

Central Kentucky Karst Hydrology

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ABSTRACT

Three aspects of underground flow in the Central Kentucky Karst are considered. First, the underground drainage pattern is examined as a set of systems tributary to the Green River. The relation of inputs such as vertical shafts to horizontal passages is delineated, and the extent to which structure determines passage alignment is evaluated. Calculations based on rainfall and spring-flow measurements indicate that a substantial portion of the input cannot be accounted for by the discharge of presently known springs and underground streams. Second, the quantity and quality of water flowing underground is examined, and new evaluations are made of the location, character, and extent of limestone solution in the area. Known and extrapolated cave passages cannot account for the amount of limestone removal indicated. Third, the underground drainage is examined as a set of transportation systems for mechanical sediment. Estimates are made of the amount and character of sediment moving from the surface of the region underground to the Green River. This sediment far exceeds the amount brought into the systems by back-up water during floods of the Green River.

It is concluded that the active underground drainage systems are more complex than their known parts indicate, with major water channels probably existing beneath the present-day base level; that a major amount of solution activity occurs in the mantle and on the bedrock surface below it causing a general lowering of the land surface through removal of limestone which far exceeds that removed during the formation of cave passages; and that most of the sediment in the cave passages, even in back-up areas near the Green River, is provided by the flow which moves from the surface through the cave systems to the Green River.

INTRODUCTION

This paper consists of summary statements on three general aspects of underground flow in the Central Kentucky Karst: (1) the underground drainage pattern as a set of systems tributary to the Green River; (2) the solution activity of the underground water; and (3) the underground drainage as a set of transportation systems for mechanical sediment. My conclusions are based on 10 years of observation and study, and upon many discussions about their extensive work with R. W. Brucker, G. H. Deike, E. R. Pohl, and W. B. White, all of whom might be listed here as joint-authors except that none of them can be held responsible for my speculative opinions. E. R. Pohl was especially helpful with part 3. Institutional assistance was provided by Mammoth Cave National Park and the Cave Research Foundation.

The Central Kentucky Karst lies on Mississippian rocks dipping 30 feet to the mile northwest in south-central Kentucky, along the southwestern edge of the Cincinnati Arch in the Interior Lowland Province, its center 100 miles south of Louisville (Pohl and others, 1964). It is part of a karsted limestone belt which extends from southern Indiana south through Kentucky into Tennessee along the entire west flank of the Cincinnati Arch. The boundaries of the Central Kentucky Karst are drawn on a hydrologic basis, resulting in an oblong area, at a minimum 20 miles from east to west, and 10 miles from north to south, with Mammoth Cave National Park near its center. The northern boundary is the drainage divide between the Green and Rough Rivers, north of which no recharge into the area is possible. The southern boundary is the drainage divide between the Green and Bar-

ron Rivers. To the east, the boundary is near Munfordville beyond which the Green River flows on limestone from which the important caprock of the area has long been removed. The western boundary is near Brownsville where the Green River is located stratigraphically above the caprock so that discharge of underground water into the river is not possible. The Central Kentucky Karst consists of three major physiographic units separated by two major escarpments. From southeast to northwest, these are the Sinkhole Plain, the Dripping Springs Escarpment, the Mammoth Cave Plateau, the Pottsville Escarpment, and the Hilly Country. These have been described by Livesay and McGrain (1962) and by Watson and Smith (1963).

THE UNDERGROUND DRAINAGE PATTERN AS A SET OF SYSTEMS TRIBUTARY TO THE GREEN RIVER

There are both perennial and ephemeral underground streams in the Central Kentucky Karst. We know most about the ephemeral flows. After heavy rains and during wet seasons, the amount of vertical flow in the cave systems increases, water seeping or dripping from joints, and cascading down vertical shafts. The inputs for this water are relatively open to the surface, flow increasing in some places within half an hour after a heavy rainfall starts. Ephemeral sinking creeks also start up during rainy times, and when rain continues for several days, ephemeral ponds form on the Sinkhole Plain and on the floors of the karst valleys of the Mammoth Cave Plateau. The underground streams formed by water flowing through the open inputs and from the slowly draining ponds flow only so long as direct meteoric water is available.

The second sort of underground flow is found in perennial streams such as Hidden River, Cave City Water Supply River, Eyeless Fish River, Candlelight River, Roaring River, and so on. The ephemeral streams are tributary to these perennial streams, and during wet periods increase their flow greatly. However, each of these streams flows at a few cfs (cubic feet per second) year around, obtaining its water from no known reservoir. Presumably they are fed by the constant in-

seep of subsurface water, though no stream can be followed far enough upstream to gather a direct notion of the total collecting mechanism. However, Brucker (1960; in press) has demonstrated that the vertical shaft complexes beneath the edges of the truncated caprock of the Mammoth Cave Plateau are headwater tributaries of such streams as Eyeless Fish River. Many of these shaft complexes supply water which seeps down their walls even during the driest parts of the year. White and Deike (1963; unpublished) in their studies of the paleo-hydrology of the region have found evidence to support the notion that some extensive high-level horizontal passages which are now perennially dry were once stream beds related to former vertical shafts which now are collapsed and eroded. It might be concluded that present perennial streams are fed entirely by water which perennially seeps and drips down vertical shaft complexes. That known complexes do not provide enough water is not conclusive evidence against this hypothesis, since it is difficult to get into some complexes, and many must exist inaccessible to man. Further, it might be concluded that the extant stream systems are models upon which to explain the genesis of high-level dry passages. Brucker (1960; in preparation) gives good evidence for these conclusions.

However, there are numerous discordant elements which do not fit this hypothesis in any simple way. One of the most obvious is that much more water falls onto the Central Kentucky Karst, considered at the very minimum as a 200 square mile drainage area with 48 inches of annual rainfall, than discharges from the known surface and spring tributaries to the Green River in the area. Estimating an annual total discharge from all these sources of 100 cfs (which is probably high) 7 times more water falls on the area than discharges from it through these sources. If one considers the 444 square miles of area undrained by surface streams (Cushman and others, 1965), then more than 17 times more water falls on it than is known to discharge from it. Of course these figures may mean little; an immense amount of work remains to be done on the water regime of the region. During heavy rains much

water flows directly into the Green River; there probably are unknown rises in the Green River bed; and some ground water probably seeps out of the region. I present the calculations primarily as basis for the following speculation: The underground streams now known in the Central Kentucky Karst are probably tributary to much larger underground master trunk streams which flow perennially at or just below present regional base level. Only one such master trunk stream can be explored for any distance under the Mammoth Cave Plateau. This river, in a cave which opens out of Cedar Sink on Joppa Ridge, has a flow of 20 cfs, and can be followed for about 300 feet. That these inferred master streams are not now open to exploration because they are below present base level can be explained if two things are taken into consideration. First, the bed of the Green River has been filled with Pleistocene gravel to a depth in places of 30 feet, and the underground trunk drainage systems were probably established prior to this filling. Second, the Brownsville Dam has raised the level of Green River at least six feet through the Central Kentucky Karst. (If it were not for this artificial raising of the water level, there would be no boat trips inside Mammoth Cave. The large body of water with sections known as Styx River, Echo River, and Roaring River is not a master stream, but is backponded water from the Green River. Upstream underground above the backponding, flow is only a few tenths of a cubic foot per second.) The mouths of the big springs discharging into the Green River are filled with silt, and scuba diving has shown that the floor of the underground stream discharging at Pike Spring is about 30 feet below the present bed of the Green River at that point (Smith, 1957). If Pike Spring is considered as an outlet of a major underground trunk stream, further evidence can be given. The only known underground stream in the area is Eyeless Fish River, which can be followed underground to within 300 feet of the Pike Spring outlet, and is undoubtedly tributary to it (Smith, 1964, fig. 1). However, Eyeless Fish River flows at only 1.5 cfs, which is only a tenth of the flow out of Pike Spring. The master stream must have many other

sources of water than Eyeless Fish River, and it must flow below present base level.

Recent exploration under the Mammoth Cave Plateau suggests a further possibility. Extensive work in the Candlelight River complex of small canyons under Houchins Valley, the large karst valley separating Flint Ridge from Mammoth Cave Ridge, indicates that these passages are drains for water from the ephemeral sinking creeks of Houchins Valley. They probably also drain vertical-shaft complexes in Mammoth Cave Ridge. No large passages have been found below the valley, but of course they may be below base level. In general in this area as much as 1 cfs of water perennially flows down-dip to the northwest toward Flint Ridge. The total year-around sources of this water are unknown. Other exploration from Mammoth Cave Ridge up Roaring River has penetrated beneath Doyel Valley toward Joppa Ridge, with water flowing from that area northwest toward Mammoth Cave Ridge. It appears that the floors of the solutional karst valleys separating the major ridges of the Mammoth Cave Plateau represent headwater highlands in the underground systems. A karst-valley floor with its sinking creeks, and with vertical-shaft complexes along each of its walls, is thus a highland up dip from the major ridge north of it. The impermeable caprock of the ridges keeps water from flowing vertically into the passages under each ridge, but water flows in general down dip from the uncapped shaft complexes and karst-valley headlands to master streams below the capped ridges. I would suggest that there is at least one master underground stream below each of the three major ridges of the Mammoth Cave Plateau. This conclusion comes from the observation that Doyel Valley south of Mammoth Cave Ridge and Houchins Valley south of Flint Ridge both are sites of small perennial underground streams, and that these karst valleys are obviously headland collection basins for water which flows into them from the surface of the ridges and below ground from the surface of the impermeable caprock of the ridges.

There is further evidence that these inferred major underground trunk streams extend headward 10 miles or more beneath the

Mammoth Cave Plateau out under the Sinkhole Plain. Such a larger drainage area would better account for the suspected large perennial flow. Very extensive drainage systems are indicated by some of the present high-level passages which are several miles long and perhaps once extended farther out into the Sinkhole Plain. The configuration of some of these passages also suggests that they were formed in circumstances where the stream flowing through them filled them completely rather than simply flowing along their floors. It is probable that they formed just below a formerly higher base level. Further details are given by White and Deike (1963; unpublished) and Brucker (in press). Deike is completing a doctoral dissertation in which he considers the relations of linear features such as joint patterns to cave passages in the Central Kentucky Karst, and when this is available more can be said about the drainage nets.

THE SOLUTIONAL ACTIVITY OF UNDERGROUND WATER

The second major problem I want to consider very briefly in this paper is the matter of underground solution in the Central Kentucky Karst. Many estimates have been made of how much rock is removed in limestone regions by solution. Let me quote one of the more conservative:

If each year 14,000,000 cubic feet of water [15 percent of 40 inches annual rainfall] are available for solution beneath each square mile of the Kentucky blue-grass region, and if each million parts dissolves 155 parts (volume) of rock materials, then in a single year 2,170 cubic feet of rock are taken into solution. If all of the rock excavation of a single year were concentrated in one tunnel 3 by 6 feet in cross-section, a cavern over 120 feet long would be formed under each square mile of surface. (Swinnerton, 1932, p. 679).

Swinnerton goes on to say that the Blue-grass region has been stable for several hundred thousand years. The obvious thing I want to point out is that neither in the Blue-grass region nor in the Central Kentucky Karst are there cave passages or other solutional voids underground (as estimated from

known and extrapolated cave passages and solutional voids observed in quarry excavations) which even begin to represent the volume indicated by Swinnerton's conservative estimate. Yet, I think it obvious that such solution takes place. The voids exist in the Central Kentucky Karst in the form of the major karst valleys on the Mammoth Cave Plateau and the areas where an immense amount of rock has been removed above the present surface of the Sinkhole Plain. Solution of limestone to form sinkholes accounts for some of the removal, but even more must be accounted for by solution in the mantle and on the bedrock surface. As I say, this is usually pointed out as an obvious fact. It has not yet, however, been considered in all its implications by those who theorize about the genesis of karst forms. The major amount of solutional work in the Central Kentucky Karst must be extensive subsurface solutional activity in the mantle and on the limestone bedrock surface. Incidentally, water seeping slowly through the soil and mantle is undoubtedly the chief source of water for those underground rivers with perennial flow. Once this view is taken of the karst region, one can see the dry cave systems as merely the remnant roots of a once dynamic organism, the vast upper bulk of which has been reduced by solution and removed by transportation through the lower drainage system. Again, the known and extrapolated drainage nets active today are neither the largest parts of the dynamic system, nor the sites of the greatest solutional activity. The active cave systems today in the Central Kentucky Karst are primarily the drainage lines for water which does its major work in the massive karst processes of solution in the mantle and on the bedrock surfaces above the cave passages.

THE UNDERGROUND DRAINAGE AS A SET OF TRANSPORTATION SYSTEMS FOR MECHANICAL SEDIMENT

The picture I have drawn so far is of several drainage nets which extend from the mouths of perennially flowing big springs at the Green River, back beneath the Mammoth Cave Plateau as major subsurface streams fed by tributaries from karst valleys and vertical-shaft complexes, and on out

under the Sinkhole Plain where water enters through sinking creeks and sinkholes, and where water seeps through the mantle at the outermost limit of the drainage nets. With this picture in mind, I turn to the third problem to be considered in this paper, the underground transportation of mechanical sediment in the Central Kentucky Karst.

Collier and Flint (1964) conclude on the basis of measurements between October 1959 and June 1962

that sedimentation in [Mammoth] cave is closely related to flooding of nearby Green River. The Green River, which is hydraulically connected to Mammoth Cave by Echo River spring and River Styx spring, is the chief source of sediment and floodwater to the cave.

I shall argue that these conclusions are incorrect in their general implications and in detail.

The Green River is a master through-flowing surface karst stream. It flows 55 miles from Munfordville to Brownsville through the Central Kentucky Karst with no perennial surface tributary. Mammoth Cave lies about two-thirds of the distance downstream on this course. The Green River has a mean annual discharge of 3300 cfs at its junction with the Nolin River 15 miles below the spring outlets of Mammoth Cave (U. S. Geol. Survey, Lexington, Kentucky open files). In the Mammoth Cave region it drains a total area of approximately 300 square miles, almost completely by way of underground drainage systems. The mean annual discharge of the Green River at Mammoth Cave is 2000 cfs (Cushman, and others, 1965). The most distant extension of this drainage system at right angles from the Green River is approximately 12 miles, with underground headwater drainage lines there lying at a level as much as 200 feet above the pond stage (425 feet at the Brownsville dam) of the Green River.

Drainage into this underground network comes from five sources: (1) Water moves underground on the Sinkhole Plain through sinking creeks. (2) It similarly enters on the plain through sinkholes. The water from these first two sources never travels less than five miles from the Sinkhole Plain beneath

the Mammoth Cave Plateau to the river. (3) Some of the precipitation on the ridge tops of the Mammoth Cave Plateau goes underground to flow along the top of the impermeable caprock of sandstone and shale. Where this caprock is truncated by the large solutional valleys between the ridges, and by the valley of the Green River, water descends rapidly to base level through vertical features of solution in the underlying limestone; it then discharges horizontally into the Green River. (4) Between the ridges of the Mammoth Cave Plateau all precipitation in the solutional karst valleys, which are closed depressions, and all water which flows into them, enters the underground drainage network through swallow holes and sinks on the valley floors. (5) Water draining from the Hilly Country on the north side of the Green River generally goes underground through vertical courses.

I am primarily concerned, however, only with the first four sources which provide water from the south side of the Green River, where lies the Mammoth Cave System.

The outlets of this water are five known big springs—Blue, Hix, Pike, Styx River, Echo River—flowing into the Green River at river level; and two known big springs—Turnhole and one unnamed—which rise from the river bottom. These big springs have an estimated mean flow of approximately 100 cfs. As already remarked, it appears probable that there are unknown rises in the bed of the Green River.

The Mammoth Cave Region provides no exception to the observation that the lowering of a karst surface is relatively rapid, and often spectacular. Swinnerton's estimate of the extensive amount of limestone probably removed in solution has already been quoted. Processes of mechanical erosion are no less apparent. From the Mammoth Cave Plateau, debris of sizes from clay to five-foot boulders of sandstone are washed into the drainage systems through vertical openings which may be only joints widened a fraction of an inch, or vertical shafts 50 feet in diameter. On the Sinkhole Plain, the ravages of soil erosion are often apparent. Here, with sporadic forest cover and intensive agriculture, great quantities of silt and clay are washed into the underground drainage systems each year.

Besides mechanical removal of this material, chemical analyses (U. S. Geol. Survey, Lexington, Ky., open files; Cushman and others, 1965) show spring discharges with over 800 ppm dissolved solids, indicating extensive breakdown and removal of material.

Boulders, cobbles, pebbles, sand, silt, and clay are found throughout the vast underground drainage systems. Indeed, many of the headwater channels are nearly closed by the influx of silt. Many sinkholes on the Sinkhole Plain (where there are as many as a thousand sinkholes to the square mile) support ephemeral ponds when their outlets become plugged with clay. Clay and silt pan fills are known up to 30 feet deep, and some are no doubt deeper. When a plug is breached, the movement of clay and silt through the new opening is often phenomenal. Soil erosion is the greatest problem of any karst region. In Eastern Europe and the Near East there are now barren regions of exposed limestone which have been within historic times green and forest laden. Soil erosion is a problem in the Mammoth Cave Region, and it should be a warning sign that recently in some isolated areas soil has been removed to bedrock and karren has begun to appear.

Therefore, it must be concluded that the chief source of sediment in Mammoth Cave, which is known to extend at least four miles back from the Green River and more than 100 feet above its highest flood level, is not the Green River, but is the drainage network extending underground into the Mammoth Cave Plateau and the Sinkhole Plain. This conclusion is based on extensive observations over 30 years throughout more than 100 miles of underground passages in the Mammoth Cave region. The distribution of fluvial sediment in the cave systems is consistent only with the conclusion that these underground passages are part of an immense drainage net as described in the first two parts of this paper.

Thus, though I agree that "sedimentation in the cave is closely related to flooding of nearby Green River", I would argue *not* that "the Green River . . . is the chief source of sediment and floodwater to the cave", but, on the contrary, that *the cave systems*

are the chief LOCAL sources of sediment and floodwater to the Green River.

The flooding of any river is resultant upon the inflow of water from its tributaries. Over most of the Central Kentucky Karst, water from rainfall and snow-melt during the usual flood times can move only underground. At this time, water levels throughout the cave systems rise rapidly. Where only trickles of water fall from vertical shaft ceilings or flow along horizontal passages during most of the year, streams of water flowing as much as 5 cfs appear. Four miles from the Green River on the Sinkhole Plain, Hidden River in Hidden River Cave, 40 feet above the Green River pond stage, which normally flows at 4 to 5 cfs, has been observed to flood to a maximum of 60 feet above its usual level. This is more than 50 feet higher than the highest recorded floods of the Green River and the areas of Mammoth Cave adjacent to it.

The conclusion must be that the rise of water level in the caves is general to the region, subsequent upon the general rise of the underground water level in wet seasons. The rise of water level in Mammoth Cave during flood time is as much a result of the rise of water in the total set of underground drainage systems tributary to the Green River in the Central Kentucky Karst, as it is the result of the rise of the Green River fed by sources outside the local area. The floodwater of the Green itself must come in part from the high underground water of the Mammoth Cave Plateau and Sinkhole Plain drainage basin. This conclusion is at least in part implied by Davies and Chao (1959); Hendrickson (1961), and Cushing and others (1965).

In Hidden River Cave, floodwaters some years leave a deposit of as much as 10 inches of silt. Yet, the cave is not plugged with silt, nor is Mammoth Cave plugged with silt. The total year-around result is removal of sediment from the cave systems. The essential process is one of transportation, not deposition. The caves are simply the ever-evolving underground passages through which water and debris are moved from the drainage basin to the Green River. Thus, though I do not wish to deny the fact that near the

Green River during time of flood some backwater enters the cave systems and deposits some sediment, I do wish to argue that such flooding and deposition is not of major significance, even for the large quantities of water and silt found in the caves near the Green River during the flood. The major influx of water and sediment in the caves is from the Mammoth Cave Plateau and the Sinkhole Plain, not from the Green River.

Two final items will conclude this discussion. First, since "the sediments in the lower levels of the cave are similar in physical character and mineralogy to the sediments on the flood plain of the Green River" (Collier and Flint, 1964, p. D141), they obviously come from the same source. It is my conclusion that they do not come from outside the region to be deposited on the extended underground floodplain of the Green River in the lower levels of Mammoth Cave. Rather, the sediments in the cave and on the flood plain are similar because they both derive from the immediately adjacent Mammoth Cave Plateau and Sinkhole Plain.

Second, it seems enigmatic that water enters the cave systems rapidly while the Green River rises rapidly, but that it does not leave the systems as rapidly as the river lowers. Rather than postulating some intricate valve-system of passages, I conclude that this circumstance is another confirmation of the conclusion that the major source of underground water in the caves during flood is not the Green River. The water lowers less rapidly than it rises in the cave near the Green River because inflow from the extensive underground drainage net continues to be high for several days after the Green River begins to lower. This is because of the more restricted underground flow. Thus, the total rise of the Green River, which is only partially dependent upon local sources, causes some backflooding into the cave systems. But the high level of the underground water which lasts for a few days after the Green itself begins to lower is not the result of capture of backwater, but of the continued high flow of water into the system along underground courses.

CONCLUSION

It is concluded that the active underground drainage systems in the Central Kentucky Karst are more complex than their known parts indicate with major water channels probably existing beneath the present-day base level; that a major amount of solutional activity occurs in the mantle and on the bedrock surface below it causing a general lowering of the land surface through removal of limestone far exceeding that removed during the formation of cave passages; and that most of the sediment in the cave passages, even in back-up areas near the Green River, is provided by the flow which moves from the surface through the cave systems to the Green River.

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DISCUSSION

GEORGE W. MOORE, *U. S. Geological Survey, Menlo Park, California*: You say that all the solution from infiltrating water occurs at the bedrock surface, and that solution by water flooding seasonally from the river into the cave system and out again, as Thraillkill has suggested, is unimportant. I presume then that you favor Bogli's idea of solution where ground water and infiltrating water, both saturated but with different carbon dioxide partial pressures, mix at depth to form an undersaturated solution?

WATSON: No, actually I favor Swinnerton's hypothesis, and Thraillkill's position is similar. The fluctuation that takes place during the wet periods is related to the rising of the river, but it isn't necessarily backflooding that causes the fluctuation. The fluctuation also comes from water flowing in from the ground-water reservoir.

MOORE: And the infiltrating water still maintains undersaturation by the time it gets down into the cave passages?

WATSON: Very probably. You said I said all the solution takes place in the mantle and on the bedrock surface. Of course some of the solution does form cave passages. It

is clear that solution is increased in the areas of fluctuating water level. Whether this is explained by Bogli's hypothesis of mixture corrosion is not clear. Certainly in the cave passages quite near the Green River there is extensive mixing of Green River backup water and water flowing toward the Green River in underground streams, and this might lead to increased solution potential. But such massive mixing would not occur in areas far from the Green River, where water levels also fluctuate. There, mixing resulting in greater solution potential would have to be of two batches of water which have infiltrated from the surface. Perhaps the agitation of the water during the fluctuation has as much to do with the solution as does the mixing. WILLIAM I. GARDNER, *U. S. Bureau of Reclamation, Denver, Colorado*: One of the problems in limestone terrain is getting an estimate of ground-storage capacity. I wonder if you have been able to arrive at an estimate for this basin, or to estimate the average effective porosity on a basin-wide basis?

WATSON: No, I have not. We can give rough estimates, taking how much water falls and how much goes out. One of our problems is that there must be other outlets in the bed of the Green River which we do not know of. We have a program of scuba divers going along with thermometers to check for such rises.

I want to comment on the hydrostatic flow nets which have been illustrated in several papers today. I am sure that the flow-net surface is quite flat in the Central Kentucky Karst. The Green River valley is always shown as a great opening, which flow arrows originating in highlands come up to from great depth. That opening is probably no more significant to the flow net as a point of release than openings which extend as much as ten miles back under the Mammoth Cave Plateau and Sinkhole Plain. The whole region is underlain by underground streams that are within 100 feet of the Green River level. No high head exists in the Central Kentucky Karst from which deep-lying flow lines can derive. Therefore, no arrows should be shown rising from great depth to the Green River valley.