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Abstract

Karst ground-water basin divides are generally depicted as two-dimensional lines on maps, but they are better considered as three-dimensional surfaces within the subsurface. Dye traces are necessary to map out these surfaces and to locate conduits inaccessible to cave surveyors, and are indispensable for understanding the geometry of the complex networks of flow paths through the aquifer.

A key reason why the Mammoth Cave System is the world's longest known cave is that its passages extend over several major ground-water basins. The divides between these basins define the drainage system geometry and precise location of them is critical for understanding and protecting the cave and its remarkable aquatic ecosystem. In 1999 we initiated a long-term program of dye tracing within the Mammoth Cave System to more precisely locate the divides and to understand their increasingly apparent complexities. In this paper we report on results of some of the more interesting dye injections of the program. Although the Mammoth Cave Karst Aquifer is perhaps the best understood conduit flow network in the world (with over 700 traces), we have found that much more work is needed to provide the level of understanding necessary for protection and conservation. The first reason is a matter of scale and resolution: with the current distribution of traces that define the ground-water basins, many regional basin divides are only approximately defined. In areas where this condition exists in combination with potential threats to ground-water quality (primarily urban and transportation areas) additional tracing is needed to know the flow paths of individual recharge points. A second reason for additional traces is to increase our understanding of the plumbing of active conduits through the karst aquifer. While this type of dye tracing is logistically demanding, requiring visits to in-cave dye recovery locations, it is adding a new level of detail to our understanding of the nature of the karst aquifer.

Introduction

Since the first dye-trace was performed at Mammoth Cave in 1925 – Anderson, working for Louisville Gas and Electric, conducted several traces, including Three Springs to Echo River Spring, to demonstrate that ground water can travel through adjacent ridges which would pose engineering problems for a proposed high-dam on the Green River near Pike Spring (Brown, 1966) – dye-tracing has been used as the primary investigative tool for understanding, and thus, protecting the karst aquifer. A major effort was undertaken in the mid 1970's through the early 1980's (Quinlan and Ray 1981, 1989), which resulted in the first major survey of the ground-water Basins in the Mammoth Cave region. Among other important conclusions, their work showed that approximately 60% of the aquifer's recharge area extends beyond the boundary of Mammoth Cave National Park, and was thus impacted by agricultural land use. During the early 1990's Meiman and Ryan (1992) concentrated dye tracing efforts to the north side of the Green River where 16 ground-water basins were defined, again with many basins recharged by private lands. There have been many "specialized" traces over the past ten years, including a series of quantitative traces by Ryan (1992), flow-velocity traces by Murphy (1992), flood pulse tagging Hall (1994) and Ryan and Meiman (1996), and traces along Interstate 65 by Meiman and Capps (1995). It cannot be overstated that without these works we would know very little about the overall hydrogeology of the Mammoth Cave karst aquifer.

Within the past year and a half there has been a renewed interest in dye tracing at Mammoth Cave, with more than 20 dye injections since late May of 1999. While at first glance it might appear that the ground-water basin definition gained by these earlier studies

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has provided all the information needed to fully delineate karst ground-water basins in and around Mammoth Cave National Park, we have found it necessary to further these efforts with additional tracing.

There are two main reasons, in this arguably most intensively investigated karst aquifer in the world, that additional tracing is needed. The foremost reason is a matter of scale and resolution; as the areal distribution of traces, which define the ground-water basins, is quite lacking in detail proximal to many basin divides – of special concern as 60% of the national park's karst watershed is located on private lands (Figure 1). In some cases there are several kilometers between injection sites with basin divides drawn somewhere in between, and in large part based upon ground-water potentiometric data. In areas where this condition exists in combination of potential threats to ground-water quality (primarily urban and transportation areas) additional tracing is needed to know the flow paths of individual recharge points. This situation is best represented in the Cave City area where the boundary between the Turnhole Spring ground-water basin (which drains northwestward into the national park) and the Gorin Mill ground-water basin (which drains to the east through Hidden River Cave). This three-kilometer segment of boundary, through the continuously developing urban sections of Cave City, is defined by only three dye traces.

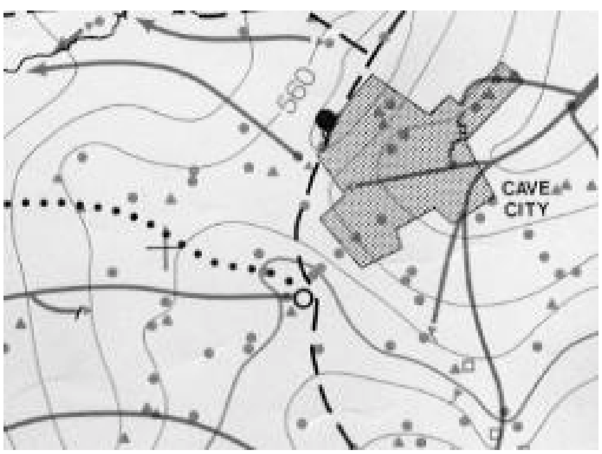

Figure 1. A portion of the 1:138,000 scale map "Groundwater Basins in the Mammoth Cave Region, Kentucky", Quinlan and Ray (1989). Ground-water basin and sub-basin divides are shown as dashed and dotted lines, respectively. Approximately 10 km^2 are shown in this view.

A second reason for additional tracing is to increase our understanding of the plumbing of active conduits through the karst aquifer. For the most part past tracing efforts have focused on surface injection points and spring recovery points, defining regional boundaries in a basic two-dimensional projection of the aquifer. We know, for example, that if a dye is introduced into a sinkpoint on the surface, and emerges at a spring, that the dye course has traversed active flow cave conduits. It would be very helpful, in respect to examining cave evolution and development, if a more detailed picture of the flow routes were described. As one could imagine this type of dye tracing is logistically demanding (requires visits to cave dye recovery locations), but it can be very rewarding. This in-cave tracing is the main focus of this paper.

Upon reading this paper you may notice the ubiquitous use of place-names. While the reader may not be familiar with these locations it would not be possible to write this paper without them. We will attempt to briefly describe these areas when necessary.

Turnhole Spring Ground-water Basin

The 244 km^2 ground-water basin, by far the largest contributing flow into the park, has been the focus of study and water quality initiatives over the past 25 years. It is divided into the Mill Hole, Proctor, Cave City and Patoka Creek sub-basins. Each sub-basin is drained by a main trunk conduit: the Mill Hole stream, Hawkins River (Red River in Whigpistle Cave) Logsdon River, and Hawkins River, respectively. The vast majority of the sub-basins are under-represented by accessible cave streams. We know that there is active cave passages within these areas, but, for the most part, cannot gain access – usually due to passage collapse or sumps.

Denial River

The portion of the Cave City sub-basin adjacent to the boundary of the Pike Spring basin within Roppel Cave presents an atypical situation, as many active flow passages are present. Near the upstream termination of Logsdon River at the S-188 Sump lies a complex tangle of small stream passages, one of which is called Denial River. This upstream portion of Logsdon River is also geologically interesting as Logsdon is apparently perched atop the Corydon Chert for much of its eight-kilometer traverse downstream to Pete Strange Falls, and then flows to Turnhole Spring on the Green River. There have been numerous air-filled stream passages found at elevations above and *below* Logsdon River in this area. Denial River was traced in order to begin unraveling this picture. Previous traces show that lower streams in this area, the flow from the Western Kentucky Parkway passage for example, drains

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northwards to Pike Spring. On October 19, 1999 approximately 0.5 kg of powder eoscien dye was injected into Denial River, which receives flow from a series of vertical shafts. Dye was recovered within two weeks at Pete Strange Falls and not at Pike Spring, showing that Denial River is a tributary of Logsdon River and thus within the Turnhole Spring Basin. This was the first in a series of traces from this area of the cave and many more traces will be necessary to fully understand its complex plumbing.

Turnhole-Roaring/Echo Overflow

During the flurry of dye tracing in the late 1970's and early 1980's, Quinlan and Ray (1981 and 1989) discovered the existence of a high-level overflow route linking the main trunk of Turnhole Spring's Proctor sub-basin to the Echo River Spring ground-water basin. This overflow junction is inaccessible due to sumps in all river passages leading to it. Meiman and Ryan (1993) injected dye into Logsdon River during the recession limbs of various floods and demonstrated that this overflow route – which allows water from the Turnhole Basin to spill over into the adjacent Echo River Basin– is active when the stage of Logsdon River near its confluence with Hawkins River exceeds three meters over base flow stage (Figure 2). This was important information as the Echo River ground-water basin, which is almost exclusively within park boundaries during low flow times and harbors the endangered Kentucky Cave Shrimp, receives flow from nearly 100 km^2 of lands beyond the park boundary when Logsdon River stage is greater than three meters. Stage excesses of three meters is quite common. A reconstruction of float level records between 1984 and 1988 shows that this horizon was exceeded 38 times; periods when the aquatic ecosystem of Roaring and Echo Rivers were recharged largely by non-park lands.

Figure 2. Simplified diagram of the hydrogeology of the Turnhole Spring basin with the inter-basinal overflow to Echo River Spring.

Some discoveries are unintentional. On April 24, 2000, in support of a pesticide flood pulse-sampling effort, approximately two kg of powder fluorescein dye were injected into the Big Clifty/Girkin contact swallet at Cinnamon Falls – the Big Clifty is a sandstone unit overlying the 100 meter-thick carbonate sequence, with the Girkin being the uppermost limestone formation . Under almost any other circumstances investigators would not use such a copious quantity of dye. However, this trace, injected on the leading edge of a forecasted large rainfall event, was designed to place a sufficient amount of dye to "tag" a flood pulse and to detect in grab samples some five kilometers downstream in Logsdon River. Rainfall was intense during the injection, however within minutes after the dye was underground the rain event stopped. It did not rain again for weeks. This left 2 kg of fluorescein slowly coursing through base-flow cave streams. The flood pulse sampling operation was aborted. Two weeks later, while collecting dye receptors along the Green River, the Echo River Spring site exhibited a very strong presence of fluorescein. The highest stage in Logsdon River since the injection was approximately 0.5 meters above base level. A subsequent dye receptor recovery within Roaring River (an upstream tributary to Echo River Spring within the cave) also showed a strong positive. Dye (and thus water) is leaking into Roaring/Echo Rivers from Logsdon River during base

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flow. We believe that this flow route was not observed by previous investigators because, until now, no one had made the mistake of using far too much dye during base flow conditions, as "normal" quantities of dye would dilute into Roaring/Echo Rivers in concentrations below detection limits.

What does this mean? One possible explanation, relative to speleogenesis, is that we are witnessing the earliest stages of ground-water basin piracy. For many years Hawkins and Logsdon Rivers were the upstream portion of Roaring/Echo Rivers. At some point – perhaps due to a retreating nick-point in the Green River passing the Turnhole Bend cause by a increased incision rate of the Green – a more efficient route was established pirating flow from Hawkins River to Turnhole Bend Spring. Over time, as this piracy became the dominant flow route, the original route into Roaring/Echo was only used during high-flow periods as an overflow. It may be possible that this low-level "leak" marks the beginning of Roaring/Echo taking its flow back. Another explanation may be that the present overflow route, although a large, higher conduit, is simply wrought with many small "leaks" at lower elevations.

It is also possible for dye introduced into Logsdon River to find a secondary route before it even reaches the confluence of Hawkins River and the downstream sump and overflow area (one possibility is that the dye may enter Roaring/Echo via is upstream tributary Mystic River, however that idea was discounted as the above-mentioned dye receptor, which is far upstream of the confluence of Mystic, was positive). It remains possible, however, that the dye is taking an unknown route to the upstream segment of Roaring River. Additional simultaneous traces at Cinnamon Falls and at the Hawkins Sump under similar flow conditions are planned.

Aside from a hydrogeologic curiosity, what relevance does this have to cave management and protection? The discovery of the overflow route brought about major changes to conservation efforts of park managers, as it was proven that the sewer-less community of Park City flowed directly into endangered species habitat of the main active flow trunk of Mammoth Cave. This discovery was extremely important to the realization of a regional sewer system. Until now, it was thought at least Roaring/Echo River would be spared contamination events during low flow, but apparently not.

Crystal Cave

Because Cooper and Collins Springs (both Haney Limestone springs perched upon the Big Clifty Sandstone) are well within the delineated bounds of the Pike Spring ground-water basin they, have apparently never been traced. With the assistance of Art and Peg Palmer, we placed dye receptors at six locations within the Crystal Cave section of the Mammoth System and introduced dye into the Big Clifty/Girkin contact swallets below Cooper and Collins Springs. Both dyes appeared at Pike Spring as suspected. Although the dye from Cooper Spring was not recovered within any of the monitored springs within Crystal Cave, the trace from Collins Spring (located 900 m north of Cooper) was detected in a strong positive at the C-3 Waterfall Campsite within the cave. We have not given up on finding and in-cave recovery point for Cooper Spring. This fall we re-traced the Cooper swallet after placing receptors in three locations in Sides Cave (nearby but not directly connected to the Mammoth System by exploration), which terminates near Crystal Cave and will retrieve them when weather permits.

Outward Bound

In support of a Western Kentucky University Hoffman Environmental Research Institute study of land use delineation for the U.S. Fish and Wildlife Service a trace was initiated from the eastern-most known stream in the Roppel Cave section of Mammoth, therefore, the eastern most stream in the Mammoth System. It was possible that this stream recharged the proximal Suds Spring along the Green River. If so, this would mean that the Mammoth Cave System spans seven major ground-water basins and sub-basins – perhaps adding additional relevance and protection to the Suds Spring basin. The Outward Bound trace flowed to Pike Spring, and thus did not end up adding to the known recharge area of the cave system. Nonetheless, this added new hydrogeologic information.

Three Springs

As mentioned in the introduction, the first dye trace in the Mammoth Cave area was performed at Three Springs. Quinlan and Ray (1981, 1989) traced this perched Haney Spring to Styx Spring. Meiman and Ryan (1993) found both Echo River Spring and River Styx Spring to receive flow from Three Springs. During the late fall of 1999 dye was again introduced into the Big Clifty/Girkin contact swallet of Three Springs, except this time, in addition to placing receptors at Echo and Styx Springs, we also monitored eight locations along River Styx within the cave. All receptors were positive – from the First Arch to the Dead Sea in the Cave, as well as Echo and Styx Springs. Although the Styx/Echo conduits were not experiencing a flow reversal event (water from the Green River entering Styx Spring, running through the cave and exiting at Echo River Spring), the system was not quite at base-flow levels. The flow conduit from Three Springs may enter the Echo/Styx Rivers upstream from the flow bifurcation of Echo River (see the next trace description to further examine the relationship between Echo and Styx). Additional tracing is needed, with receptors placed in Roaring and Mystic Rivers to pin-down its location.

An additional curiosity was found during autumn 1999 when Park Ecologist Rick Olson removed a visitor-constructed rock dam at Styx Spring. The removal of this dam, which increased the pool elevation of Styx Spring by several centimeters, did not register with the stage monitoring probe in the Dead Sea (which can resolve stage changes of 0.01 mm). This may indicate that there exists a free-surface segment of River Styx between its sump, as the change in stage was not propagated to the Dead Sea from Styx Spring.

Service Station

All parking lots (and associated contaminants) within Mammoth Cave National Park drain into the cave system. The lot surrounding the service station near the main campground is no exception. During the fall of 1999 we injected dye into the Big Clifty/Girkin contact swallet behind the service station after placing receptors throughout the River Styx area of the cave. It should be noted that five endangered Mammoth Cave Shrimp were observed while placing receptors in the Hades section of River Styx. The highest elevation that dye was recovered was Shaller's Brook (a shaft drain off of Gratz Avenue). From there, after dropping through Lee's Cistern, the dye appeared at Hades, River Styx, the Dead Sea, and Styx and Echo River Springs. The park will soon begin construction of oil, grit, and metal removal filters on all major parking lots within the park.

The fact that dye which entered River Styx via the Hades stream – which is at the downstream end of Styx near the Dead Sea and well downstream of the Echo-Styx split – was also detected at Echo River is perplexing. Recall that the trace from Three Springs also appeared in Styx and Echo Springs, although that injection site was well distal and upstream of the Echo-Styx bifurcation. The service station trace was also conducted under "normal" flow conditions, that is to say, low-flow with no flow-reversal. Is it possible that a second conduit exists between River Styx and Echo River downstream of the River Styx sump? If not, was there a flow bifurcation within the vertical shafts leading down into the base-level, shunting flow to both Echo and Styx Springs? A rather simple trace by dumping dye into the Styx sump was preformed in November of 2000 and dye was only detected at Styx Spring, leading us to believe that the bifurcation is somewhere in the vertical shafts above the base-level streams upstream from Echo and Styx springs.

Floating Mill Hollow

Upon close inspection of the map "Groundwater Basins of the Mammoth Cave Region, Kentucky" (Quinlan and Ray, 1989) one might find a few apparently minor springs along the Green River for which their recharge area is unknown. There are other small springs that do not appear on this or any other map. One such spring was found near the mouth of Floating Mill Hollow in 1999. Most of the time this spring does not appear to flow, because like other small springs, base-flow is discharged into the riverbed through alluvial filled under-flow spring. Basically, the surface springs orifice, where the dye receptors were placed, acts as an overflow discharge.

In the late spring of 1999 we placed receptors in all known springs from the upstream park boundary to Echo River Spring in preparation for a trace from Candlelight River, a small shaft drain stream along the famous Flint Ridge-Mammoth Cave connection route of 1972. According to the map of Quinlan and Ray (1989), Candlelight River should drain to Pike Spring. A few "old-timers" also had opinions on the spring that receives water from Candlelight – either Pike or Echo River Spring. If nothing else, dye-tracing came be a humbling enterprise: the dye appeared at neither Pike nor Echo, rather the newly discovered Floating Mill Hollow Spring (Figure 3). A new watershed was defined.

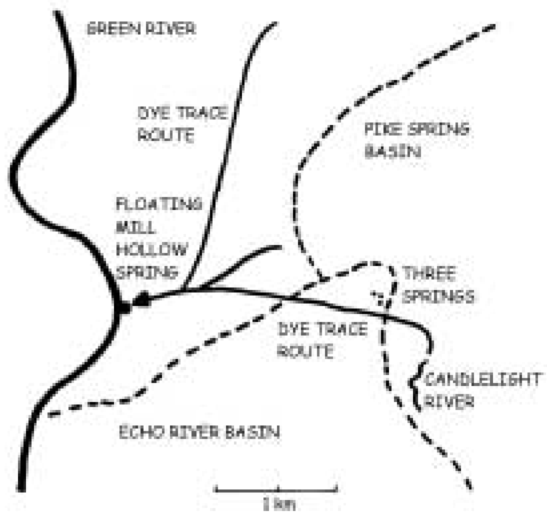

Figure 3. Dye traces to Floating Mill Hollow Spring. Dashed black lines, Quinlan and Ray (1989) ground-water basin boundaries, Quinlan and Ray (1989), solid lines, hypothesized flow routes from recent traces.

The fact that Candlelight River, which was originally placed within the Pike Spring basin, drains to Floating Mill Hollow Spring is of particular interest as in order to reach Floating Mill Hollow Spring it must either pass over, under, or around the Three Springs portion of the Echo River basin. We can hypothesize three possible scenarios. It seems quite possible that the flow route from Candlelight River actually passes over the conduit draining Three Springs. As far as we know the shaft complexes beneath such large Haney springs such as Three Springs have not been discovered – if a cave explorer is interested in finding the largest vertical shafts in the Mammoth Cave System we have some ideas on where to look. The fact that they exist should not be an issue, as even non-descript sink-points can produce large shafts (Bottomless Pit is a good example). Given that a shaft exists beneath Three Springs, it is very likely that it is very large and deep, as it receives perennial flow from Three Springs in addition to runoff from rainfall events. It is possible that such a shaft cuts deep to base-level, ignoring lithologic changes. Conversely, a small shaft drain as Candlelight River is perched upon local resistant lithologies. This perching might cause such a small stream to run horizontally for several hundred meters before it falls towards base-level (Figure 4).

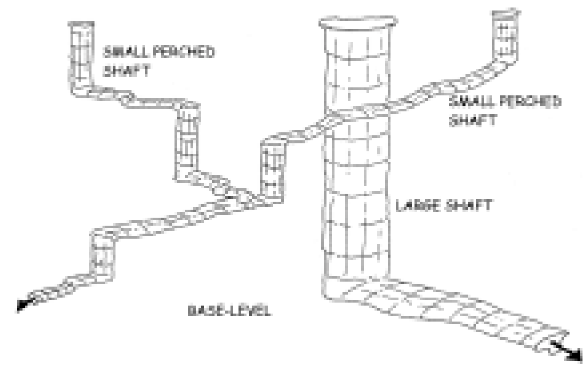

Figure 4. A simplified sketch of the complex three-dimensional nature of over-lapping karst ground-water basin divides – a possible explanation for the Candlelight River/Three Springs conundrum.

The discovery of a new ground-water basin led to two additional traces. Receptors were placed at Bögli Shafts and the river springs for a trace originating from the Big Clifty/Girkin contact swallet above the shafts. This trace was also recovered at Floating Mill Hollow Spring, however the receptors at Bögli Shafts were negative. It is very possible that individual shafts have such specific inputs that it is difficult to always make a connection.

A third trace was recovered at Floating Mill Hollow Spring from at trace initiated from the Big Clifty/Girkin contact swallet of Holton Hollow (the sinkpoint approximately 2.25 km north-northeast of the spring). Additional traces are planned for Rigdon, Taylor Coats, and an unnamed hollow, all which lie between Holton and Floating Mill Hollows.

Conclusions

The past year and a half has been used as a trial to gauge the success of in-cave dye tracing. As predicted, such work is strenuous but provides important detail to interpret the hydrogeology of the cave and aquifer. We have learned a great deal already. Over the course of the next few years we plan many additional traces along these same lines. In addition to the future traces described above, we also plan on focusing on refining ground-water basin boundaries on the Pennyroyal Plateau, especially within developed portions of the watershed.

Another aspect of karst hydrogeology is becoming readily apparent from detailed in-cave dye tracing, especially proximal to basin boundaries: the complex three-dimensional nature of basin divides. This actually comes as no surprise as mature cave systems, such as the Mammoth Cave System, display intricate three-dimensional relationships between cave conduits, and therefore, ground-water basin boundaries are governed by the detailed geometry of flow routes.

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