

# AN EXAMINATION OF PERENNIAL STREAM DRAINAGE PATTERNS WITHIN THE MAMMOTH CAVE WATERSHED, KENTUCKY

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*Quantitative relationships describing the nature of surface drainage networks have been used to formulate flood characteristics, sediment yield, and the evolution of basin morphology. Progress has been slow in applying these quantitative descriptors to karst flow systems. Developing geographic information system (GIS) technology has provided tools to 1) manage the karst system's large, complex spatial datasets; 2) analyze and quantitatively model karst processes; and 3) visualize spatially and temporally complex data. The purpose of this investigation is to explore techniques by which quantitative methods of drainage network analysis can be applied to the organization and flow patterns in the Turnhole Bend Basin of the Mammoth Cave Watershed.*

*Morphometric analysis of mapped active base-flow, stream-drainage density within the Turnhole Bend Groundwater Basin resulted in values ranging from 0.24 km/km<sup>2</sup> to 1.13 km/km<sup>2</sup>. A nearby, climatologically similar, nonkarst surface drainage system yielded a drainage density value of 1.36 km/km<sup>2</sup>. Since the mapped cave streams necessarily represent only a fraction of the total of underground streams within the study area, the actual subsurface values are likely to be much higher. A potential upper limit on perennial drainage density for the Turnhole Bend Groundwater Basin was calculated by making the assumption that each sinkhole drains at least one first-order stream. Using Anhert and Williams' (1998) average of 74 sinkholes per km<sup>2</sup> for the Turnhole Bend Groundwater Basin, the minimum flow-length draining one km<sup>2</sup> is 6.25-7.22 km (stated as drainage density, 6.25-7.22 km/km<sup>2</sup>).*

A major emphasis in geomorphology over the past six decades has been on the development of quantitative physiographic methods to describe the evolution and behavior of surface-drainage networks (Horton 1945; Leopold & Maddock 1953; Leopold & Wolman 1957; Abrahams 1984). These parameters have been used in various studies of geomorphology and surface-water hydrology, such as flood characteristics, sediment yield, and evolution of basin morphology (Jolly 1982; Ogunkoya *et al.* 1984; Aryadike & Phil-Eze 1989; Jensen 1991; Breinlinger *et al.* 1993).

Many well-developed karst aquifers display drainage characteristics that appear similar to surface networks. The degree of similarities and their consistency throughout the whole of the karst drainage network are, however, generally unknown. Quantitative descriptors, known as morphometric parameters, have long been used to describe and predict stream network behavior for surface-flow systems. The purpose of this investigation was to explore techniques by which quantitative methods of drainage-network analysis can be applied to shed light on the evolution, organization, and flow patterns in the Mammoth Cave Watershed. Since an estimated 7-10% of the world's land surface is underlain by karst aquifers (Ford & Williams 1989), understanding the processes and behaviors of karst landscapes and their subterranean stream networks may help humankind to better utilize and manage the earth's natural resources.

## STUDY AREA: TURNHOLE BEND GROUNDWATER BASIN

The focus of this investigation is the Turnhole Bend Groundwater Basin, which is part of the Mammoth Cave Watershed. The Mammoth Cave Watershed consists of the Pike Spring, Echo River, Double Sink, River Styx, Floating Mill Hollow, and Turnhole Bend Groundwater Basins. Spanning 245 km<sup>2</sup>, the Turnhole Bend Groundwater Basin comprises over 75% of the 317 km<sup>2</sup> Mammoth Cave Watershed (Fig. 1).

The Mammoth Cave region lies 160 km south of Louisville, Kentucky, and 160 km north of Nashville, Tennessee (Fig. 1). The karst aquifer within the Mammoth Cave Watershed has developed in an ~160 m thick unit of Mississippian limestones. The aquifer is primarily developed in the Girkin, Ste. Genevieve, and St. Louis Limestones (Haynes 1964; Miotke & Palmer 1972). The cavernous limestones are overlain by the Big Clifty Sandstone, a relatively insoluble layer of Mississippian sandstone and shale. Three physiographic subprovinces comprise the Mammoth Cave Watershed: the Glasgow Uplands in the south, the Sinkhole Plain in the central region, and the Mammoth Cave Plateau in the north (Fig. 2).

The Green River, a tributary of the Ohio River, is the outlet for the Mammoth Cave Watershed. Mammoth Cave's karst flow networks are tributaries to the Green River and are, thus, controlled by the river's location and behavior. The close com-

**Table 1. Caves over one km long within the Turnhole Bend Groundwater Basin**

Cave Name	Cartographers	Cave Length (m)	Lateral Stream Length (m)
Martin Ridge Cave System	Alan Glennon, Don Coons, and Steve Duncan	52,143	14,777
James Cave	Glen Merrill	16,496	*
Lee Cave	Pat Wilcox	12,875	2,199
Parker Cave	Don Coons	10,461	5,198
Smith Valley Cave	Joel Despain	4,731	1,730
Coach Cave	Glen Merrill	3,218	300m estimate, not included in total
Emerson-Gift Horse Cave	Jim Borden	3,000	612
Brushy Knob Cave	Dave Black	2,104	*
Long Cave	Tim Schafstall	1,797	*
Cedar Spring Saltpeter Cave	Don Coons	1,217	*
Diamond Caverns	Gary Berdeaux	1,207	*
Renick Cave	Jim Borden and Jim Currens	1,030	*
Neighbor Cave	Alan Glennon	1,005	9
**minor caves: less than one km in length	Alan Glennon, Bob Osburn, Don Coons, and Jim Borden	-	235
Mammoth Cave System	Bob Osburn, Pat Kambesis, and Jim Borden	50,000 in Turnhole Basin (571,327 entire system)	16,173 in Turnhole Basin
<b>Total</b>		<b>161,284</b>	<b>40,933</b>

\* no surveyed perennial streams.

\*\* Numerous caves, less than a kilometer in length, contain perennial streams. However, these stream lengths have a lateral length less than 5m. Surveyed exceptions include Monroe Sandstone Cave 25 m, Mickey Mouse Cave 9 m, Indian Cave 30 m, Glennon Spring Cave 5 m, Cripple Creek 91 m, Owl Cave 15 m, South Valley Cave 60 m, and Pighistle Cave.

munication between the cave streams and Green River is exhibited in cave-level development within the caves as related to the geomorphic history of the Green River Valley. Fluvial downcutting of the Green River Valley is mirrored within the cave system, and has led to the development of tiered levels within the cave (Palmer 1981). As the Green River continuously downcuts its valley, lowering regional base level, cave streams develop conduits correspondingly deeper, and abandon higher flow routes. Consequently, the Mammoth Cave area is typified by multilevel caves, with the lowest levels containing the major active conduits hence, in general, the youngest cave passages. Beryllium and aluminum dating of quartz gravels by Granger *et al.* (2001) in the region's higher, abandoned cave levels, have found that Green River downcutting averages 30 m/Ma. These data reveal that major conduit development within Mammoth Cave's karst aquifer has been ongoing for at least three million years.

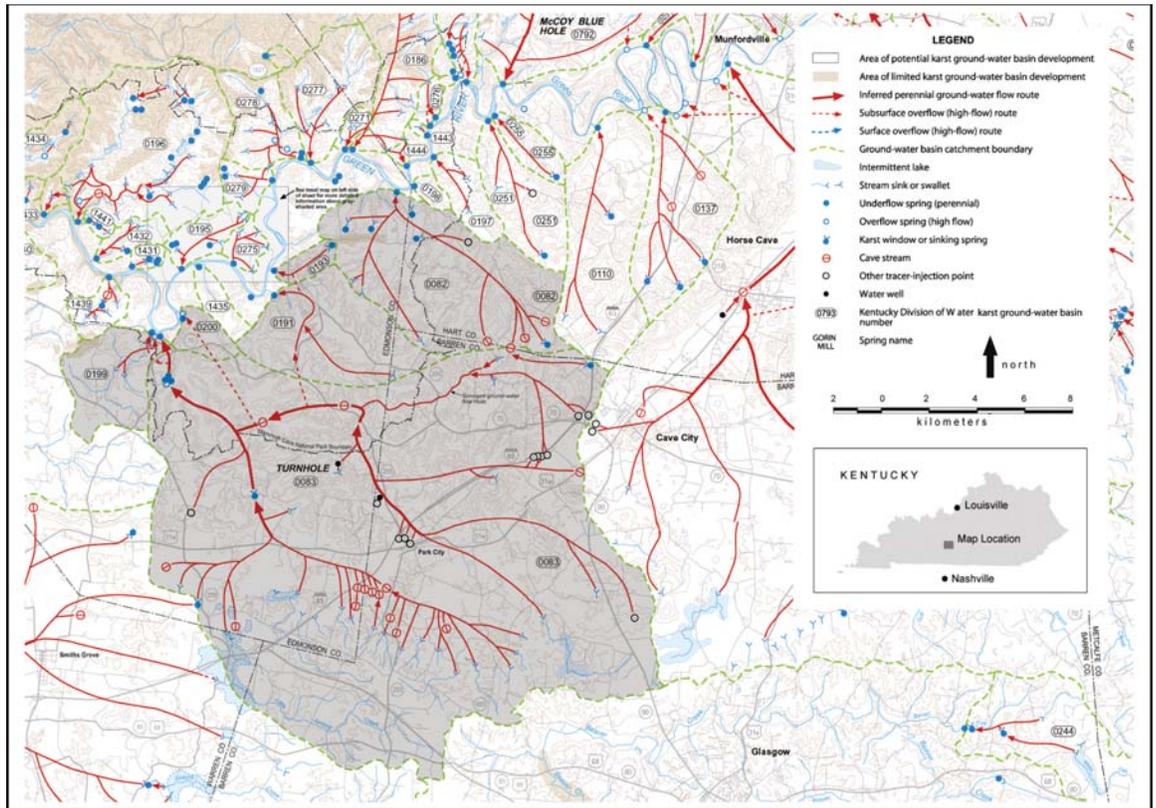
Within the Turnhole Bend Groundwater Basin, 120 individual caves possessing 10 m or greater true horizontal length have been cataloged for this project, 46 of these with perennial base-flow streams (Table 1).

## METHODS

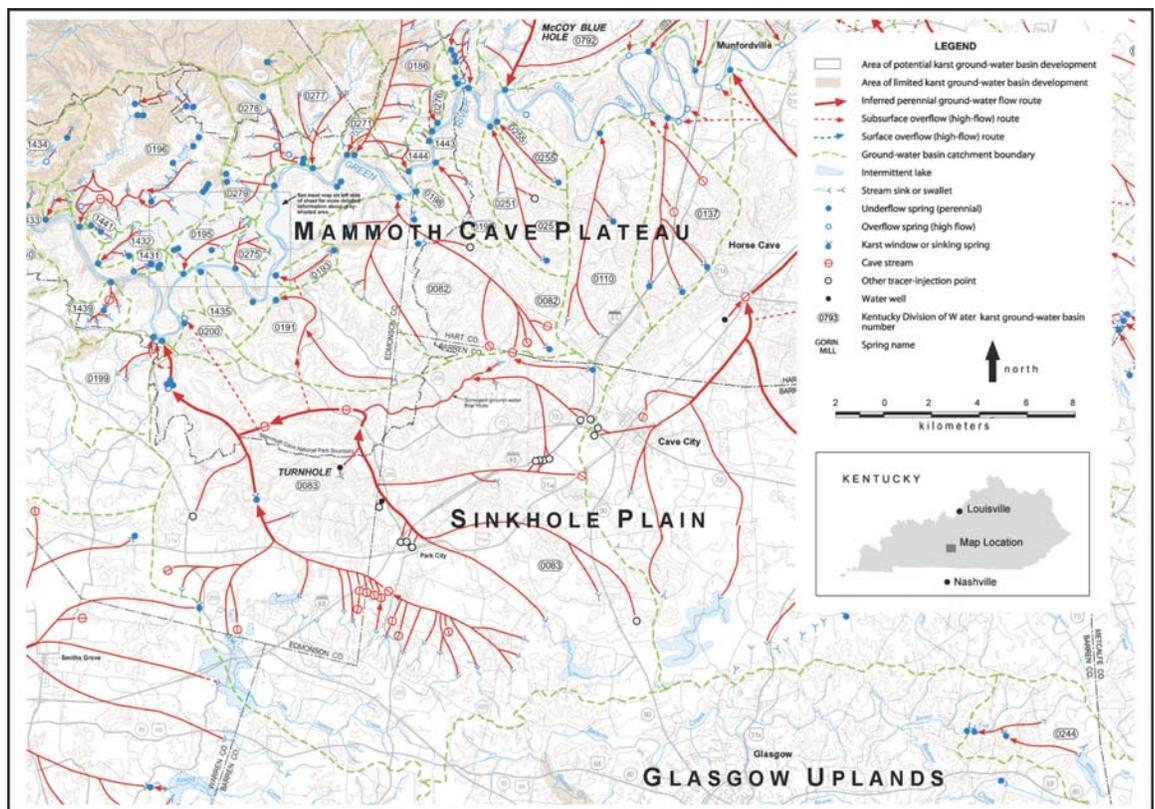
Compiling a consistently formatted dataset is one of the great challenges for the karst-aquifer modeler. In-cave survey data for the Mammoth Cave Watershed have been acquired over the last 180 years (e.g., Lee 1835; Hovey 1909; White & White 1989). Only within the last 20 years, however, have cave mappers increased survey standards to consistently include not only x and y coordinates but also elevation (z coordinates). Fortunately, since 80% or more of the cave streams within the Turnhole Bend Groundwater Basin have been discovered within the last 20 years, a majority of the dataset for this investigation includes accurate x, y, and z data.

Cave-survey data were acquired digitally from many different digital cave-data reduction programs. These included SMAPS, COMPASS, WALLS, Cave Mapping Language (CML), and spreadsheet macro-programs. Furthermore, much of the cave survey-data were available only as final paper cave maps. ArcView GIS and Arc/Info 8 were used to import these differing datasets and integrate them into a standard dataset. Each of the caves' data were imported into ArcInfo coverages and ArcView shapefiles using either AutoCAD import protocols, ArcView CaveTools, or manual digitizing.

**Figure 1.** Groundwater basins of the Mammoth Cave Watershed. Turnhole Bend (0083), Pike Spring (0082), Echo River (0191), Double Sink (0199), River Styx (0193), and Sand House (0200) Groundwater Basins comprise the Mammoth Cave Watershed (shaded). (modified from Ray & Currens 1998a, 1998b).



**Figure 2.** Location of Turnhole Bend Groundwater Basin (0083). For this investigation, the Double Sink Groundwater Basin (0199) is also included as part of the Turnhole Bend Groundwater Basin (modified from Ray & Currens 1998a, 1998b).



Cave passageways and streams were georegistered in the GIS using Universal Transverse Mercator coordinates, North

American Datum 1927, Zone 16. This projection and coordinate system were used in order to be consistent with datasets

**Table 2. Drainage Density Formulas**

Drainage Density (D)	Area Examined (A)	Surface Stream Length (s)	Cave Stream Length (c)	Dye Trace Length (d)
(1)	Total basin	Measured	Measured	Not included
(2)	Total basin	Measured	Measured	Straight Line
(3)	Total basin	Measured	Measured	“Smoothed” line
(4)	Total basin	Measured	Measured	Straight line * 1.5 <sup>a</sup>
(5)	Sub-basins total	Not included	Measured <sup>b</sup>	Not included

<sup>a</sup> 1.5 represents average sinuosity of other mapped large cave streams in the basin.

<sup>b</sup> only those stream lengths and areas with clear catchments included

Method	Drainage Density Equation	
(1)	$D = \left( \frac{s + c}{A} \right)$	<i>al.</i> 1999). Drainage basins were determined and digitized and included as ArcView shapefiles. In several cases, basins were further delineated in terms of sub-basins by normalized base-flow calculations (Quinlan & Ray 1995).
		DRAINAGE DENSITY
(2)	$D = \left( \frac{s + c + d}{A} \right)$	As a result of the nature of work performed by previous investigators and the nature of their collected datasets, this investigation focuses on two-dimensional, <i>areal</i> , morphometric relationships. Sustained research work in the Mammoth Cave area since the 1950s provided the necessary data on locations of cave streams, drainage area values, base-flow discharges, the potentiometric surface, and flood hydrographs (Meiman 1989; Quinlan & Ray 1989; Coons 1997; Duncan <i>et al.</i> 1998; Ray & Currens 1998a, b; Glennon 2001; Osburn 2001).
(3)	$D = \left( \frac{s + c + d}{A} \right)$	
(4)	$D = \left[ \frac{s + c + (d * 1.5^a)}{A} \right]$	The initial attempt at calculating a quantitative parameter for the Mammoth Cave Watershed was an examination of basin drainage density. Drainage density is defined as the combined length of all streams in a basin divided by the area of the basin (Strahler <i>et al.</i> 1958). It is a measure of average length of streams per unit drainage area, and describes the spacing of the drainage ways. Drainage density has been interpreted to reflect the interaction between climate and geology (Ritter <i>et al.</i> 1995). The inverse of drainage density, the <i>constant of channel maintenance</i> , indicates the minimum area required for the development and maintenance of a unit length of channel (Schumm 1956). Due to the prior scarcity of sufficient data and processing technology for the karst aquifer, drainage density represents a previously uncalculated numerical measure describing the manner in which a basin collects and transmits water through its network.
(5)	$D = \left( \frac{c^b}{A^b} \right)$	Five different techniques were used to calculate active, base-flow drainage density given the incomplete dataset available (Table 2). For all five methods, stream-segment lengths were calculated by adding perennial stream lengths as projected onto a horizontal plane. The following paragraphs outline how stream lengths were calculated and areas defined for the drainage-density calculation for each of the five methods.

<sup>a</sup> 1.5 represents average sinuosity of other mapped large cave streams in the basin.

<sup>b</sup> only those stream lengths and areas with clear catchments included

produced at Mammoth Cave National Park.

Once the cave datasets were integrated into ArcView and ArcInfo, several other layers were imported or created, including: hypsography (1:24,000), digital orthophotography (1:12,000), surface catchments above the Martin Ridge Cave System (1:12,000), perennial surface streams (1:24,000), and surface geology (1:24,000) (Glennon & Groves 1999; Pfaff *et*

## TECHNIQUE 1

First, the sum of mapped-segment lengths from subsurface and surface streams was calculated. Drainage density was calculated by dividing the stream-length summation by the area of the entire Turnhole Bend Groundwater Basin (Table 2). Since mapped cave streams reflect only a fraction of all streams in the karst flow network, several other approaches were devised to obtain possible drainage-density values.

## TECHNIQUE 2

A second approach to calculating drainage density entailed a procedure similar to technique 1, but with the inclusion of regional dye-trace data and surface-stream lengths (Table 2). This investigation calculated dye-trace flow lengths from a digital version of the Ray and Currens (1998a, b) maps. All mapped cave streams in the Turnhole Bend Groundwater Basin were summed to include the total length of surface streams and straight-line dye-trace route lengths. The dye-trace length can be calculated using straight-line lengths from dye input points to its output receptors. As streams converged, a minimum straight line flow length geometry was maintained for each segment. Together, these represent a minimum flow length within the Turnhole Bend Groundwater Basin that considers more of the unmapped and phreatic portions of the aquifer.

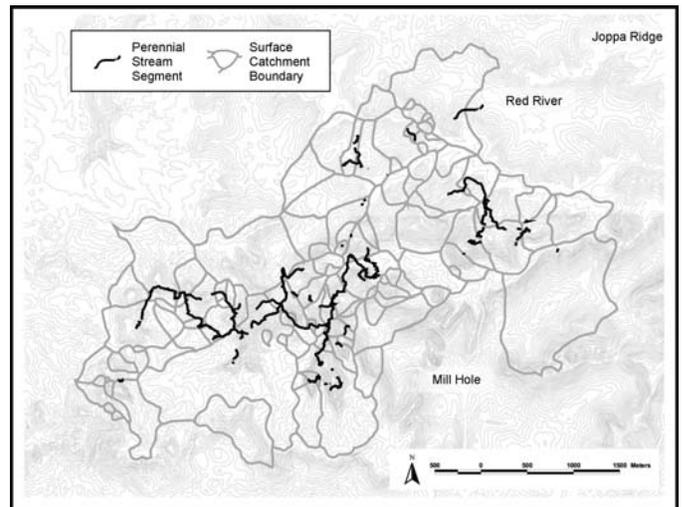
## TECHNIQUE 3

Quinlan and Ray (1989) derived their dye-trace routes by taking into account known caves and the potentiometric surface (Table 2). By considering the caves, potentiometric surface, and topography, the interpolated flow routes are curves approximating the regional flow routes of the Turnhole Bend Groundwater Basin.

The length of their interpolated curves was divided by the total area of the Turnhole Bend Groundwater Basin to obtain another value for drainage density. As with Technique 2, this value underestimates the actual drainage-density value for the basin because it includes only streams represented by dye tracing. In the Turnhole Bend Groundwater Basin, dye tracing has only been conducted on a regional scale. Thus, the derived value for drainage density accounts for only the largest conduits in the karst system.

## TECHNIQUE 4

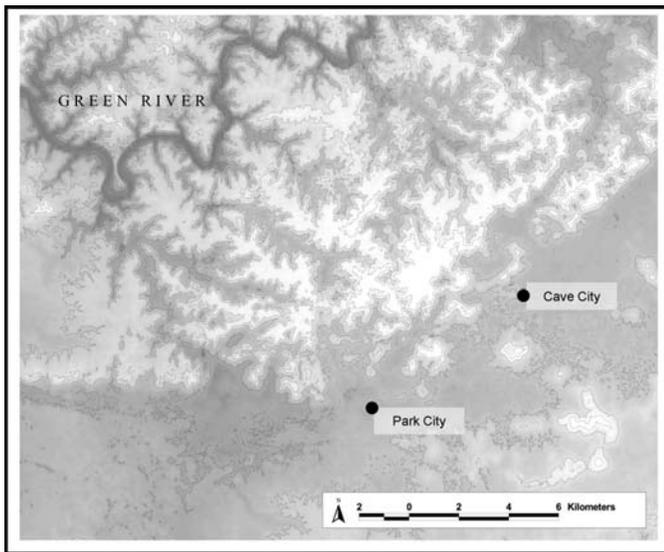
Straight-line dye-trace lengths do not account for the sinuosity that has been measured in known stream conduits within the aquifer. A regional groundwater flow length value can be calculated by including the sinuosity of the cave streams along individual dye-trace segments. A sinuosity value was calculated using all stream segments exceeding 500 m in the Turnhole Bend Groundwater Basin. For the average stream exceeding 500 m long, the watercourse flows 1.5 kilometers for every one kilometer of straight-line distance. A final drainage density value was calculated incorporating cave-stream sinuosity into the equation (Table 2).



**Figure 3. Surface catchments overlying perennial streams within the Martin Ridge Cave System.**

## TECHNIQUE 5

Lastly, a focused approach on the Martin Ridge Cave System delineated the individual catchments of the cave's mapped streams (Fig. 3). By comparing the mapped streams and their catchments, another value for drainage density was calculated. Since most of the streams discussed below were only recently discovered, the surface drained by Martin Ridge Cave has not yet been delineated through systematic dye tracing. Until additional fieldwork can be done, a provisional set of rules and assumptions has been developed to delineate the most appropriate recharge basin for each of the underground streams within the flow network. Only one stream in Martin Ridge Cave was excluded from method 5 analysis. With a recharge basin exceeding 100 km<sup>2</sup>, the Red River, the downstream segment of the Hawkins River, was not used in the analysis. The remaining streams drained small to intermediate-sized catchments (Fig. 3). Streams within Whippistle Cave were examined to determine their elevation with respect to surface catchments and their most likely sinkhole recharge areas. Several streams approached the surface closely enough to allow clear determination of their recharge zone. Streams in the central portion of the system are "hemmed in" by a large karst valley. The highest elevations in the streams generally are above the level of the valley floor, so it is assumed these streams drain the valley area and the nearby surrounding ridgetop areas. These provisional methods likely overestimate drainage basin boundaries, and results of analyses using these boundaries may be subject to revision. This likelihood is especially true as basins are more firmly established by future hydrogeologic fieldwork. Catchment areas defined in this investigation provide maximum, bounding values of recharge areas for underlying streams. This logic was used to remain consistent with the objective of obtaining a minimum drainage-density value. With areas so defined, the drainage



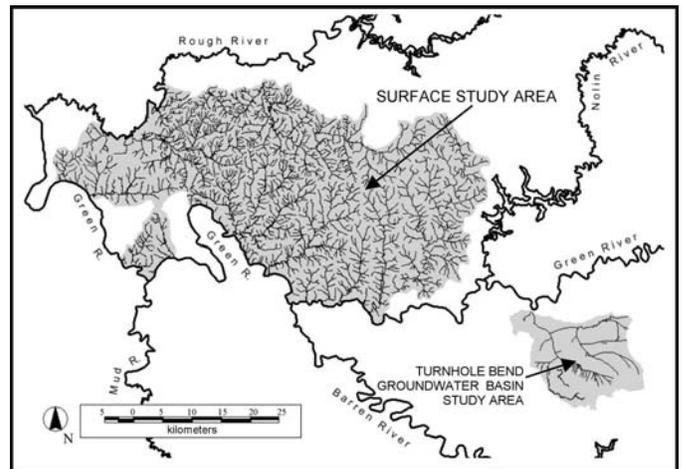
**Figure 4. Elevation model of Mammoth Cave region. Lighter shades are higher elevations. The contour interval is 30 meters.**

area was summed and densities calculated. Drainage density formulas are summarized in Table 2.

#### THE SURFACE-DRAINAGE NETWORK

In the Mammoth Cave Watershed, subsurface karst drainage appears to be influenced by the surface drainage that existed before the development of the karst landscape. Dye tracing experiments ongoing since the 1920s provide a map of current flow routes through the aquifer (Anderson 1925; Ray & Currens 1998a, b). The map shows a dendritic network of smaller-order streams draining into larger-order streams (Fig. 1). At coarse, regional scales, surface-elevation maps of the Mammoth Cave region portray an organized, dendritic surface network (Fig. 4). However, the modern Turnhole Bend Groundwater Basin is pitted with sinkholes and large karst valleys.

GIS was used to examine possible regional surface-elevation patterns. A 30-m Digital Elevation Model (DEM) was compiled of the Mammoth Cave Watershed and adjacent area (USGS 1993, 2001). The 30-m DEM is a raster dataset in which an array of 30-m x 30-m grid cells each possess a single elevation value. The grid provides a continuous surface of elevation values for the study area. In the Mammoth Cave Watershed and surrounding area, thousands of internally drained depressions exist. Likewise, in the DEM, thousands of internally drained depressions, or *sinks*, exist. These *sinks* are defined as cells (or groups of cells of equal elevation) in which all neighboring cells are higher in elevation (ESRI 1999). While GIS applications are able to determine flow direction and networks by comparing the elevations of the DEM, *sinks* are problematic for the GIS. The GIS flow-network algorithm is accustomed to stream networks converging on a single or small number of trunk streams. In the Mammoth Cave area, as



**Figure 5. Location of surface study area.**

a result of *sinks*, the flow-network algorithm creates thousands of disjointed streams draining into individual, internally drained basins. Therefore, the hydrologic-network algorithm used by the GIS has little use in a highly karstified landscape. However, in nonkarst landscapes, a small number of *sinks* sometimes exist in a typical DEM. These errors are common enough that ArcView and ArcInfo have functions to remove the *sinks*. The function, "FILL," is an iterative process which raises the value of a grid cell (or cell groups) until it is no longer bounded by higher elevation cells.

In order to examine the regional surface-elevation patterns that appear to exist in the Turnhole Bend Groundwater Basin, the "FILL" function was performed on the basin's DEM. The procedure effectively "smoothed" the Turnhole Bend Groundwater Basin's sinkholes and karst valleys, filling them to their lowest saddle drain. Using the GIS, a flow network was then constructed on the "FILLED" DEM. The result is a channel network that accentuates the current basin-wide surface-drainage patterns, and possibly reflects the shape of the pre-karst drainage network of the Turnhole Bend Groundwater Basin. The results section of the investigation compares the product of this model to the current and theorized historical flow network.

## RESULTS

#### DRAINAGE-DENSITY RESULTS

Based on the equations presented in Table 2, drainage-density numbers were calculated for the Turnhole Bend Groundwater Basin. Table 3 summarizes the results. In order to compare the karst system's drainage values with a related surface network, a nearby 1880 km<sup>2</sup> non-karst site was examined (Fig. 5). The drainage-density value for this nearby climatologically similar surface-study area is 1.36 km/ km<sup>2</sup>. The value includes 1856 streams analyzed with a total length of 2550 km.

**Table 3. Drainage Density Formulas**

Drainage Density (D)	Area Examined (A)	Surface Stream Length (s)	Cave Stream Length (c)	Dye Trace Length (d)
(1)	245 km <sup>2</sup>	18,325 m	40,933 m	Not included
(2)	245 km <sup>2</sup>	18,325 m	40,933 m	108,187 m
(3)	245 km <sup>2</sup>	18,325 m	40,933 m	129,711 m
(4)	245 km <sup>2</sup>	18,325 m	40,933 m	162,280 m
(5)	13.115 km <sup>2</sup>	Not included	14,777 m	Not included

<sup>a</sup> 1.5 represents average sinuosity of other mapped large cave streams in the basin.

<sup>b</sup> only those stream lengths and areas with clear catchments included

Method	Drainage Density Equation	Result	
(1)	$D = \left( \frac{s + c}{A} \right)$	0.24 km/km <sup>2</sup>	<p>Basin and adjacent basins. This location may represent a critical point in the geomorphic history of the Turnhole Bend Groundwater Basin. For further comparison, a map of the contemporary drainage routes is presented in Figure 8.</p> <p style="text-align: center;">DISCUSSION</p> <p>These initial efforts describe an orderly subsurface-flow network with numerical results that allow for comparison of the karst-flow network to surface fluvial systems. Additionally, quantitative examination of karst subsurface-drainage patterns and overlying surface catchments revealed several curious locations that appear to have large deviations from overlying surface valleys or possibly reflect moments of large-scale change in the development of the basin. For instance, unlike other streams in the basin, the Logsdon River flows perpendicular to overlying valleys. Most subsurface streams flow roughly parallel to the axis of surface valleys and overlying catchments. The saddle northwest of Mill Hole may also reflect a moment of great change in the geomorphic history of the Turnhole Bend Groundwater Basin. The saddle's elevation implies that the watershed for the developing Turnhole Bend Groundwater Basin was much smaller than today, but when water was able to flow underground through the karst aquifer (without regard to the elevation of the saddle), the watershed size increased dramatically. These assumptions complement the hypothesized basin-evolution model proposed by Quinlan and Ewers (1981). Critical locations like the Mill Hole Saddle display how quantitative analysis holds promise in bringing forth new hypotheses that may help unravel the geomorphic history of karst drainage basins.</p> <p>Morphometric analysis of mapped active base-flow drainage density within the Turnhole Bend Groundwater Basin resulted in values ranging from 0.24 km/km<sup>2</sup> to 1.13 km/km<sup>2</sup>. A nearby, climatologically similar, non-karst surface-drainage system yielded a drainage density value of 1.36 km/km<sup>2</sup>. Since the mapped cave streams necessarily represent only a fraction of the total of underground streams within the study area, the actual subsurface values are likely to be much higher. Also, in the Turnhole Bend Groundwater Basin, of the 40.3 km of mapped cave streams, only 1 km of physically mapped cave</p>
(2)	$D = \left( \frac{s + c + d}{A} \right)$	0.68 km/km <sup>2</sup>	
(3)	$D = \left( \frac{s + c + d}{A} \right)$	0.77 km/km <sup>2</sup>	
(4)	$D = \left[ \frac{s + c + (d * 1.5^a)}{A} \right]$	0.90 km/km <sup>2</sup>	
(5)	$D = \left( \frac{c^b}{A^b} \right)$	1.13 km/km <sup>2</sup>	

#### IDENTIFYING SURFACE-ELEVATION TREND ANOMALIES

Based on the sinkhole "FILL" drainage pattern developed from the 30-m DEM of the Turnhole Bend Groundwater Basin, a drainage map was produced (Fig. 6). From this map, a key location was identified to the northwest of Mill Hole Karst Window. By eliminating the existing saddle northwest of Mill Hole Karst Window, another "FILL" drainage network map was created (Fig. 7). The resulting map shows drainage flowing through Cedar Spring Valley toward Turnhole Bend. By comparing the two "FILL" maps, the elevation of the saddle northwest of Mill Hole represents a point of great influence over flow directions within the Turnhole Bend Groundwater

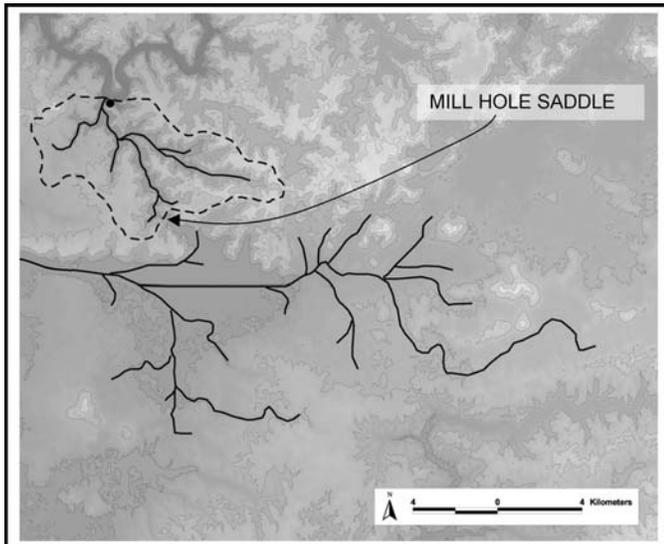


Figure 6. “FILLED” stream network. Lighter shades are higher elevations. The contour interval is 30 meters. The dashed line represents the watershed boundary draining to the Green River near Turnhole Bend Spring. Turnhole Bend Spring is denoted (•). Solid lines represent stream networks derived by the GIS from the 30-meter DEM.

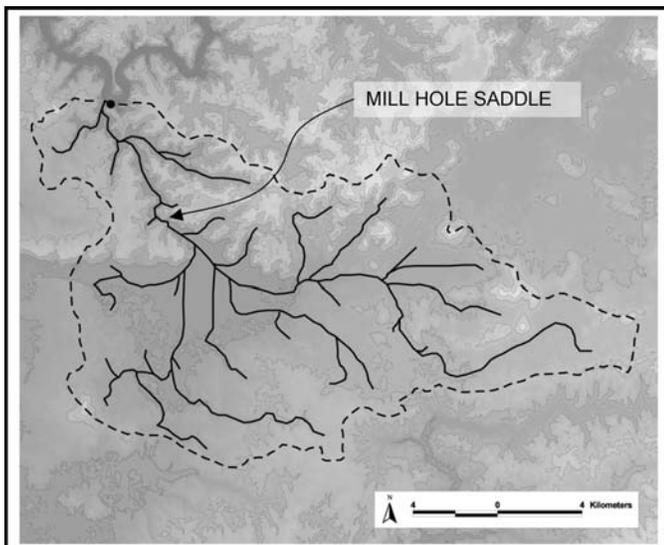


Figure 7. “Lowered saddle - FILLED” stream network. Lighter shades are higher elevations. The contour interval is 30 meters. The dashed line represents the watershed boundary draining to the Green River near Turnhole Bend Spring. Turnhole Bend Spring is denoted (•). Solid lines represent stream networks derived by the GIS from the 30-meter DEM.

streams lies in the phreatic zone. Cave divers’ future mapping in underwater cave passages will provide data to adjust the model, thereby reducing the current bias toward the vadose

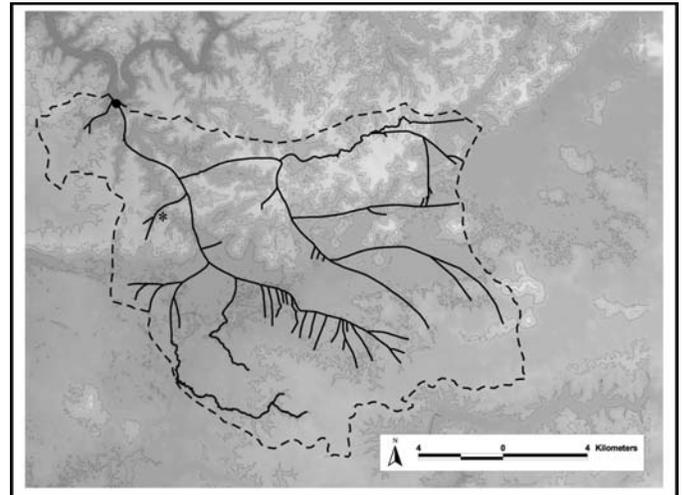


Figure 8. Contemporary Turnhole Bend Groundwater Basin. Lighter shades are higher elevations. The contour interval is 30 meters. The dashed line represents the hypothesized groundwater basin boundary. Solid lines represent either perennial streams flowing on the surface or hypothesized subsurface flow routes from dye traces. Turnhole Bend Spring is located at (#). The saddle northwest of Mill Hole is denoted by a (\*). (Modified from Ray & Currens 1998a,b).

areas of the karst aquifer. For future researchers, careful examination of abandoned phreatic tube complexes may provide a reasonable alternative for wholesale underwater cave mapping.

#### A MODEL FOR CALCULATING A MAXIMUM DRAINAGE DENSITY FOR THE TURNHOLE BEND GROUNDWATER BASIN

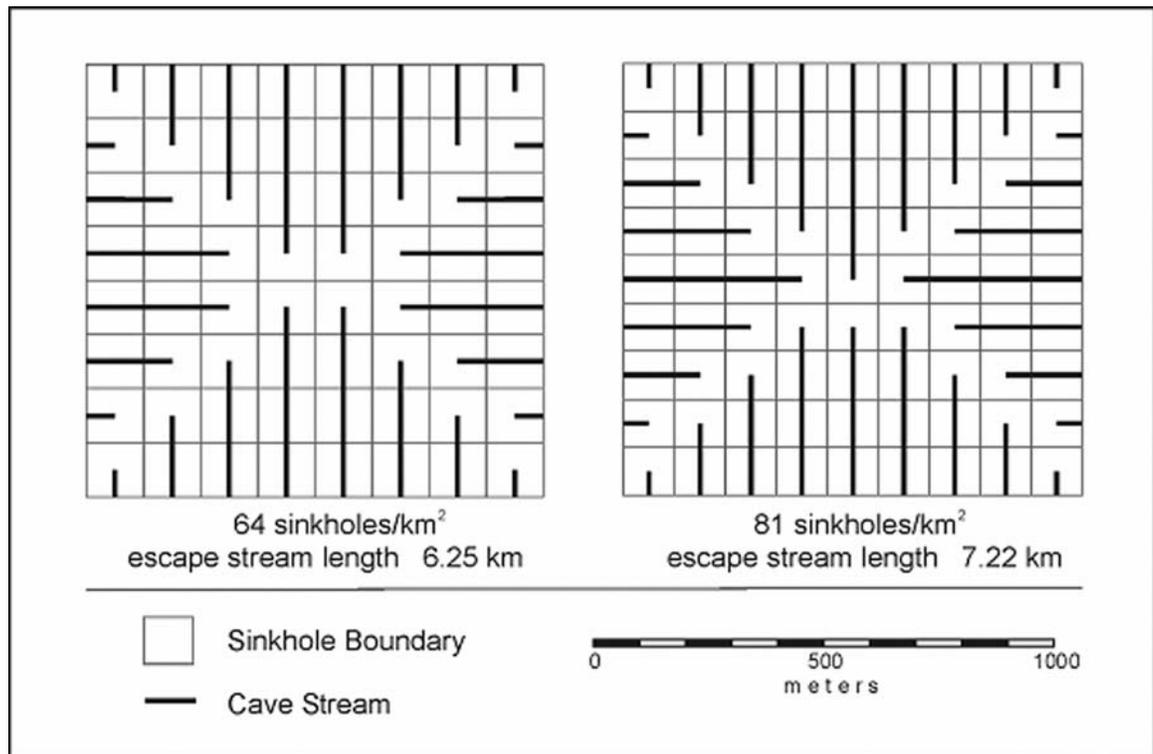
While it is assumed that the Turnhole Bend Groundwater Basin drainage-density value will increase beyond the surface study site value as more streams are mapped, not enough data exist to determine a maximum drainage density value. To provide insight on the upper limit of perennial drainage density in the Turnhole Bend Groundwater Basin, a 1 km<sup>2</sup> hypothetical model was developed to calculate a maximum drainage density within the Sinkhole Plain (Fig. 9). For this investigation, the initial model makes the following assumptions and constraints:

- 1) That within the Turnhole Bend Groundwater Basin, the Sinkhole Plain has a higher drainage density value than the Mammoth Cave Plateau or Glasgow Uplands (Fig. 2). This assertion is based on the assumption that there is lessened evapotranspiration on the Sinkhole Plain because, unlike the Glasgow Uplands and Mammoth Cave Plateau, the Sinkhole Plain contains no surface streams. More available subsurface water is likely to create a longer subterranean stream network. Thus, the value obtained for the Sinkhole Plain will represent a maximum drainage density for any part of the basin;

- 2) That each sinkhole in the 1 km<sup>2</sup> possesses an identical square shape and size;

- 3) That each sinkhole drains one first-order stream that

**Figure 9.**  
A model for calculating maximum drainage density within the Turnhole Bend Groundwater Basin.



originates in its center; and

4) That each stream will follow the most-direct route to the edge of the 1 km<sup>2</sup> model in two-dimensional space. This constraint yields a minimum flow length for the streams to leave the 1 km<sup>2</sup> area.

For the Turnhole Bend Groundwater Basin Sinkhole Plain, Anhart and Williams (1998) counted an average of 74 sinkholes per km<sup>2</sup>. In order to follow the constraints of the model, where each sinkhole has an identical square shape, two 1-km<sup>2</sup> sinkhole plains were created (Fig. 9): one with 64 sinkholes/km<sup>2</sup> and one with 81 sinkholes/km<sup>2</sup>. The drainage density for the 74 sinkholes/km<sup>2</sup> number lies within the range of the two models. By following the constraints of the model, the 64 sinkholes/km<sup>2</sup> plain yielded a value of 6.25 km streams. The 81 sinkhole/km<sup>2</sup> plain yielded 7.22 km of streams. Therefore, for a 1-km<sup>2</sup> area containing 74 similarly shaped sinkholes, the flow-length lies in a range between 6.25 and 7.22 km (stated as drainage density, 6.25-7.22 km/km<sup>2</sup>).

#### CONCLUSIONS

In this investigation, the researcher examined the use of GIS to store, analyze, and visualize surface- and subsurface-spatial data for the Mammoth Cave Watershed. GIS was used to store information and hydrologic attributes for all known caves within the Turnhole Bend Groundwater Basin.

Our work proposes preliminary drainage-density values for the Turnhole Bend Groundwater Basin. These values range from 0.24 km/km<sup>2</sup> to 1.13 km/km<sup>2</sup>. Drainage density for a nearby non-karst basin yielded a value of 1.36 km/km<sup>2</sup>. As

more streams are discovered, explored, and surveyed within the Turnhole Bend Groundwater Basin, the drainage density value is likely to exceed the nearby surface value. In order to assess a potential maximum drainage density value for the karst aquifer, a theoretical model was developed to describe the amount of two-dimensional stream length necessary to drain a square-kilometer of the Turnhole Bend Groundwater Basin Sinkhole Plain. Given this theoretical model, a maximum drainage density value for the Turnhole Bend Groundwater Basin is 6.25-7.22 km/km<sup>2</sup>.

This work also describes the use of GIS to assess and uncover regional surface-elevation trends and anomalies within a karst watershed. For the Turnhole Bend Groundwater Basin, the GIS analysis highlighted a location immediately northwest of the Mill Hole Saddle that may have played a pivotal role in the development of the current flow regime of the watershed.

All data collected and analyzed for this investigation suggest that karst aquifers, though complex, are consistent with an orderly system. Like surface drainage networks, the karst drainage system exists to reduce potential energy most efficiently. Seemingly unusual patterns exist within the network not as a reflection of disorder, but as a reaction to the hydrogeologic setting of its flow path.

#### ACKNOWLEDGMENTS

The authors wish to thank the numerous cavers, scientists, and survey projects that provided data for this work: particularly, Cave Research Foundation, Central Kentucky Karst

Coalition, Martin Ridge Cave Project, James Cave Project, and the Science & Resource Management Office of Mammoth Cave National Park. We also would like to acknowledge Don Coons, Bob Glennon, Rita Glennon, Deana Groves, Joe Meiman, and Rhonda Pfaff for their support.

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