Obviously, the temperature of the underground rivers does not instantaneously change when the river direction changes. There is a lag time between when a reverse flow event begins and when the change in water temperature is detected by the data loggers, or is evident in a graph. Another lag time occurs at the end of a reverse-flow event and may be a different duration than the beginning lag time. The original USGS studies (Hendrickson, 1961; Brown, 1966) would have suffered from similar challenges, but in terms of salinity instead of temperature. Despite the challenges associated with using proxies to determine flow direction, the patterns identified are supported by the data.

Timing and Duration

Based on data from April 30 to May 16, 1954, Brown (1966) concluded the River Styx stays in a stable, reverse-flow condition for most of the winter and early spring. He also concluded that the stable, reverse-flow conditions would be interrupted only when locally heavy rainfall resulted in a temporary rise in the level of the River Styx. The data from this study failed to support Brown's conclusions.

During the three winters and early springs of this study, the number of days when the River Styx primarily flowed backward, either due to stable, reverse-flow events or back-flooding, was only 148 days or approximately 26 % of the time (Table 4). The highest percentage of time when the River Styx was reversed during any of the three winters and early springs was 29 % of the time between October 23, 2009 and April 2, 2010. No reverse flows were detected in November 2010 or April 2011. Overall, the River Styx primarily flowed forward and exited the cave at River Styx Spring for approximately two-thirds to three-quarters of the time during each of the 2009–2010, 2010–2011, and 2011–2012 winters.

One potential explanation to the differing results of the two studies could be a matter of scale. Brown (1966) indicated that the River Styx Spring could potentially alternate between in-flow and out-flow several times within a half-hour period. If this is the case, then the current study could have missed a substantial number of rapid, reverse-flow events because the loggers only recorded data once every two hours. Also, visual analysis of the data was conducted from graphs, representing one week of data. If the data were re-analyzed by graphing the data on a daily basis, it may be possible to detect smaller-magnitude or shorter-duration, reverse-flow events that were undetectable on a weekly basis. This conclusion is supported by comparing the current analysis with the original analysis done by the students.

The students originally graphed the data on a monthly basis and identified 15 stable, reverse-flow events. By graphing the data on a weekly basis, this study identified more than twice as many stable, reverse-flow events. However, increasing the number of stable, reverse-flow events detected does not necessarily increase the amount of time in which the River Styx was detected as flowing backward. Many shorter events could add up to approximately the same length of time, or possibly even less time, than a single event that encompassed all of the shorter events. Therefore, it seems unlikely that the different rate of data recording and scale of analysis could fully explain the high degree of difference observed between Brown's study and the current study. To fully explain the difference, physical explanations, such as the influence of the Green River stage, the influence of precipitation patterns, and anthropogenic influences on the Green River, need to be explored.

Influence of Green River Stage

Hendrickson (1961) indicated that reverse-flow conditions were possible whenever the Green River is above a gage height of 129.1 m. This would be equivalent to a reading of 1.1 m on the NPS staff gage at the Green River Ferry, before Lock and Dam 6 failed. (A level of 1 m on the Green River Ferry staff gage prior to Lock and Dam 6 failing was equal to approximately 128 m in the older USGS studies, which were reported as height above mean sea level.) Brown (1966) concluded the stable, reverse-flow conditions would occur whenever the Green River stage is high and the River Styx stage is low. According to Brown (1966), only a 0.06 m difference in stage heights between the River Styx and the Green River could change the direction that the River Styx was flowing.

Logistic regression confirmed a strong relationship between the level of the Green River and River Styx reversals. However, it is not a simple relationship because there were numerous times during the study period, when the Green River was high but the River Styx was flowing out of the cave. One potential explanation could be that the karst basin was at high flow during those times, thus preventing the Green River from entering River Styx Spring. This explanation fits with the conclusions of Hendrickson (1961), Brown (1966), and Meiman (2006), that stable, reverse-flow events typically take place when the Green River is at a higher stage than the River Styx, and the karst basin is at low flow.

Influence of Precipitation

Brown (1966) stated that locally heavy rainfall could result in interruptions of stable, reverse-flow events. Precipitation is also one of the factors that can affect the level of the Green River. Local precipitation and/or precipitation upriver from the park, therefore, could be important factors contributing to the reverse-flow events. However, logistic regression failed to detect a significant relationship between daily precipitation and the direction of the River Styx for either local precipitation or precipitation upriver from the park at Greensburg.

Despite the lack of a direct relationship between the River Styx reverse-flow events and daily precipitation, an indirect relationship with precipitation still exists. Climate change in the southeastern U.S. is predicted to affect the timing, duration, and intensity of precipitation events (Melillo et al., 2014). These changes will have obvious impacts on the timing and duration of any regional or local flood or drought conditions, and thus, on the level of the Green River and the amount of karst flow. As discussed earlier, there is a strong relationship between the level of the Green River and the River Styx's flow direction. Therefore, it stands to reason that any changes in the timing, duration, and frequency of droughts or floods in the Green River, Echo River, and River Styx drainage basins will also affect the timing, duration, and frequency of the River Styx reverse-flow events.

Anthropogenic Influences

The potential role of precipitation in stable, reverse-flow or back-flooding events is complicated by the fact that the level of the Green River is only partially controlled by precipitation. A number of artificial structures also greatly affect the level of the Green River.

Green River Dam is the largest anthropogenic influence on the Green River. The dam did not exist when Hendrickson and Brown conducted their studies on the River Styx and its stable, reverse-flow events. At that time, precipitation was the primary factor influencing the level of the Green River. However, that is no longer the case. In the spring and summer, water is held behind the dam for flood control and recreational purposes. Each fall, the U.S. Army Corps of Engineers releases 2.1 m of water from the Green River Dam to drop the lake to winter pool level. Those releases temporarily raise the level of the Green River through Mammoth Cave National Park, and can cause the River Styx to enter a stable, reverse-flow or back-flooding event.

The dam releases do not necessarily correspond to daily precipitation events, and can complicate any conclusions based solely on recorded precipitation. Over the last few years, the timing of the annual winter drawdown has shifted from earlier in the fall to later in the fall. This later timeframe is closer to the time when winter rains in the area would naturally begin causing the River Styx to flood, or set up a stable, reverse-flow pattern. However, while the general timing of the releases may be closer to a more natural, precipitation-driven pattern for higher Green River levels, that still does not mean there is a simple correlation between daily precipitation patterns and river level.

Until recently, Lock and Dam 6 also influenced the level of the Green River within Mammoth Cave National Park. The pool created by Lock and Dam 6 artificially raised the level of the Green River, Echo River and River Styx. The U.S. Army Corp of Engineers stopped operating Lock and Dam 6 in 1951. In a report to the National Park Service Advisory Board, Dunn (1951) recommended the U.S. Army Corps of Engineers remove Lock and Dam 6 to allow the Green River, and its underground tributaries within Mammoth Cave, to return to their more natural 19th-century levels. From 1951 through 2016, Lock and Dam 6 continued to deteriorate, while the U.S. Army Corp of Engineers conducted numerous studies on the Green River locks and dams.

On November 25, 2016, Lock and Dam 6 failed, causing the level of the Green River at the Green River Ferry to drop approximately 0.34 m in the first eight hours after the failure. At the Green River Ferry, the level of the Green River continued to drop at a much slower rate until the afternoon of November 28, 2016, when a rain event moved into the area. The level of the Green River is still adjusting to the new conditions, and research on the impacts of Lock and Dam 6 on the levels of the Green River and its underground tributaries is ongoing. It is hypothesized that the breach of Lock and

Dam 6 will result in fewer River Styx back-flooding and stable, reverse-flow events. Fewer stable, reverse-flow events are hypothesized because the lower Green River base-flow elevation will require an additional rise before reaching the stage where it begins to flow into the River Styx Spring. This will likely be a more natural condition than what has been experienced over the last 110 years. Data collected in this study will provide important additional data for testing this hypothesis.

Conclusions

Proxies can provide important information on stable, reverse-flow and back-flooding events in River Styx. To gain a more detailed understanding of these events, especially during transition periods, future research is needed that directly correlates proxies with a direct measurement of flow direction.

Over the last 50 years, the frequency and duration of reverse-flow events in River Styx has changed. The primary cause of this change is likely due to the anthropogenic influences of the Green River Dam on the level of the Green River.

This study provides a baseline, multi-year dataset of temperature variation in Mammoth Cave's underground rivers before the removal of Lock and Dam 6. As such, the data are now irreplaceable.

With Lock and Dam 6 in place, back-flooding and stable reverse-flow events could affect the temperature, nutrient availability, and potential contaminants in River Styx for approximately 20 % of the time each year. These changes could directly affect the aquatic ecosystems of River Styx, including habitat for the endangered Kentucky cave shrimp. By driving micro-climatic changes in the lower passages, the reverse flow events also had the potential to indirectly affect archeological and geological resources.

Now that Lock and Dam 6 has been removed, this study needs to be repeated to better understand the effect of Lock and Dam 6 on the River Styx and its stable, reverse-flow events. If, as hypothesized, the removal of Lock and Dam 6 results in fewer stable, reverse-flow events, new studies may be needed to determine how the aquatic ecosystem in River Styx responds to the more stable water temperatures resulting from fewer stable, reverse-flow events.

Future studies should include collecting water level data in the River Styx, at the River Styx Spring, and in the Green River near where the spring run for the River Styx Spring enters the Green River. The data on water levels will provide a better understanding of how the level of the Green River and the amount of karst flow interact, especially during stable, reverse-flow events and back-flooding events.

Additional studies are needed on the interactions of cave sediments and karst flow in River Styx and Echo River. During back-flooding and high, karst flow events, large amounts of sediment can be rearranged in the vicinities of the underground rivers. This includes creating and removing natural sediment dams in parts of the underground rivers. The patterns of movement related to these sediments could change as a result of the lower Green River, River Styx, and Echo River levels since the removal of Lock and Dam 6.

Better understanding the causes and impacts of the stable, reverse-flow events in River Styx could provide additional information for making science-informed, management decisions about anthropogenic controls of the Green River, such as releasing water from the Green River Dam. In recent years, the U.S. Army Corps of Engineers changed the timing and pattern of its water releases in the fall to minimize the impacts on freshwater mussels living in the Green River. Currently, little to nothing is known about the impact of the water releases on the endangered Kentucky cave shrimp or other cave aquatic organisms.

New research is needed to monitor the cave meteorology in the lower passages of Mammoth Cave. The cave meteorology data will help determine how the stable, reverse-flow events and back-flooding events in River Styx influence the micro-climates of the lower cave passages, and how far those effects extend away from the underground river passages. Understanding the micro-climatic changes related to the River Styx stable, reverse-flow and back-flooding events is important because those changes can affect the biological, geological, archeological, and cultural resources found in the cave's terrestrial environments. Long-term collection of water temperature and river levels in River Styx, Echo River, and the Green River could help document and better understand the direct effects of climate change on Mammoth Cave's aquatic environments and the indirect effects on resources found in the cave's terrestrial passages.

Acknowledgments

The authors thank the teachers, Susan Ryan and Kim Weber, and the approximately 120 students who collected data, analyzed data, and presented earlier results of the project. Thanks also to the T. K. Stone Middle School administration and teachers, who allowed the students to miss class so they could conduct this research. In addition, the authors thank Dr. Tom Byl and the anonymous reviewers who provided valuable advice for improving this paper.

References

Brown, R.F., 1966, Hydrology of the Cavernous Limestones of the Mammoth Cave Area Kentucky: Geological Survey Water-supply Paper 1837, 63 p.

Dunn, A.V., 1951, Report on Hydrological Investigation, Mammoth Cave National Park, August 29 to September 6, 1951, United States Department of the Interior, National Park Service, Washington, D.C, 17 p.

Edwards, A., 2009, The Hydrochemistry of surface water back-flooding into a karst spring and into cave stream passages in Mammoth Cave, Kentucky, USA [M.S. Thesis]: Bowling Green, Kentucky, Western Kentucky University, 81 p.

French, C. and Trimboli, S., 2017, A Preliminary investigation into the source of micro-climatic changes observed in the lower passages of Mammoth Cave, Bowling Green, Kentucky, Western Kentucky University, 2017 Student Research Conference.

Hendrickson, G.E., 1961, Sources of water in Styx and Echo Rivers, Mammoth Cave, Kentucky, U.S. Geological Survey Professional Paper, 424-D: D41−D43.

Meiman, J., 2006, Water Resources Management Plan: Mammoth Cave National Park. United States Department of the Interior, National Park Service, Washington, D.C, 258 p.

Melillo, J.M., Richmond, T.C., and Yohe, G.W., editors, 2014, Climate change impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. https://doi.org:10.7930/J0Z31WJ2.

National Oceanic and Atmospheric Administration, 2016, Climate Data Online: http://www.ncdc.noaa.gov/cdo-web/ (accessed November 15, 2016).

Olson, R., 1996, This old cave: the ecological restoration of the historic entrance ecotone of Mammoth Cave and mitigation of visitor impact: *in* Proceedings of the 5th Annual Mammoth Cave National Park Science Conference, p. 87−95.

Onset, 2017, HOBO Pendant® temperature/light 64K data logger specifications, Online: http://www.onsetcomp.com/products/data-loggers/ua-002-64 (accessed September 28, 2017).

Ruhl, M., 2005, Flow reversal events increase the abundance of nontroglobitic fish in the subterranean rivers of Mammoth Cave National Park, Kentucky: Master thesis, Western Kentucky University. http://digitalcommons.wku.edu/thesis/475.

Trimboli, S.R., Toomey, R.S., Weber, K., and Ryan, S., 2011, The misbehaving spring: studying unique underground river flow patterns with advanced middle school science students: *in* Proceedings, George Wright Society Conference on Parks, Protected Areas, and Cultural Sites, p. 311−316.

United States Geological Survey, 2016, National Water Information System: Web Interface: http://waterdata.usgs.gov/nwis/uv/?site_no=03308500&amp (accessed December 16, 2015).

XLSTAT, 2017, Logistic regression (Binary, Ordinal, Multinomial, …): Online: https://www.xlstat.com/en/solutions/features/logistic-regression-for-binary-response-data-and-polytomous-variables-logit-probit (accessed September 28, 2017).