ISSN 0075-5591

KENTUCKY GEOLOGICAL SURVEY
UNIVERSITY OF KENTUCKY, LEXINGTON
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James C. Currens and C. Douglas R. Graham

Report of Investigations 7
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FLOODING OF THE SINKING CREEK KARST AREA IN JESSAMINE AND WOODFORD COUNTIES, KENTUCKY

James C. Currens and C. Douglas R. Graham

ABSTRACT

Tashamingo Subdivision in Sinking Creek Karst Valley, a tributary of the Garretts Spring Drainage Basin in Jessamine and Woodford Counties, Kentucky, was flooded in February 1989. To determine the cause of flooding, the boundary of the ground-water basin was mapped, discharge data were measured to determine intake capacity of swallow holes, and hydrologic modeling of the basin was conducted. Swallow-hole capacity was determined to be limited by the hydraulic parameters of the conduit, rather than by obstruction by trash. Flooding from a precipitation event is more likely, and will be higher, when antecedent soil moisture conditions in the watershed are near saturation. Hydrologic modeling shows that suburban development of 20 percent of the southeastern basin will cause an increase in flood stage at Tashamingo Subdivision.

INTRODUCTION

Project History and Objectives

From mid-February to early March of 1989 the Tashamingo Subdivision and the Delaneys Ferry Road area of Jessamine County flooded when the Sinking Creek Karst Valley was unable to accommodate a prolonged and intense storm; 8.4 inches (21 cm) of rain fell from February 13to 16. Several homes were isolated by blocked roads, and two homes were flooded; one was damaged extensively (Figs. 1 and 2). In response to the concerns of area residents, the Kentucky Geological Survey (KGS) initiated this study to determine if future flooding could be prevented.

The first goal of the study is to predict what type of storm will cause flooding that threatens property, given the current degree of residential development. The second goal is to determine, for any given storm, what the effect of continued development in the basin will be. These data will be essential for project design should an engineering solution be chosen to mitigate future flooding. This study represents the first time a major karst ground-water basin in the Inner Blue Grass has been monitored for an extended period of time.

Location and Physiographic Setting

Garretts Spring Karst Drainage Basin lies in Jessamine and Woodford Counties in the Inner Blue Grass region of central Kentucky (Fig. 3). The Inner Blue Grass is a gently rolling upland with a subdued karst topography formed on Ordovician limestones. The upland is roughly bounded on the south and west by the entrenched Kentucky River flowing in a gorge as much as 400 feet (130 m) deep. The gradients of streams flowing off the upland steepen abruptly as they approach the gorge. Except along the gorge of the Kentucky River, local relief is generally less than 150 feet (50 m). Karst windows and sinkholes seldom have more than 100 feet (30 m) of relief, and many sinkholes are too shallow to show up on topographic maps. Springs and caves are common, but the caves are usually very wet and most cannot be explored more than a few hundred feet.

Garretts Spring is the headwaters of the northern branch of Clear Creek, which flows approximately 14 miles (22.5 km) to the Kentucky River. The drainage basin covers approximately 4,766 acres (1,929 hectares [ha]). The basin is composed of two branches, the confluence of which is underground near the resurgence at Garretts Spring. Three major karst features and hundreds of smaller ones are within the drainage basin. Chenault Karst Window lies in the northwestern subbasin. Water emerges from a spring at the northern end of the karst window, and flows 1,500 feet (457 m) to the southern end, where it sinks. The water then flows 1,900 feet (580 m) to Garretts Spring. Owens Karst Window lies in the southeastern branch between Sinking Creek and Garretts Spring. Flow from Sinking Creek rises in Owens Karst Window at several springs along the eastern

Figure 1. Home damaged during the February 1989 storm. The building is a split level, and 2 to 3 feet of water is in the upper level.

upstream wall, and sinks in a series of swallow holes on the western wall to flow to Garretts Spring, 3,800 feet (1,158 m) to the west.

Sinking Creek Karst Valley forms the headwaters of the southeastern branch. The topographically closed portion of the basin covers 197 acres (78 ha). Sinking Creek originates as surface runnels and small springs emerging just above the grade of the creek. The stream follows a smooth, gradual gradient to the karst valley, without measurable flow loss, until it approaches the footwall area. At the footwall, Sinking Creek diverges into three distributaries that convey flow to the three principal groups of swallow holes.

GENERAL GEOLOGY AND HYDROGEOLOGY

Geology

The Garretts Spring Basin is underlain by the Lexington Limestone, which consists of thinly interbedded carbonates, argillaceous carbonates, and shales of Middle Ordovician age (Cressman, 1965). Members of the Lexington Limestone exposed within the drainage basin of Garretts Spring are, from bottom to top, the Grier Limestone Member, the Tanglewood Limestone Member, the Brannon Member, and the Devils Hollow Member (Fig. 4). The Grier Limestone is irregularly thin bedded, with occasional shale or silt interbeds. The Macedonia Bed, a mappable argillaceous unit a maximum of 9 feet (2.7 m) thick, occurs within the Grier, 50 feet (15 m) below the top of the Grier. Overlying the Grier is the Tanglewood Limestone, a thinly crossbedded, but relatively pure carbonate. The Tanglewood intertongues with the Grier and several other lithologies within the Inner Blue Grass. The Brannon Member, a thin-bedded, argillaceous carbonate, is from 8 to 30 feet (2.4 to 9.1 m) thick and intertongues with the Tanglewood only 10 to 25 feet (3 to 7.6 m) above the top of the Grier. The Devils Hollow Member is a pure, highly fossiliferous limestone, 10 to 15 feet (3 to 4.6 m) thick, which also intertongues with the Tanglewood approximately 30 feet (9 m) above the Brannon.

The study area is near the crest of the Cincinnati Arch, and although the strata are relatively flat lying, they dip gently to the northwest at 15 feet per mile (2.8 m/km). No faulting is mapped within the drainage basin, although prominent joints have been observed in the field. A barite vein is mapped just north of Garretts Spring. The vein strikes due north, and projects along the axis of the Chenault Karst Window. It may represent an unmapped fault.

Hydrogeology

The general hydrogeology of the Inner Blue Grass has been described by numerous authors (Hamilton, 1950; Palmquist and Hall, 1960, 1961). More recently Thrailkill and others (1982) have conducted more detailed studies. Thrailkill and others defined two principal types of karst aquifers in the region: interbasins and ground-water basins. Interbasins occur between ground-water basins where flow takes place in shallow conduits and channels that are eroded into bedrock, but roofed with soil. Some of these conduits are perched on argillaceous units, at least for short reaches. This shallow flow quickly returns to the surface, but then sinks again toward the interior of the basin. The interior of the basin is the ground-water basin where conduits may breach and flow beneath the argillaceous units. This deep flow occurs in well-developed caves or conduits, and resurges at a major spring near local base level. Both interbasin watershed boundaries and ground-water basin boundaries are known to cross surface watershed boundaries, although most commonly the interbasin boundary roughly coincides with the surface watershed.

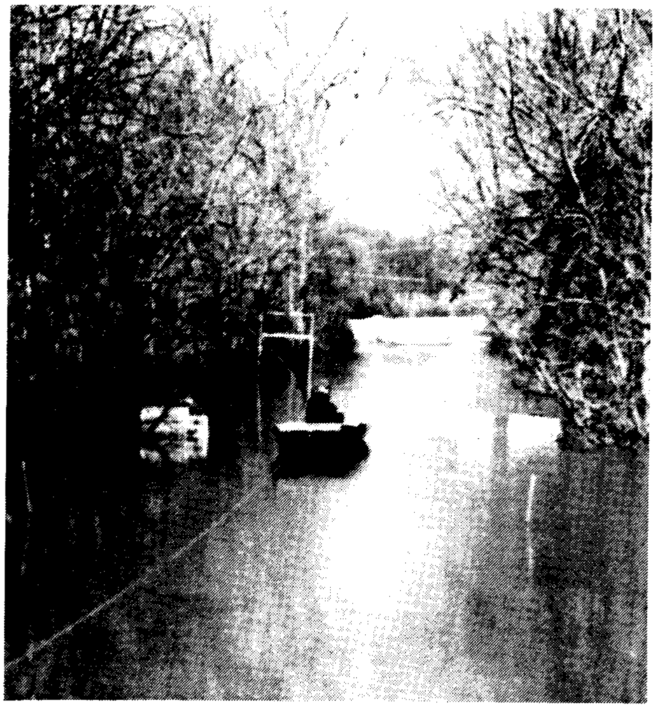


Figure 2. Flooded Sinking Creek Karst Valley at Cherrywood Lane, Tashamingo Subdivision, February 1989. The roadway is covered with approximately 3 feet of water.

METHODOLOGY

Three separate tasks were essential for understanding flooding in the Garretts Spring Basin: first, mapping the watershed boundary; second, measuring the intake capacity of the Sinking Creek swallow holes under various stages of flooding; and third, collecting hydrologic data, which are input into a digital hydrologic model to estimate the basin response caused by various storm events and changes in land use.

Ground-Water Dye Tracing

The boundary for the Garretts Spring drainage basin could not be unambiguously drawn because of the karst topography. Sixteen ground-water dye traces were conducted to determine where the divide lay (Fig. 5). Results for 14 other traces performed by Larry Spangler (personal communication, 1989) were also obtained and are shown on Figure 5. Standardized techniques, discussed in detailed by numerous authors (Aley and Fletcher, 1976; Thrailkill and others, 1983; Jones, 1984; Davis and others, 1985; Quinlan, 1987; Mull and others, 1988) were used.

Traces conducted by the authors utilized four fluorescent dyes: Fluorescein (C.I. Acid Yellow 73), Rhodamine WT (Acid Red 388), Diphenyl Brilliant Flavine (C. I. Direct Yellow 96), and Tinopal CBS-X (optical brightening agent 351) (Smart, 1984). Straight-line distances traced ranged from 1,900 feet (580 m) to 6,300 feet (1,920 m). The Fluorescein and Tinopal were introduced into swallow holes as dry powder, while the Direct Yellow was premixed with sufficient distilled water to dissolve the powdered dye. Dry quantities of dye used ranged from 1.1 pounds (500 gm) of Tinopal to as little as 0.1 pound (50 gm) of Fluorescein. The Direct Yellow was 20 percent active ingredient by weight, the Rhodamine a 20 percent solution, and the others 100 percent active ingredients.

Dye detectors were mounted on concrete anchors (called "gumdrops" by Quinlan, 1987) and consisted of activated carbon charcoal in fiberglass screen-wire packets and surgical cotton later replaced with bleached cotton broadcloth (Testfabrics, cat. no. 419). The use of manufacture and trademark names does not constitute an endorsement of the product by KGS or the University of Kentucky; they are included for reference only.

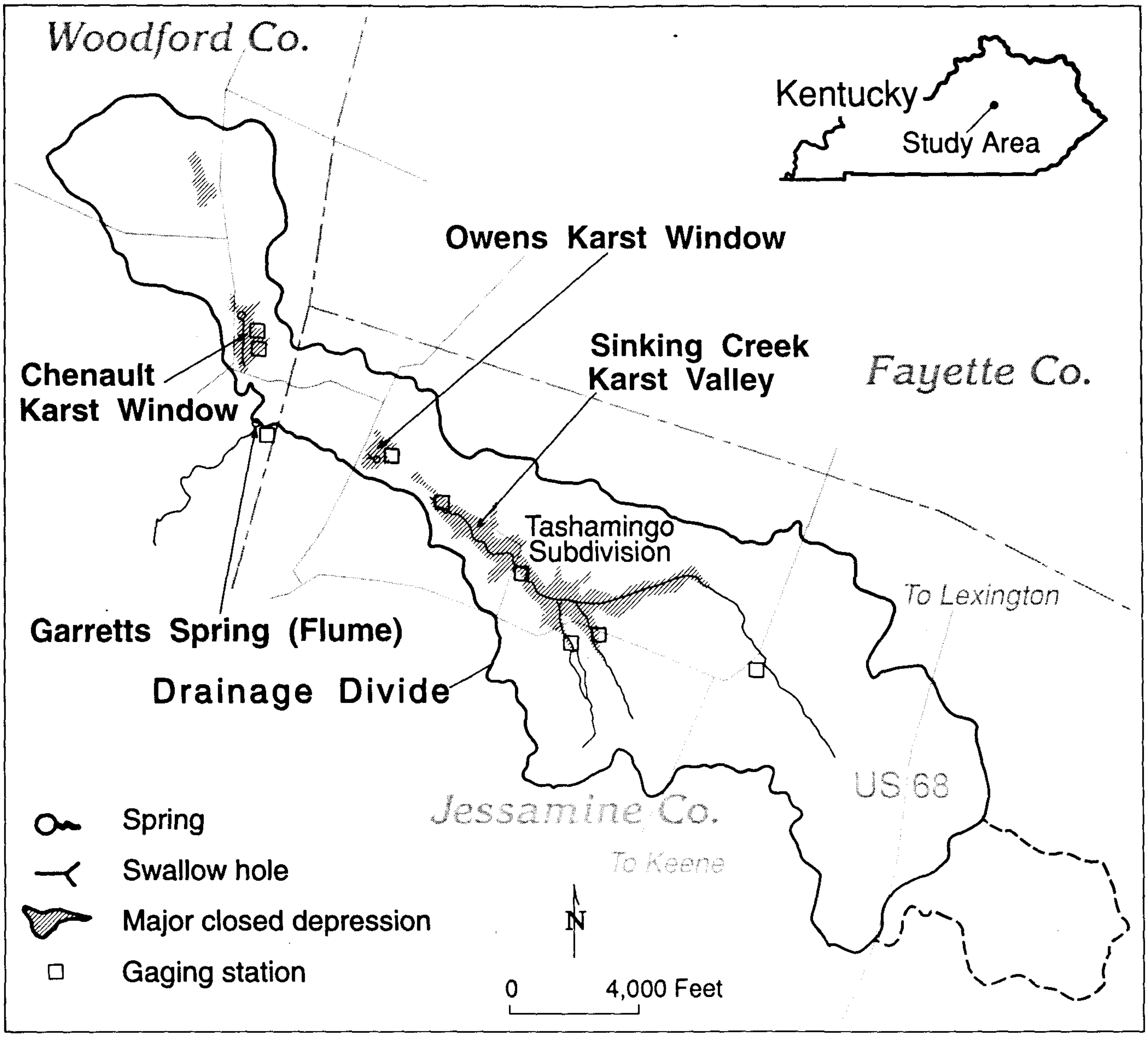
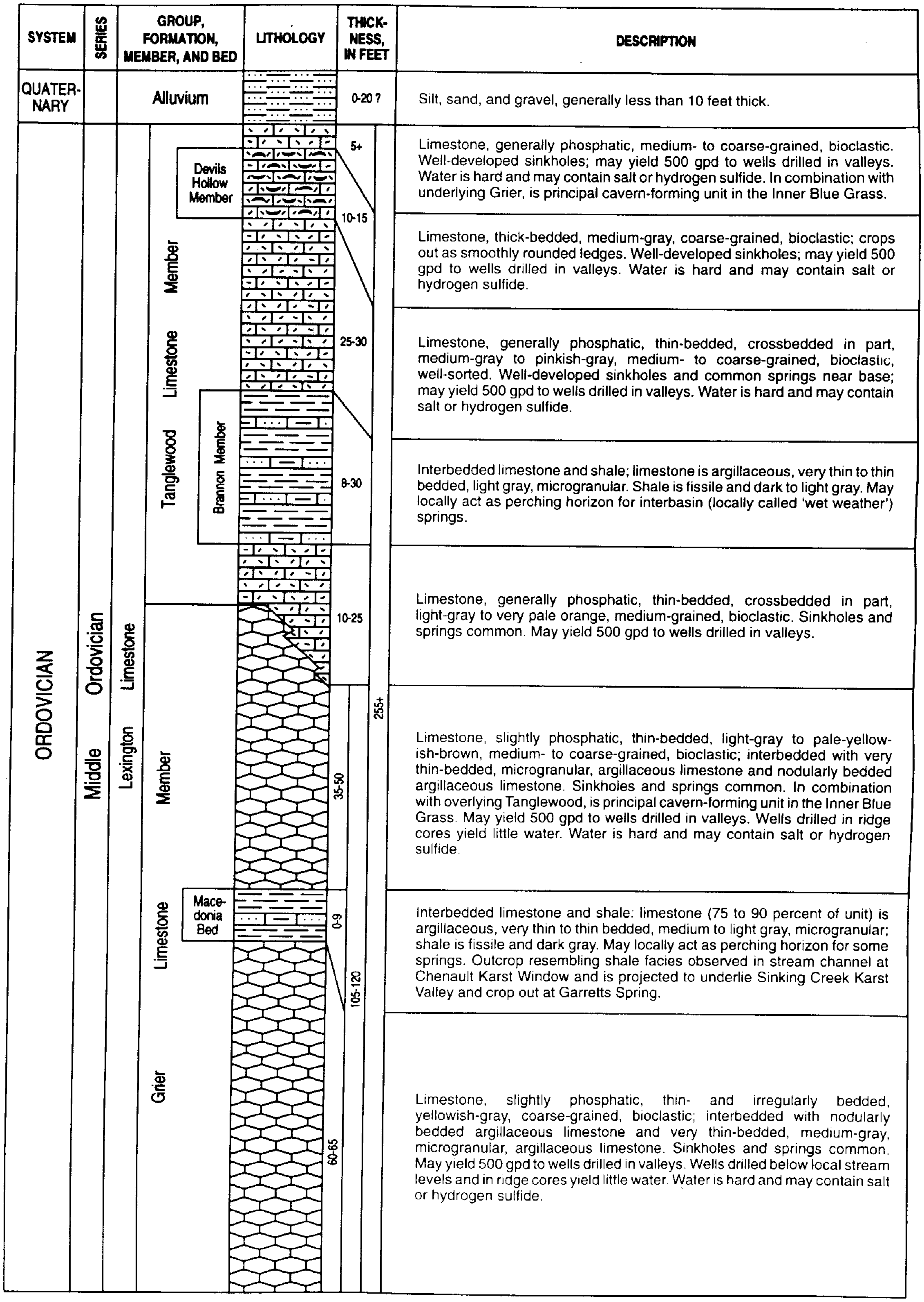


Figure 3. The Garretts Spring drainage basin.

Surgical cotton was occasionally lost because of mechanical erosion and attack by crayfish. Wire frames supporting a cotton-fabric swatch were tried (Thrailkill and others, 1983). These proved much more durable; however, manufacturing these "bugs" was time consuming. Experimental traces were run using fabric both on a frame and as a ribbon, 1 1/2 x 18 inches (3 cm x 50 cm), tied into a "bow tie." Visual inspection of the positive fabric bugs showed equally good dye adsorption for both methods, but the bow ties proved much more durable than surgical cotton. During a hiatus in the tracing program, bow ties were left in the field for 3 months during the winter. Although severely degraded, one-fourth to one-half of the fabric remained; surgical cotton would have disappeared in a week or 10 days.

Samples for quantitative traces were collected with ISCO model 2900 programmable automatic samplers. Intake lines were purged before each sample and emptied after sampling to minimize mixing with residue from the previous sample. The ISCO model 2900 is only available with polyethylene bottles, which adsorb Rhodamine dye readily. Therefore, glass culture tubes were used that closely fit inside the mouth of the plastic ISCO bottles and were of correct length to allow the sampler distributor to clear the mouth of each tube. The



SYSTEM	SERIES	GROUP, FORMATION, MEMBER, AND BED	THICKNESS, IN FEET	DESCRIPTION
QUATERNARY		Alluvium	0-20 ?	Silt, sand, and gravel, generally less than 10 feet thick.
ORDOVICIAN	Middle Ordovician	Lexington Limestone (255+) Tanglewood Limestone Member Devils Hollow Member	5+	Limestone, generally phosphatic, medium- to coarse-grained, bioclastic. Well-developed sinkholes; may yield 500 gpd to wells drilled in valleys. Water is hard and may contain salt or hydrogen sulfide. In combination with underlying Grier, is principal cavern-forming unit in the Inner Blue Grass.
		Tanglewood Limestone Member	10-15	Limestone, thick-bedded, medium-gray, coarse-grained, bioclastic; crops out as smoothly rounded ledges. Well-developed sinkholes; may yield 500 gpd to wells drilled in valleys. Water is hard and may contain salt or hydrogen sulfide.
		Tanglewood Limestone Member	25-30	Limestone, generally phosphatic, thin-bedded, crossbedded in part, medium-gray to pinkish-gray, medium- to coarse-grained, bioclastic, well-sorted. Well-developed sinkholes and common springs near base; may yield 500 gpd to wells drilled in valleys. Water is hard and may contain salt or hydrogen sulfide.
		Brannon Member	8-30	Interbedded limestone and shale; limestone is argillaceous, very thin to thin bedded, light gray, microgranular. Shale is fissile and dark to light gray. May locally act as perching horizon for interbasin (locally called 'wet weather') springs.
		Tanglewood Limestone Member	10-25	Limestone, generally phosphatic, thin-bedded, crossbedded in part, light-gray to very pale orange, medium-grained, bioclastic. Sinkholes and springs common. May yield 500 gpd to wells drilled in valleys.
		Grier Limestone Member (105-120)	35-50	Limestone, slightly phosphatic, thin-bedded, light-gray to pale-yellowish-brown, medium- to coarse-grained, bioclastic; interbedded with very thin-bedded, microgranular, argillaceous limestone and nodularly bedded argillaceous limestone. Sinkholes and springs common. In combination with overlying Tanglewood, is principal cavern-forming unit in the Inner Blue Grass. May yield 500 gpd to wells drilled in valleys. Wells drilled in ridge cores yield little water. Water is hard and may contain salt or hydrogen sulfide.
		Macedonia Bed	0-9	Interbedded limestone and shale: limestone (75 to 90 percent of unit) is argillaceous, very thin to thin bedded, medium to light gray, microgranular; shale is fissile and dark gray. May locally act as perching horizon for some springs. Outcrop resembling shale facies observed in stream channel at Chenault Karst Window and is projected to underlie Sinking Creek Karst Valley and crop out at Garretts Spring.
		Grier Limestone Member	60-65	Limestone, slightly phosphatic, thin- and irregularly bedded, yellowish-gray, coarse-grained, bioclastic; interbedded with nodularly bedded argillaceous limestone and very thin-bedded, medium-gray, microgranular, argillaceous limestone. Sinkholes and springs common. May yield 500 gpd to wells drilled in valleys. Wells drilled below local stream levels and in ridge cores yield little water. Water is hard and may contain salt or hydrogen sulfide.

Figure 4. Units exposed in the Garretts Spring drainage basin with general hydrogeologic characteristics (after Cressman, 1965, and Palmquist and Hall, 1960).

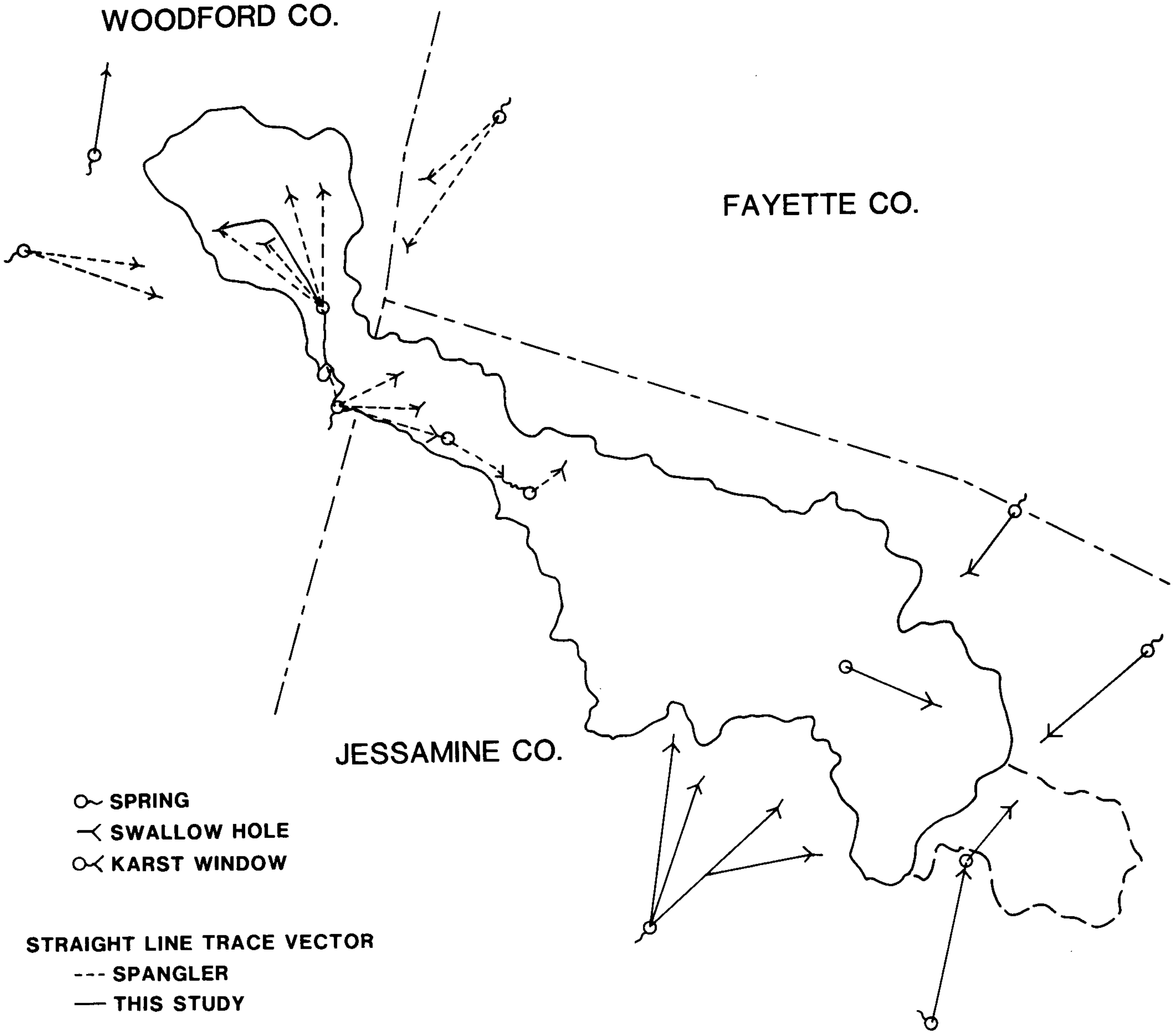


Figure 5. Ground-water dye-trace vectors defining the Garretts Spring drainage basin. The area with the dashed outline at the east is included in the basin on topographic maps, but ground-water tracing shows flow is pirated to the south.

small size of the culture tubes required careful calibration of the sample volume in the field. Dye concentrations were determined on a Turner Designs model 10 fluorometer. Discharge during the traces was determined directly with Price meters, rather than by using the stage and rating curve.

Stream Gaging and Discharge Data

Nine gaging stations and four discharge observation points, involving 17 channel cross sections, were established for monitoring stream and spring flow. Three sites were instrumented with continuous-stage recorders: Chenault Karst Window (CHEN recorder), Owens Karst Window (OWEN recorder), and Sinking Creek at Cherrywood Lane in the Tashamingo Subdivision (TASH recorder). Telog Instruments WLS-2109 single-channel digital recorders were coupled with Druck PDCR 830 pressure transducers. Observations of the water depth, calibrated in feet, were made every second, and the mean was recorded every 15 minutes. Two of the Druck transducers have a 0 to 10 psi range (23.11 ft.; 7.04 m of water), and the third has a range of 0 to 20 psi (46.22 ft.; 14.08 m of water), with an accuracy of +/- 0.3 percent. The data were downloaded to a laptop computer, either directly from the recorder or via a Telog Instruments data transfer unit, then uploaded to a data base on the VAX 8550 at KGS. The pressure transducers were mounted in stilling wells constructed of PVC, which were imbedded in the channel bank. Elevations were leveled to a datum scribed on each stilling well to obtain elevation head.

Discharges were measured using the partial-sections method (Buchanan and Somers, 1976) and Price flow meters (Teledyne-Gurley models 622 and 625). Because the water-level recorders were installed in karst valleys and windows, ponding influenced the hydrograph during high flow. Determination of the inception of ponding was based on topography and the elevation of the stage recorder relative to the sinking point of the stream, changes in the hydrograph curve, and other onsite observations. Ponding at the swallow holes had two effects on discharge measurement. First, even at sites where flow was still confined to a distinct channel, measurements were logistically more difficult to obtain because of deep water (6 to 15 ft.; 2 to 5 m). Second, accuracy of the Price flow meters was reduced because of sluggish velocities of the ponded flow.

Perhaps the most important water-level recorder was the one in the Tashamingo Subdivision at Cherrywood Lane because it provided the only continuous record of runoff from the headwaters of the southeastern branch of the basin. Sinking Creek flows under Cherrywood Lane through three corrugated steel culverts penetrating an earth-fill causeway. The causeway creates an effective dam, and virtually all flow upstream of Cherrywood Lane is forced through the culverts until the roadway is overtopped at a stage of 11.2 feet (3.4 m). The station misses minor discharge from small springs and overland flow between the recorder and the swallow holes.

The Chenautt Karst Window and Owens Karst Window sites did not have the benefit of a structure to control discharge. The Chenault Karst Window stilling well was a few meters upstream of the outcrop of the Macedonia Bed, which acted as a control section during low flow. The control shifted to the channel during moderate flow, and shifted again to pressure flow when the pool from the flooded swallow holes reached the elevation of the stilling well. At Owens Karst Window the stilling well was installed in the channel from the middle spring. At Owens Karst Window four major openings discharge into three channels, and discharges from the three channels were summed and applied to the rating curve. control was by the channel from low stage until backflooded. At stages over 12 feet (3 m) the banks of the channels from the springs were overtopped and channel control was lost.

Discharge data at Garretts; Spring were obtained from a flume operated by Dr. Gary Felton of the University of Kentucky Department of Agricultural Engineering. The spring is naturally impounded, but has been further dammed for an irrigation supply. Conditions at the site imposed limits on the dimensions of the flume, which had a maximum capacity of 30 cubic feet per second (cfs) (0.85 cubic meter per second [cms]). Unfortunately, the maximum discharge at Garretts; Spring is known to exceed 60 cfs (1.7 cms) (Fig. 6). Furthermore, the dam supporting the flume has leaked at various times since the flume's installation. Also, a secondary spring downstream is known to have received a small percentage of flow from the basin. When possible, discharges from Garretts Spring were also measured with flow meters.

Determination of Swallow-Hole Capacity

The suspected principal control on the flooding of Sinking Creek Karst Valley was the intake capacity of the swallow-hole zone at the western end of the valley. Access to the footwall area of Sinking Creek Karst Valley was denied during the first year of the project, which precluded direct observation of both stage and inflow at the swallow holes. Measurement of the intake capacity by indirect methods was tried until access was obtained in January 1991. The methods used to measure intake included determining head loss coupled with estimated hydraulic characteristics of the conduits, budgeting measured outflows at Garretts Spring and Chenault Karst Window, budgeting estimated storage and inflow, measuring inflow at critical points in the stage hydrograph, and directly observing inflow at the swallow holes and outflow at Owens Karst Window. The two

Figure 6. Discharge at Garretts Spring exceeding the capacity of the flume during the December 1990 flood.

budgeting techniques proved too imprecise to develop a rating curve, although the values set limits on realistic swallow-hole inflow rates. The most useful data were eventually obtained by observing discharge at critical stages and directly measuring inflow.

Rating-Curve Development

Rating curves were constructed using techniques developed by the U.S. Geological Survey (Kennedy, 1984). A gage-zero flow for each station was selected by choosing the offset resulting in the largest Pearson correlation coefficient for the regression of the discharge on the stage. Data were insufficient to define hysteresis from overbank storage.

The stage-discharge relationships for all three stage-recorder sites and the Sinking Creek swallow holes are complex. The rating curve for the Sinking Creek and Chenault Karst Window swallow holes consists of free-fall and confined-flow limbs (Figs. 7 and 8). The rating curve for Tashamingo is in two parts, free-fall and ponded (Fig. 9). The rating curve for Owens Karst Window is even more problematic: the flow data suggest a multiple-step curve, but data are insufficient to clearly define the curve. A single, straight line was regressed to the available Owens Karst Window data (Fig. 10). Discharge data for the free-fall segment of the curve for Sinking Creek swallow holes were measured at a cross section upstream from the divergence of the first distributary. Discharge data for the pressure-flow segment were derived from discharges measured at Owens Karst Window and were coupled with stage observations at either the swallow holes or Tashamingo. Only 85 percent of the flow through Owens Karst Window was accounted for at the three discharge measuring stations during moderate to high flow. The Owens Karst Window data were adjusted for the unaccounted-for flow because the swallow hole rating curve was to be used with the HEC-1 model.

Discharge Hydrograph Computation and Flow Budget Modeling

A computer program was written to calculate discharge from stage data measured at Tashamingo, Owens Karst Window, and Chenault Karst Window us-

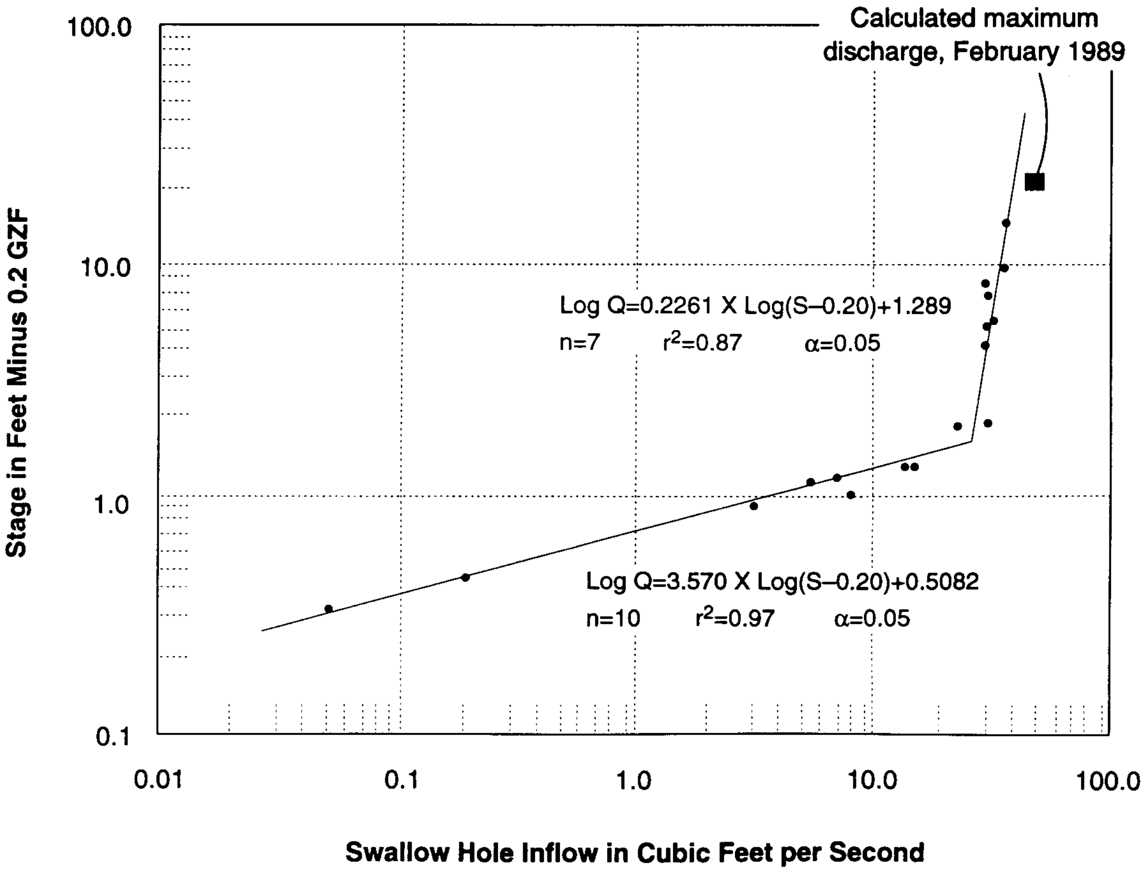


Figure 7. Stage-discharge rating curve for the Sinking Creek Karst Valley swallow holes. The estimated maximum discharge through the swallow holes for the February 1989 event is plotted with a solid square.

ing algorithms developed from the rating curves for these sites. The program was written in Digital Equipment Corporation Datatrieve language to access the stage data stored in a data base and the discharge hydrographs for these sites were computed with this software. The flow into Owens and Chenault Karst Windows was then summed to give an estimated minimum discharge at Garrefts Spring.

Precipitation Data

Precipitation data were obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station at nearby Blue Grass Field, 4.6 miles (7.3 km) northwest of Garretts Spring, and a volunteer NOAA station at Keene, 3.8 miles (6.1 km) southeast of the spring. Additional precipitation data were obtained from a weighing-bucket recording rain gage installed by Felton at Garretts Spring. These data were used when available because the gage is within the study area.

Land-Use and SCS Curve-Number Estimation

After the basin boundary was mapped, land use was determined by Felton (personal communication, 1992). These data were compiled into Soil Conservation Service (SCS) cover type and hydrologic condition categories based on the percentage of each hydrologic soil group in each sub-basin (McDonald and others, 1983). A weighted-average runoff curve number was then determined for each sub-basin as defined by the U.S. Army Corps of Engineers (SCS, 1986). These values were used in modeling runoff in the basin.

Runoff Modeling

The Louisville office of the U.S. Army Corps of Engineers was contracted by the Federal Emergency Management Agency to determine the 1 00-year flood plain for the Sinking Creek Basin (U.S. Army Corps of Engineers, 1990). Their study was completed with the use of the HEC-1 Flood Hydrograph Package (Computer Program 723-X6-L201 0) developed by the Corps to predict the impact of storm runoff . The Corps made the program and data files available to KGS. The Corps data were coupled with the land-use and swallow-hole-capacity data gathered by this research to compute the model flood hydrographs for Sinking Creek.

RESULTS

Ground-Water Dye Tracing

The qualitative ground-water traces resulted in several significant findings. The Nicholasville 7.5-minute topographic quadrangle map indicated that the headwaters of the southeastern branch of the basin extended several hundred meters east of U.S. Highway 68 (dashed area on Figure 5). However, tracing indicated that surface-water flow in this area had been diverted underground to the south, out of the basin. All traces conducted in this area were made during low flow, and whether high-flow discharge into Sinking Creek occurs is unknown. Also, the watershed of the northwestem branch was mapped, and two sub-basins were delineated (Spangler, 1989). The three main swallow holes of Sinking Creek were independently traced to Owens Karst Window; all principal springs at Owens Karst Window were found to receive flow from each of the three swallow holes. Finally, since it was thought possible that the flow from Chenault and Owens Karst Windows did not join underground and that the Garretts Spring rise pool was a double resurgence, dye detectors were placed in the two obvious boils in the rise pool and independent traces were run from both Chenault and Owens Karst Windows. Both detectors were positive for both traces, but dye mixing in the rise pool may have affected both detectors. A physical examination of the spring revealed that the bottom of the rise pool was completely covered with talus. However, Garretts Spring is a distributary resurgence. Positive traces to Garretts Spring were also detected at Hoffmans Spring, a small spring on the northern bank of Clear Creek, approximately 600 feet (200 m) downstream of Garretts Spring. Discharge from Hoffmans Spring is small, even during high flow from Garretts Spring.

Quantitative dye traces were used to measure mean flow velocity and determine effective conduit cross-sectional area (Table 1). Two traces were conducted from Sinking Creek to Owens Karst Window. The centroid of the dye plume and dye recovery (85.1 percent) were calculated for the first trace. Only velocity was calculated for the second trace to Owens Karst Window. Because of a higher than expected velocity, the leading edge of the dye breakthrough curve was missed for a trace from Owens Karst Window to Garretts Spring. Its centroid was estimated.

The straight-line distance that dye traces traveled was measured from topographic maps. Previous researchers have used a meander distance to straightline distance ratio of 1.5:1 (Mull and others, 1988; Thrailkill and others, 1990) for studies in Kentucky. For this study the meander ratio was determined by measuring

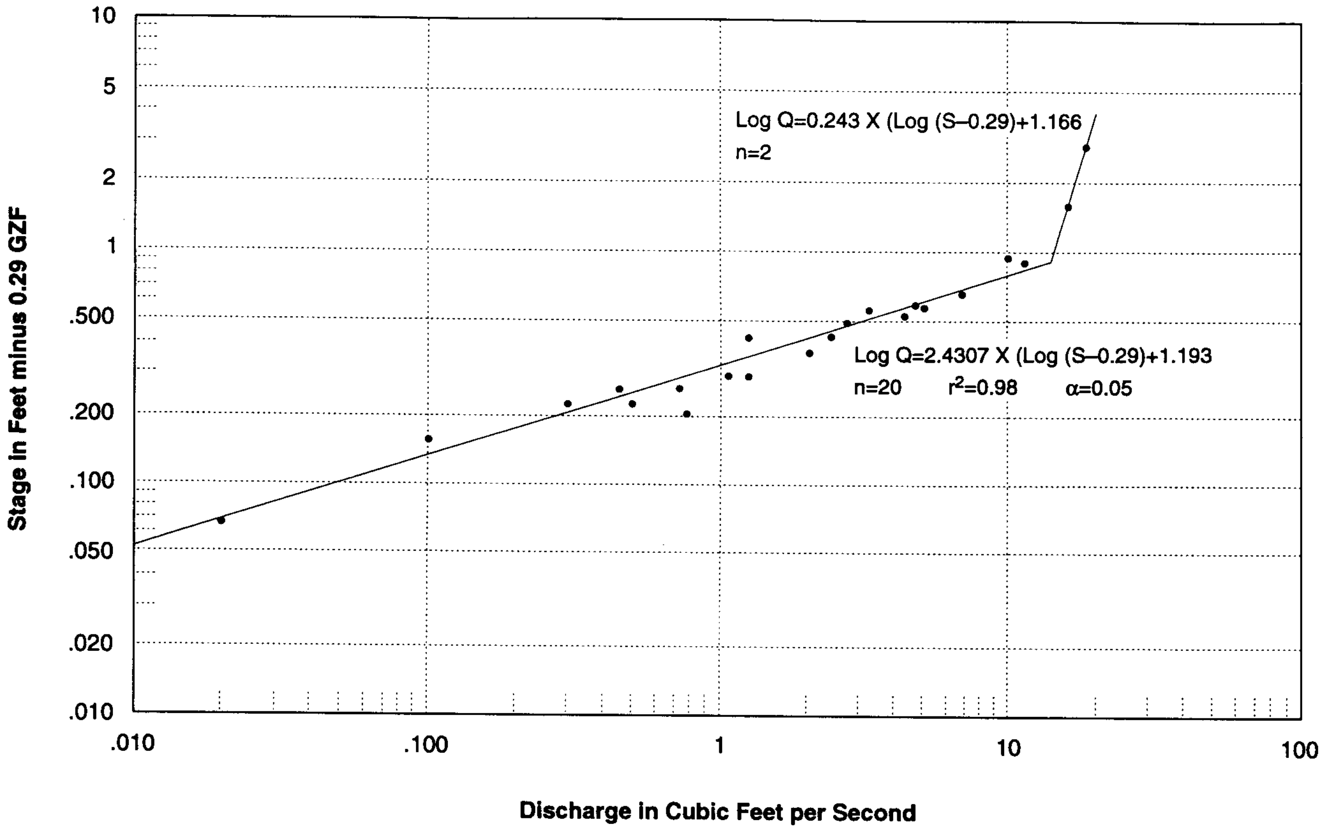


Figure 8. Stage-discharge rating curve for the Chenault Karst Window gaging station.

the meander and straight-line distances of passages with flowing streams from maps of five Inner Blue Grass caves (O'Dell and O'Dell, 1992), including one cave within the basin, and averaging the ratio. The ratio was 1.11:1, and is reasonable in light of the linear nature of many cave passages in the Inner Blue Grass.

Table 1.—Results of Quantitative Ground-Water Dye Traces.

Sinking Creek to Owens Karst Window

Trace distance = 2,100 feet X 1.1 = 2,331 feet (710 m)

Date	*Elapsed Time (seconds)*	*Velocity*		*Discharge*		*Cross Section*	
		feet/second	*meters/second*	*cfs*	*cms*	*feet*^{2}	*meters*^{2}
2–11–91	5,460	0.43	0.13	11.32	0.32	26.3	2.5
1–07–92	3,540	0.66	0.20	25.02	0.71	37.9	3.5

Owens Karst Window to Garretts Spring

Trace distance = 3,800 feet X 1.1 = 4,218 feet (1,286 m)

Date	*Elapsed Time (seconds)*	*Velocity*		*Discharge*		*Cross Section*	
		feet/second	*meters/second*	*cfs*	*cms*	*feet*^{2}	*meters*^{2}
3–19–92	9,120 est.	0.46	0.14	49.39	1.40	107.37	9.98
3–19–92	9,120 est.	0.46	0.14	32.14*	0.91*	69.87	6.49

* Discharge at Garretts Spring minus inflow into Chenault Karst Window.

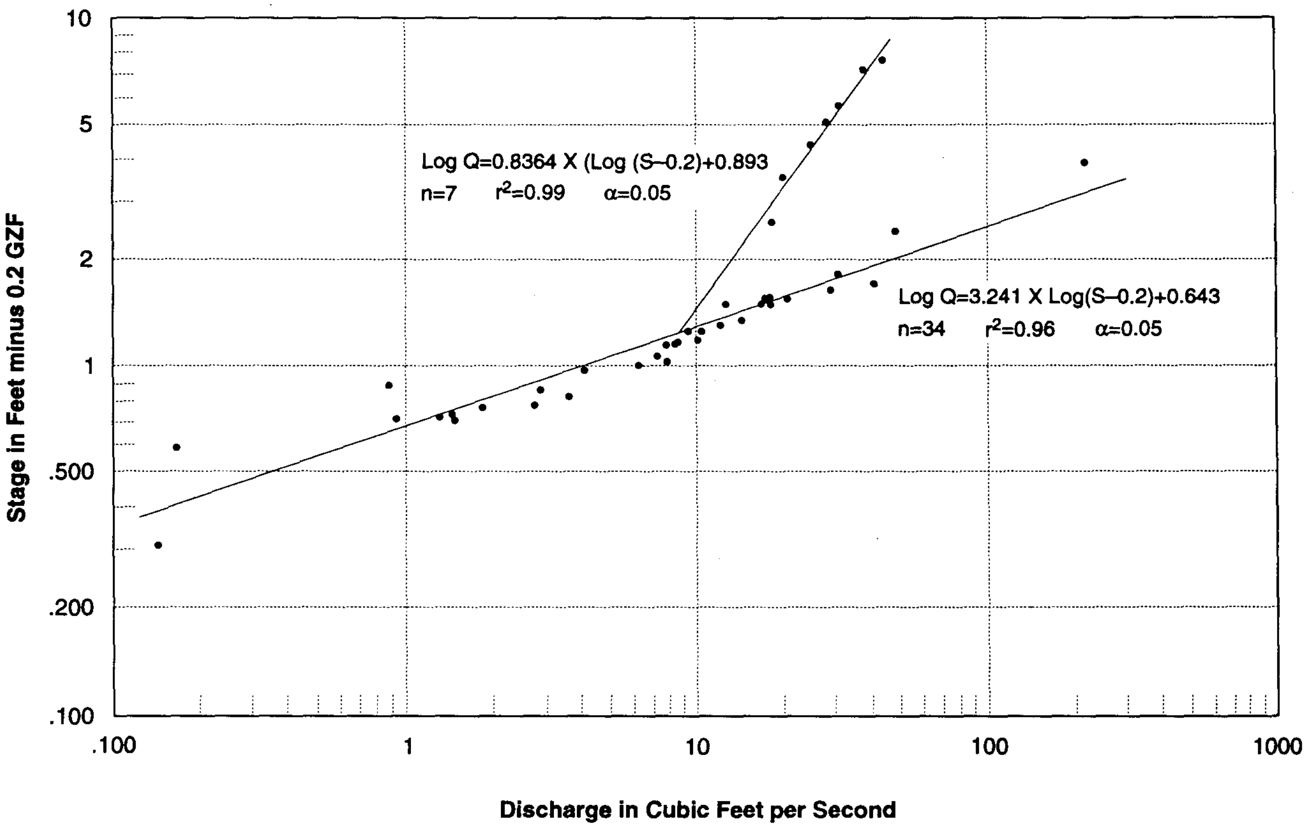


Figure 9. Stage-discharge rating curve for the Tashamingo gaging station. The upward diverging curve is for backflooded conditions.

Two quantitative traces were run by Baumgartner (1991) from Chenault Karst Window to Garretts Spring. Both traces were run under low-flow conditions and yielded a mean conduit cross-sectional area at Garretts Spring, for the combined flow from both sub-basins, of 72.4 feet2 (6.73 M2). This area is virtually the same as the cross section calculated for the trace from Owens Karst Window to Garretts Spring, minus the Chenault Karst Window flow. Baumgartner used the discharge data from the flume, while discharge for the Owens Karst Window trace was measured with Price meters. Baumgartner's dye recovery averaged 59.7 percent. Substantial flow was observed leaking through the dam at the flume during the period Baumgartner ran his traces, which explains the poor dye recovery. Therefore, the discharge he used was likely to be too small, resulting in a smaller cross-sectional area. The similarity between the cross-sectional areas of Baumgartner and this study may be coincidental. Alternatively, the missed flow may have roughly equaled the contribution from Chenault Karst Window. Data from the March 19 trace suggest that the Owens Karst Window to Garretts Spring conduit is twice the cross-sectional area of the Chenault Karst Window to Garretts Spring conduit. Both tributaries were likely to have been under pressure flow during the trace.

Estimate of Peak Discharge During 1989 Flood

Calculations of the maximum discharge for the February 1989 flood were made because it provided the highest stage recorded to date for Sinking Creek Karst Valley (Table 2). The cross-sectional area of the January 7,1992, trace was used to represent the Sinking Creek-Owens Karst Window conduit under pressure-flow conditions. Data from the March 19, 1992, trace were used for the Owens Karst Window-Garretts Spring conduit area. The Darcy-Weisbach equation was chosen to approximate the flow regime because it represents energy loss from turbulent flow in pipes. The choice of cross-sectional shape of the conduit is significant for estimating discharge because of the influence of conduit surface area on head loss. However, because of the tributary-distributary and overflow-conduit plan postulated for the conduit system, any cross-section shape would be valid only for a short reach of conduit and is therefore generally arbitrary. A circular cross section

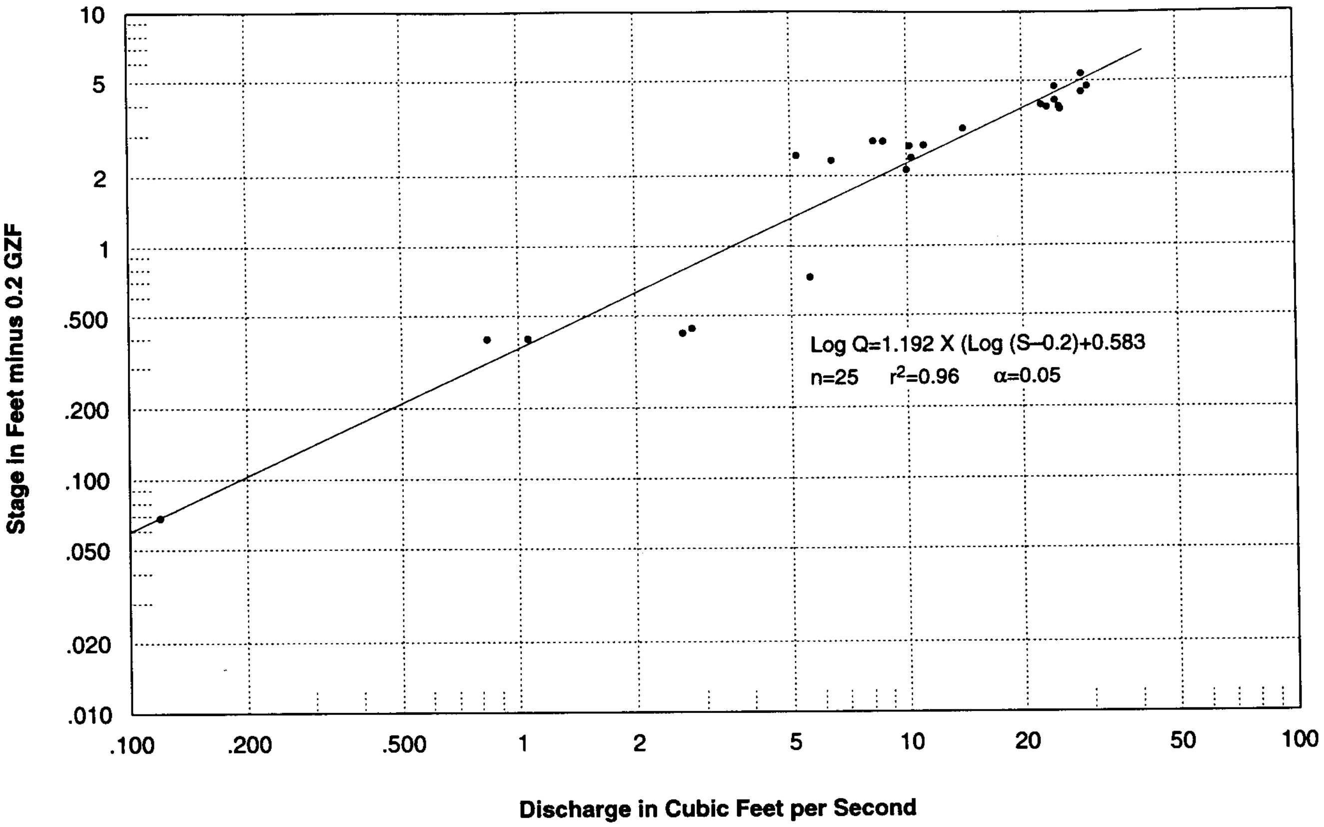


Figure 10. Stage-discharge rating curve for the combined discharge of the major springs at Owens Karst Window.

was chosen. The Darcy-Weisbach friction factor was calculated for the conduits between Sinking Creek and Owens Karst Window and from Owens Karst Window to Garretts Spring using velocity and discharge data from the quantitative dye traces. The value used in these calculations was the apparent friction factor, and represented total head loss in these conduits. The values calculated fall well within ranges reported by other researchers for karst conduits (Ford and Williams, 1989). The elevations of flotsam marks in Sinking Creek, Owens Karst Window, and Garretts Spring were recorded soon after the 1989 flood.

These calculated discharges compared favorably with discharges projected from lesser events. The flow from Owens Karst Window to Garretts Spring includes an unknown contribution from several additional inputs downstream of Owens Karst Window. Inspection of flow budget data from three flood events suggests 25 percent of the flow from the southeastern branch may be contributed by this unaccounted-for area. Also, flow from springs in Owens Karst Window that is measurable during low and moderate flow becomes inaccessible during high flow. Furthermore, the quantitative dye trace data suggest only 85 percent of the flow is accounted for during high flow. Seventy-five percent of 70.6 ft.^{3}/sec. is 53 ft. ^{3}/sec. (1.5 m^3/sec.) (Table 2), which compares favorably with the calculated flow into Owens Karst Window from Sinking Creek of 47.3 ft^3/sec. (1.3 m^3/sec.); if the unaccounted-for flow into Owens Karst Window is considered, the comparison is even better.

Stage Hydrographs

Stage data have contributed directly to understanding the hydrology of the basin. A hydrograph for the Chenault Karst Window, Tashamingo, and Owens Karst Window recorders for the largest flood event during the project is presented in Figure 11. An important consideration in interpreting the stage data is the position of the recorders relative to the swallow holes. Both the Tashamingo and Chenault Karst Window recorders are many meters upstream of the swallow holes, where backwater effects are minimized. Under ideal circumstances two recorders should be used, one upstream to record inflow and one at the swallow holes to record head. However, only staff gages were installed at the swallow holes, and the data obtained from them was unevenly distributed through time.

Table 2.—Calculation of Maximum Discharge from Sinking Creek and Owens Karst Window During February 1989 Flood.

Darcy–Weisbach equation: $Q^2=2dga^2/f \times dh/dl$
d = conduit diameter
g = acceleration of gravity constant
a = conduit cross-sectional area
f = Darcy–Weisbach friction factor
dh/dl = conduit gradient or slope
Q = discharge

Sinking Creek to Owens Karst Window

$g = 9.8$ m/sec.^{2} (32.15 ft./sec.^{2})
$dh/dl = 0.009$ (2–89 flood)
$f = 2.6$ (2–11–91 data) (apparent friction factor)
$a = 3.52$ m^2 (37.87 ft.^{2}) (1–7–92 data)
$d = 2.12$ m (6.96 ft.) (1–7–92 data)
$Q^2 = (2 \times 2.12 \times 9.8 \times (3.52)^2/2.6) \times 0.009$
$Q = 1.3$ m^3/sec. = 47.3 ft.^{3}/sec.

Owens Karst Window to Garretts Spring

$g = 9.8$ m/sec.^{2} (32.15 ft./sec.^{2})
$dh/dl = 0.014$ (2–89 flood)
$f = 8.5$ (3–19–92 data) (apparent friction factor)
$a = 6.49$ m^2 (69.82 ft.^{2}) (3–19–92 data)
$d = 2.88$ m (9.45 ft.) (3–19–92 data)
$Q^2 = (2 \times 2.88 \times 9.8 \times (6.49)^2/8.5) \times 0.014$
$Q = 2.0$ m^3/sec. = 70.6 ft.^{3}/sec.

The hydrograph from the Tashamingo recorder was typical of unconfined flow until ponding of the swallow holes rose to its intake. After ponding reached the recorder, the hydrograph flattened out, and slowly dropped as storage was removed from the karst valley. The hydrograph closely paralleled stage data for Owens Karst Window when both features were flooded (Fig. 11).

The recorder at Owens Karst Window was closer to the swallow holes than the other two recorders and was influenced by backwater effects earlier in a flood event. The stage recording at Owens Karst Window showed a consistent, rapid rise and fall in stage from 2 to 4 feet (0.6 to 1.2 m). Discharge data have been very difficult to obtain for this limb of the hydrograph because of its short duration. During a series of observations on March 18, 1992, to record this change, discharge increased from 5.7 cfs (0.16 cms) to 10.2 cfs (0.29 cms), while stage rose 1.4 feet (0.43 m) in 2.25 hours. The rapid increase in stage and discharge at Owens Karst Window was caused by the onset of flow from its northern springs. The northern springs at Owens Karst Window begin flowing at stage 1.6 feet (0.49 m) at the Sinking Creek swallow holes and discharged vigorously when the swallow holes were completely inundated. The higher northern spring is the outlet of a higher conduit now acting as an overflow route.

The stage hydrograph for Chenault Karst Window is distinctly different from Owens Karst Window or Tashamingo, showing both a rapid rise and fall in stage (Fig. 11). While the recorder is nearly 900 feet (300 m) upstream of the swallow holes, the available staff gage readings at the swallow holes suggest the fall in stage continues until free-fall flow is restored. The swallow holes at Chenault Karst Window are roughly 10 feet (3 m) lower in elevation than the swallow holes at Owens Karst Window, but the conduit from Chenault Karst Window to Garretts Spring is substantially shorter than the conduit from Owens Karst Window to Garretts Spring. Also, the gradient from the Chenault Karst Window swallow holes to Garretts Spring is slightly steeper, 0.007 versus 0.006, than from the Owens Karst Window swallow holes, suggesting that the Chenault Karst Window to Garretts Spring conduit can accommodate greater discharge before the inception of pressure flow. The rapid drop in stage at Chenault Karst Window implies that it has an efficient flow route to Garretts Spring.

Stage data for Garretts Spring are converted directly to discharge by software in the monitoring equipment and the stage data are not retained. In general terms, the stage hydrograph at Garretts Spring shows sudden drops when Chenault Karst Window and Owens Karst Window empty.

Discharge Hydrographs

Discharge hydrographs for the December 1990 storm for Owens Karst Window, Chenault Karst Window, and Garretts Spring are presented in Figure 12. Two curves are shown for Garretts Spring, an estimate using the sum of the Chenault and Owens Karst Window discharges, and the recorded discharge from the flume. Four discharge measurements made by wading are also shown. The value for January 4 is low because an inappropriate Price meter was used.

The difference between the hydrographs for Chenault Karst Window and Owens Karst Window is striking. Once a flow rate of approximately 37 cfs (1.05 cms) was reached at Owens Karst Window, it remained constant for an extended period of time before tapering off gradually at first, then dropping sharply to pre-flood levels. The sudden drop is due to the depletion of storage in Sinking Creek Karst Valley, and the sudden reduction in flow into Owens

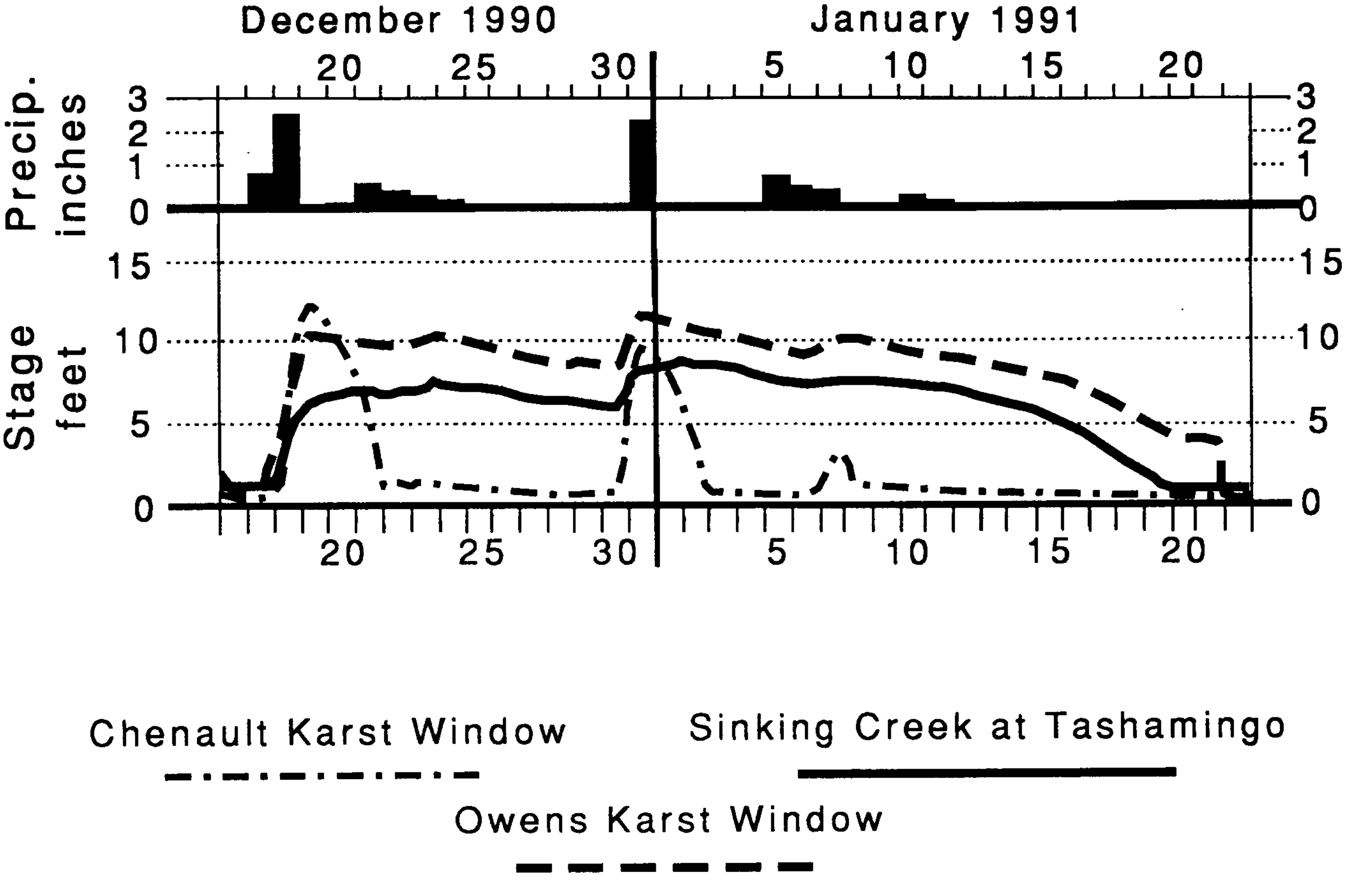


Figure 11. Stage hydrograph for the Tashamingo Subdivision, Owens Karst Window, and Chenault Karst Window water-level recorders, December 1990 event.

Karst Window. In contrast, the Chenault Karst Window hydrograph shows a series of broad, but steep-flanked peaks. This pattern reflects the rapid flooding and emptying of the karst window.

The shape of the estimated hydrograph for Garretts Spring is nearly the same as the Chenault Karst Window hydrograph because of the relatively flat curve of the Owens Karst Window hydrograph (Fig. 12). However, except during the peak flows from Chenault Karst Window, the overwhelming majority of the flow is contributed by Owens Karst Window. The hydrograph for the flume exhibits considerably more detail than the estimated hydrograph, but its magnitude is almost always roughly 10 cfs (0.28 cms) less than the estimate. This discrepancy is due to the unaccounted-for flow discussed under "Methodology." More important is the parallelism of the estimate and flume curves. Most of the major peaks match exactly. A peak in the flume data on December 25 that is not shown by the estimate is probably due to the discharge of storage in Chenault Karst Window that is below the elevation of the stage recorder. The longer duration of flow recession recorded by the flume is caused by the flow contribution between Owens Karst Window and Garretts Spring that is not accounted for by the estimate.

Although only a limited number of discharge measurements were made by wading at Garretts Spring, the Price meter measurements suggest the estimated discharge is reasonably correct. Furthermore, high flows certainly exceed the flume's capacity (Fig. 6). However, the flume shows greater detail and, by design, is more precise when flow is not bypassing it.

Both the estimated and measured hydrographs at Garretts Spring reveal the importance of the timing of storage depletion in the karst windows. Also, the relative magnitude of the contribution of flow from the two subbasins is clearly illustrated. The high flows from Owens Karst Window in the eastern sub-basin do not support conduit blockage as the cause of flooding in Sinking Creek Karst Valley.

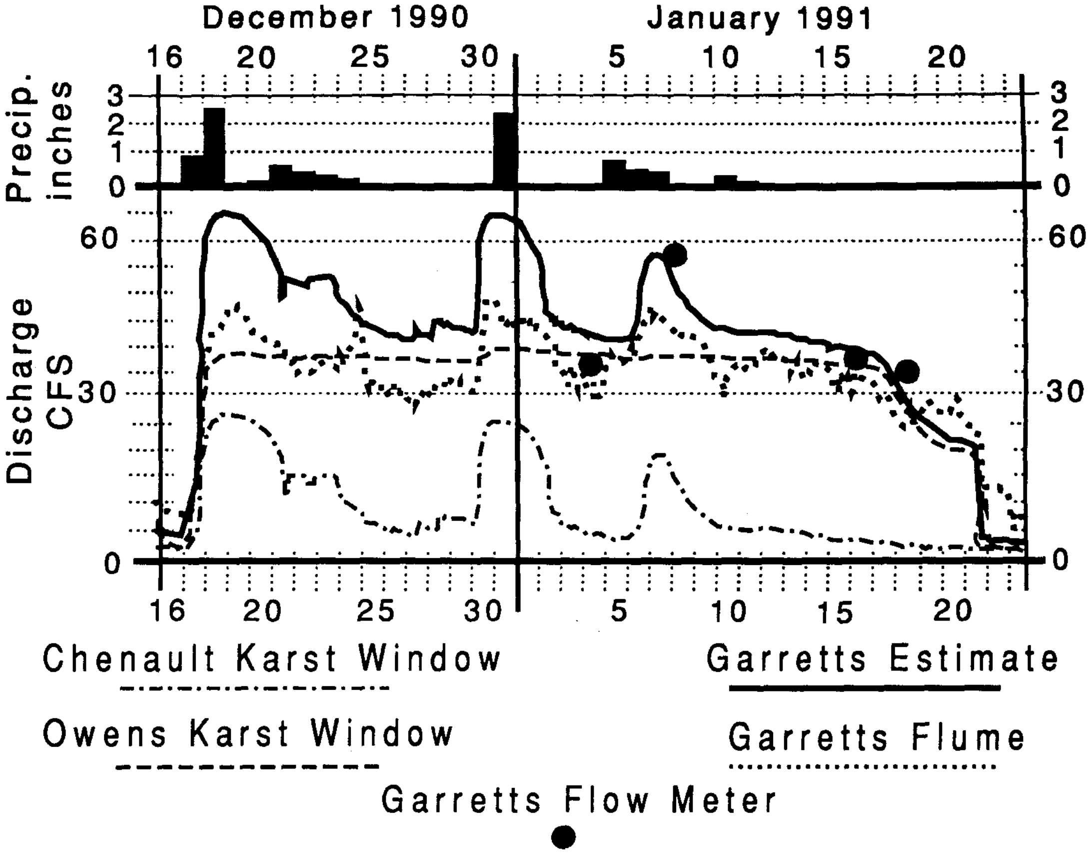


Figure 12. Discharge hydrograph for Owens Karst Window, Chenault Karst Window, and estimated, flume-determined, and flow-meter-determined discharge for the Garretts Spring December 1990 event.

Swallow-Hole Inflow Rating

The stage-discharge relationship for the Sinking Creek swallow hole is complex (Fig. 7), and overall is typical for a swallow hole (Bonacci, 1987). However, the pressure-flow segment has a subvertical slope, possibly because a component of the discharge continues as unconfined flow through normally abandoned conduits, joints, and bedding planes during high-flow events. Flow into high-stage swallow holes at Sinking Creek and from multiple high-stage springs at Owens Karst Window has been observed during floods. The regression lines for the free-fall and pressure-flow segments converge at a stage of 1.9 feet (0.58 m) and a discharge of 25.5 cfs (0.72 cms). Field observations indicate that all major swallow-hole openings are completely inundated at this stage. The estimated discharge from Sinking Creek for the February 1989 event has also been plotted on Figure 7.

Runoff Modeling

The HEC-1 Flood Hydrograph Package (Computer Program 723-X6-L2010) developed by the U.S. Army Corps of Engineers was used to model the effects of changing land use and moisture conditions in the southeastern branch of the drainage basin. The data file was originally set up by the Corps using their survey data for channel gradient, channel width, bridges, and culverts. The data file was modified for this study by applying the rating curve for the inflow capacity of the Sinking Creek swallow holes and by making new estimates of the SCS curve number from soil survey maps and land-use data gathered for this study. Each time the model was run, hydrographs were calculated for the 1989 storm and 12-hour design storms of 10-, 50-, 100-, and 500-year frequencies.

Although suburban development is accelerating in the basin, agricultural land use still predominates. Approximately 79.5 percent of the Garretts Spring Basin is in pasture or row crop. The total area up-gradient of the Sinking Creek swallow hole is 2,959.7 acres (1197.7 ha). Land use in this area is distributed as follows: 76 percent agriculture (pasture 63 percent, row crops 13 percent), 8.5 percent golf course, 8 percent residential (farmsteads, individual lots, subdivisions), 6 percent woodland, 1 percent lakes, ponds, etc., and 0.5 percent roads and highways. For this study, future suburban development was defined as 1 -acre (0.4 ha) lots, and all development was assumed to occur in former pasture. Furthermore, the increased impervious area created by access roads for the additional development was not considered. The increase in development was also assumed to be evenly distributed between each hydrologic soil type. However, most development will probably be on group B soils, since they are the most common in the basin, and type C and D soils primarily occur in poorly drained areas. The relative increase in SCS curve numbers for suburban development on type B soil is twice that of the same development on type D soil, and would increase surface runoff relative to the above assumptions.

The percentage of each soil in the basin was determined from soil survey maps (McDonald and others, 1983) and classified into hydrologic soil groups. The hydrologic groups were found to be distributed as follows: 69 percent type B, 23 percent type C, and 8 percent type D. No type A occurred in the basin, and type D occurred predominantly along the course of Sinking Creek. Curve numbers for each land-use category were individually calculated according to soil-type occurrence.

Field experience gained during the course of the study indicated that vegetative cover and antecedent soil-moisture content are critical to both volume and rapidity of runoff in the Garretts Spring Basin. Antecedent moisture condition 11 represents "average moisture content," and antecedent moisture condition III represents "nearly saturated soil." Condition III frequently occurred during the winter months when there was little evaporation or plant uptake. The SCS runoff curve numbers were calculated for both soil-moisture conditions. The weighted mean for the southeastern branch for condition 11 was 70 and for condition III was 85, under current land use. Frozen ground will produce even higher curve numbers and greater runoff.

The HEC-1 computer model was first run using basin areas and SCS curve numbers determined by the Corps and the initial estimate of swallow-hole capacity. The second run used the new swallow-hole rating curve, new runoff curve numbers (moisture condition 11), and the reduced basin area to reflect ground-water tracing results. The third, and all subsequent runs, used the new data and moisture condition Ill. For the fourth run the land use data were modified to reflect future suburban development of 20 percent of the southeastern branch. Current suburban development is 2.3 percent. Residential development of other size lots was not considered. The fifth model run was for a totally forested watershed.

The results for the current land-use model revealed the importance of antecedent soil moisture. A 12-hour/100-year-frequency storm of 5.3 inches (13.5 cm) will produce a stage elevation at Tashamingo of 920.5 feet (280.57 m) under antecedent soil-moisture condition II, while the same storm will result in a stage elevation of 923.0 feet (281.33 m) under antecedent soil-moisture condition Ill. This assumes little or no evaporation or transpiration. A more intense storm of shorter duration but greater frequency will also flood the basin. The total accumulated precipitation for the 1989 storm from February 13-16 was 8.4 inches (21.3 cm) at Keene and 7.1 inches (18.0 cm) at Bluegrass Field. The rain on February 13, 0.64 inch (1.6 cm), was sufficient to saturate the soil in the prevailing conditions of near freezing temperatures and absence of transpiration. For the 1989 storm, using the Keene total, the model calculated a stage at Tashamingo of 924.1 feet (281.67 m) for condition II and 927.2 feet (282.18 meters) for condition Ill. For comparison, the maximum stage actually reached at Tashamingo in 1989 was 928.3 feet (282.95 m); the elevation of Cherrywood Lane is 925 feet (281.94 m). Increasing development in the basin to 20 percent with 1-acre (0.4 ha) lots resulted in an increase in stage to 927.4 feet (282.67 m), 0.2 foot (0.06 m) higher than with current land use, which would cover Cherrywood Lane at the causeway with 2.4 feet of water. Treating the basin as virgin forest resulted in a stage of 925.8 feet (282.18 m) at Tashamingo, 1.4 feet lower than current land use, which would still block Cherrywood Lane with nearly a foot of water.

Miscellaneous Findings

Three Jessamine County residents who had lived in the Sinking Creek area for many years were interviewed concerning the history of flooding in the area. The late Mr. Howard Owens, former owner of Owens Karst Window, recounted repeated floodings since his childhood in the early 1900's. He recalled his father deliberately waiting for floods to help him "raft big logs out of the sinkhole." Another resident remembered 1989 being the third time Delaneys Ferry Road was blocked since the 1940's. He recalled having to haul feed to cattle stranded by one flood. The third resident recalled Delaneys Ferry Road being blocked four times since 1957. He noted that he used to hunt for duck along flooded Sinking Creek. All three people interviewed had been in continuous residence in the area since at least 1957. The Lexington and Nicholasville newspapers from 1930 through 1989 were checked for stories on floods, but other than the 1989 flood no mention of Sinking Creek was found.

A common cause of sinkhole flooding is the obstruction of an outlet by natural or man-made debris. Only occasional small pieces of trash and limited quantities of natural debris have been seen in swallow holes in the Garretts Spring Basin. The natural debris consists of wood and leaves that either float during a flood or rot, break up, and are carded through the conduit (Figs. 13-14). Although there is a trash dump in Owens Karst Window, the trash has not moved into the swallow hole area where water pressure would hold it in place. The trash is generally above flood level and is on the spring side of the karst window. During floods numerous small springs discharge along the slope below the base of the trash pile and at its base, indicating that flow is not affected (Fig. 15). If the sediment load in a sinking stream is excessive it can accumulate on wood and leaves and temporarily block a swallow hole. Likely sources of high sediment runoff are tilled fields and construction sites. Water samples have not been collected for suspended sediment, but the sediment mantle left by the 1989 flood in Owens Karst Window and Chenault Karst Window was very thin (less than 0.05 in. or 1 mm). The changes observed in stream channels since 1989 suggest a loss of sediment from channels and swallow hole areas. Because the swallow holes are free of trash and generally clear of natural debris, the flooding is unlikely to be related to limited capacity at the swallow hole.

The only significant, enterable cave known in the Garretts Spring Basin is Dry Ridge Cave. The cave has been partially mapped by the Blue Grass Grotto of the National Speleological Society (O'Dell and O'Dell, 1992). Dye traces have shown that the cave is draining an isolated sub-basin of the northwestern branch. The surveyed length of the cave is 274 feet (83.5 m). Typical passage dimensions are 2 to 6 feet wide and 9 to 12 feet high (1 to 2 m wide, and 3 to 4 m high). A small pit or shaft cave is also known in the vicinity of Chenault Karst Window and a small cave receiving drainage from a sinkhole on Dry Ridge Pike. Neither has been mapped.

HYDROGEOLOGY AND PALEOHYDROLOGY

Although Thrailkill and others (1982) found that argillaceous units are not important inhibitors of ground water in the Inner Blue Grass, field observations indicate that the Brannon Member and Macedonia Bed are locally aquitards within the Garretts Spring Basin. The Brannon crops out near the crest of ridges. Ground water perched on the top of the Brannon emerges at numerous small springs rimming the basin. One outcrop of the Macedonia Bed is known in the stream bed of Chenault Karst Window. Water from Chenault Spring flows on the Macedonia to within a hundred meters (few hundred feet) of the Chenault Karst Window swallow holes. The projected outcrop of the Macedonia at Garretts Spring is just above the elevation of the spring, suggesting headward erosion of the Macedonia toward Chenault Karst Window. Owens Karst Window is less than 10 feet (3 m) below the elevation of the stilling well. Jointing and unmapped faulting play a major role in conduit location and orientation in the Inner Blue Grass (Thrailkill and others, 1983) and probably in the basin.

Garretts Spring has an annual median discharge of 6.5 cfs (0.18 cms) (Felton, personal communication, 1992). The maximum discharge measured to date is 58.6 cfs (1.66 cms), although discharges exceeding this amount are known to have occurred. The flow from Owens and Chenault Karst Windows joins underground within 1,500 feet (457 m) of the resurgence at the spring.

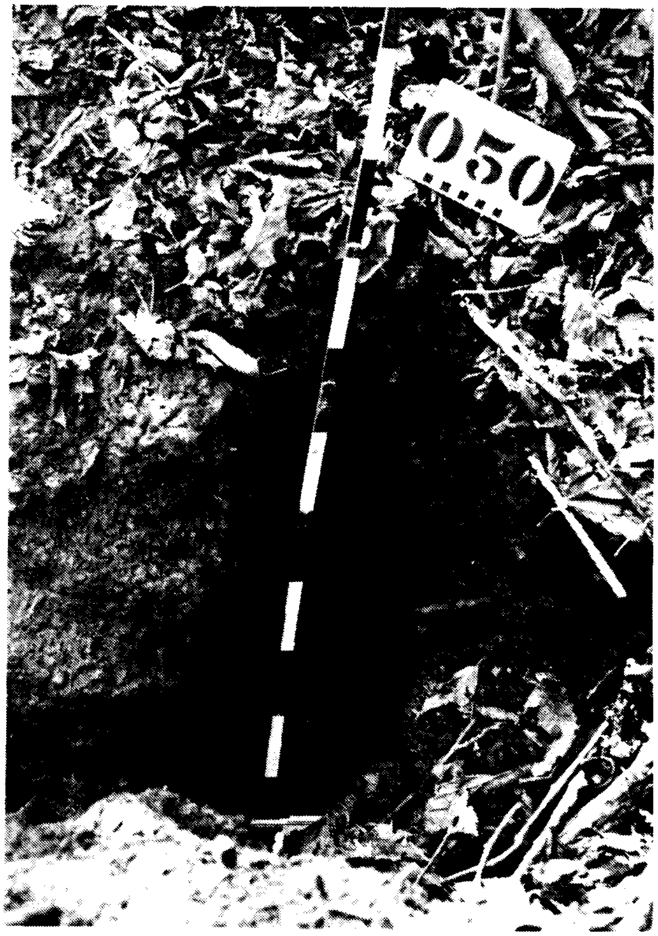


Figure 13. The largest swallow-hole opening at the footwall of Sinking Creek Karst Valley, August 1991. This intake is submerged except during drought. Hundreds of other openings in the footwall area receive flow only during high stage. Scale graduations are 10 centimeters.

Figure 14. The largest swallow-hole opening in Owens Karst Window, November 1989. Note the absence of trash in the swallow hole. The folding ruler is extended to 1 meter.

The recession limb of discharge hydrographs for Garretts Spring is stepped (Felton, personal communication, 1992).

Floods in Chenault Karst Window recede more quickly than in Owens Karst Window or Sinking Creek because of the smaller size of the northwestern branch of the basin, and the relatively more efficient flow from Chenault Karst Window to Garretts Spring. Discharge from the Chenault Karst Window spring flows in a well defined channel with minor tributaries along its course. As the flow approaches the swallow-hole end of the karst window the channel bifurcates into a distributary system feeding over 17 swallow holes. No relationship has been observed between stage in Chenault Karst Window and the rate of discharge from Owens Karst Window.

Ground-water tracing shows that flows from the three principal swallow holes in Sinking Creek are tributaries to a single conduit, which branches into a distributary system as it approaches Owens Karst Window. Nominally, three springs are active in Owens Karst Window but a fourth is active during high flow. The middle spring is lowest in elevation and the southern spring is 1.7 feet (0.5 m) higher. The two northern springs flow into a single channel and their discharge is treated as one spring. The lower northern spring is 5.9 feet (1.8 m) higher than the middle spring and the higher northern spring is 14.2 feet (4.3 m) higher. Both the middle and southern springs remain active during low flow, the middle spring persisting the longest. During extreme low flow all four springs stop flowing. However, a small karst-window-like opening near the middle spring is always flowing, indicating that ground-water flow occurs below the floor of the karst window. Further flow continues in Sinking Creek even when the Owens Karst Window springs are not flowing. Several additional openings, from 1 to 10 feet (0.3 to 3 m) above the main springs, discharge during high flow. The northern springs have significant impact on stage changes in Owens Karst Window (Fig. 16). When flow begins or ends at the northern spring, its discharge, coupled with overland and quick-return ground-water flow in the Owens Karst Window catchment, rapidly floods Owens Karst Window. During extreme high flow, hundreds of small openings discharge into Owens Karst Window.

Figure 15. Minor springs discharging from slope downhill of trash dump in Owens Karst Window after the December 1990 storm. Numerous small springs develop along the entire eastern slope of the karst window during high-flow events; all the springs are below the elevation of the dump. The main swallow hole and springs in the karst window are free of trash.

Sinking Creek Karst Valley differs in geomorphology and hydrology from an open-upstream polje only in size (White, 1988), although the structural controls associated with poljes are absent. Downstream reaches of the valley are characterized by steep, cliff-forming valley walls with local reliefs of 50 feet (15 m). Flooding of the valley occurs frequently in winter and early spring, and persists for days, sometimes weeks. Springs rim the valley just above the grade of Sinking Creek. The swallow-hole zone at the footwall of Sinking Creek Karst Valley receives flow via a distributary system that has three branches. Each branch feeds a cluster of macro-swallow-hole openings, many of which only accept flow during high stage. Throughout the footwall area are hundreds of swallow-hole openings, varying in size from 1 inch (2.5 cm) to 16 inches (40 cm) in diameter.

The parallel between the Tashamingo and Owens Karst Window hydrographs reveals the close match of outflow from Sinking Creek and outflow from Owens Karst Window. Soon after the Tashamingo hydrograph begins to rise, flooding at the swallow holes reaches sufficient depth to activate the northern springs in Owens Karst Window. Once Owens Karst Window is flooded, its outflow no longer increases rapidly with stage because inflow into the downstream conduit is controlled by the pressure limb of the hydrograph. Inflow from Sinking Creek is then slowed by the hydrostatic pressure in flooded Owens Karst Window. The hydrographs remain parallel, with inflow into Owens Karst Window nearly matching out flow, until Sinking Creek Karst Valley empties. The sudden stoppage of flow from the northern spring then allows Owens Karst Window to empty rapidly.

A potentially important factor in flooding at Tashamingo is the possible contribution of flow from the pirated eastern tip of the southeastern sub-basin. During extreme events flow may be diverted below ground, and perhaps on the surface, to the west. Unfortunately, an opportunity to trace or even observe the area during a major flood has not occurred since its potential significance was recognized.

Spangler (personal communication, 1989) speculated that a wide valley that extends from the vicinity of Tashamingo Subdivision north to Shannon Run (a tributary of South Elkhorn Creek) may be an abandoned channel of a surface-flowing Sinking Creek. The piracy of Sinking Creek, if it occurred, would have happened after the initial development of the swallow holes at the footwall of present-day Sinking Creek Karst Valley. It is possible that the conduits from the swallow holes to Garretts Spring may have had insufficient geologic time to adjust to the higher inflows from the geologically sudden increase in catchment area.

CONCLUSIONS

The discharge rate from Sinking Creek is controlled by the stage in Owens Karst Window. The discharge from Owens Karst Window is controlled by the hydraulic parameters of the conduit system to Garretts Spring. The conduit is not blocked by any man-made debris, but discharge is limited by the conduit diameter, gradient, length, and roughness. This conclusion is supported by the absence of trash in the swallow holes, the large measured discharges and flow velocities, and cross sectional areas of the conduits as determined by ground-water dye traces. The intake capacity for the Sinking Creek swallow holes at the moment flooding begins is 25.4 cfs (0.72 cms). The maximum capacity is approximately 47.3 cfs (1.34 cms); unfortunately, inflows into Sinking Creek Karst Valley can exceed hundreds of cubic feet per second (tens of cubic meters per second). Hydrologic modeling of the basin suggests that antecedent moisture conditions are critical to the potential flooding from a given storm. A 12-hour/100-year-frequency storm will flood the basin nearly to the elevation of Cherrywood Lane if it occurs when soil moisture is high and there is little loss to evaporation or transpiration. Modeling also suggests that the February 1989 storm would have flooded the valley to the elevation of Cherrywood Lane even if there was no development in the basin; but further development will cause a limited increase in depth of flooding.

Figure 16. Outflow from the upper northern spring at Owens Karst Window following the December 1990 storm. Flow from this spring begins when the stage at Sinking Creek reaches a critical level and controls flood stage in Owens Karst Window.

POTENTIAL SOLUTIONS

It is not the intent of this report to recommend a specific solution to the flooding at Tashamingo Subdivision, but rather to outline some options available to planners. There may be other solutions not mentioned here.

The intuitively obvious course of action is to enlarge the Sinking Creek swallow holes. However, this research shows that efforts to improve the intake capacity of the swallow holes by excavation at Sinking Creek, if successful, will only increase the stage at Owens Karst Window, which will then negate the increased flow from Sinking Creek. If the swallow holes at Owens Karst Window are also cleaned, only a small increase in capacity would be gained because of the hydraulic limitations of the conduit to Garretts Spring. The conduit would have to be enlarged and smoothed from Owens Karst Window to Garretts Spring, a distance of 3,800 feet (1, 158 m) to the west, to improve its discharge capacity.

Although there is no evidence the Sinking Creek swallow holes are blocked at this time, they could become blocked in the future. This would be a likely consequence if trash was dumped into the creek upstream of the swallow holes, or if the sediment load of Sinking Creek were to increase. Regulations to control sediment runoff from construction sites should be considered, as well as continued efforts by conservation agencies to control soil loss from farming. Furthermore, dumping of any kind into the headwaters of Sinking Creek should be prohibited. Structures to prevent flood debris and sediment from blocking swallow hole openings have been used in Europe to reduce peak flood stage in karst valleys. Although the construction of these structures would not substantially improve the outflow capacity of the swallow holes, they could prevent a further reduction in capacity.

Pumping after flooding begins, while technically feasible, would require that very high-capacity pumps be available year round on 24 hours notice. The six pumps available to the Kentucky Disaster and Emergency Services (DES) in February 1989 had a combined capacity of 9,400 gallons per minute (gpm) or 21 cfs (0.6 cms) (Patrick C. Conley, DES, personal communication, March 13,1989). At that pumping rate, in addition to the natural discharge, it would have taken about 9 days to lower the water to the level of Cherrywood Lane. By allowing the water to drain naturally, Cherrywood Lane was open to traffic 14 days after it was blocked. Siphoning water from the basin, while not requiring constant pumping, would be much slower per pipe, and would require the construction of staging ponds for each 25 feet (7.6 m) of lift (typical maximum practical suction lift). At least one pump would be needed for priming the pipes.

To create a new, gravity-flow outlet for Sinking Creek, deep excavations would be needed. The shortest route for a diversion ditch is to the head of Clear Creek, 2,200 feet (670 m) southwest. A cut with a maximum depth of 70 feet (22 m) would be required. An alternative route, north to the head of Shannons Run, would have a maximum depth of 20 feet (6.3 m), but would be over 5,000 feet (1,524 m) long. Furthermore, water users downstream of Sinking Creek would have their supply substantially reduced.

The HEC 1 modeling clearly shows that a significant increase in suburban development in the basin will have an adverse, but relatively small, impact on flood depth in the Sinking Creek Karst Valley. Retention basins can be required in new developments to contain increased runoff, and lengthen the runoff travel time. Sinking Creek Karst Valley is itself acting as a storm-water retention basin, and has a long storage time compared to a normal valley. Therefore, retention basins in the headwaters should be designed for a worst-case scenario and will have to retain their storage for several days.

Land-use management could be used to mitigate the impact of future floods. Many communities use flood-prone land for recreation areas. The U.S. Army Corps of Engineers has prepared a study (1990) that legally defines a 100-year flood plain for the basin. The area within the flood plain could be designated unsuitable for further development and the flood-prone property could be gradually acquired by local government. The natural beauty of Sinking Creek, with proper management, would make it a very scenic recreation area.

ACKNOWLEDGMENTS

The successful conclusion of this research would not have been possible without the cooperation of many individuals and organizations. The help and cooperation of Woodford and Jessamine County property owners is sincerely appreciated, as is the help of County Judge Executives Sherman Dean and Neil Cassidy and employees of Jessamine County. Mr. Lawrence Spangler shared results of ground-water traces he conducted during 1986 and 1987. The U.S. Army Corps of Engineers, represented by Mr. George Herbig, graciously provided surveying resources for accurate elevations of the water-level recorders, and valuable data files for the hydrologic modeling. Dr. Dan Carey of the Kentucky Geological Survey modified the HEC-1 data files, and executed the hydrologic program. Without his help the process would have taken much longer. Special thanks is due Dr. Gary Felton, of the University of Kentucky College of Agriculture, who generously shared data from the flume installation at Garretts Spring, provided additional help with the surveying, and determined land use in the basin. Finally, we thank the staff of the Kentucky Geological Survey, who helped with equipment installation and field work; reviewed, edited, and drafted this report; and worked in the field for long hours in sometimes dangerous, and frequently miserable, conditions to gather the data essential to this study.

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APPENDIX A:
Discharge Measurements in the Garretts Spring Drainage Basin

The gaging sites are presented in order from upstream locations downstream to Garretts Spring in the eastern sub–basin, then upstream in the western sub–basin. Time of day is Eastern Standard.

MEASUREMENTS AT CHAMPIONS GOLF COURSE

Green Springhouse Spring, at Delaneys Ferry Road

Datum elevation not surveyed; topographic elevation 925 ft.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jan/20/1990	12:30 Hours	Rising	1.07 ft.	6.33 cfs
Jan/30/1990	10:00 Hours	Falling	1.02 ft.	2.47 cfs
Feb/06/1990	09:45 Hours	Falling	0.80 ft.	0.85 cfs
Mar/06/1990	09:30 Hours	Falling	0.56 ft.	0.04 cfs
Jun/15/1990	10:45 Hours	Falling	0.50 ft.	0.08 cfs
Dec/19/1990	16:00 Hours	Falling	1.43 ft.	2.41 cfs
Jan/08/1991	15:45 Hours	Falling	1.40 ft.	2.65 cfs
Jan/16/1991	13:00 Hours	Falling	0.84 ft.	0.54 cfs

Spillway from Champions Lake

Datum elevation not surveyed; topographic elevation 940 ft.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jan/20/1990	11:45 Hours	Rising	1.10 ft.	6.41 cfs
Jan/30/1990	09:30 Hours	Falling	1.08 ft.	4.18 cfs
Feb/06/1990	09:14 Hours	Falling	0.51 ft.	0.82 cfs
Mar/06/1990	09:00 Hours	Falling	0.26 ft.	0.63 cfs
Jun/15/1990	10:30 Hours	Falling	0.19 ft.	0.09 cfs
Jul/13/1990	12:00 Hours	Falling	0.05 ft.	0.01 cfs
Dec/19/1990	16:30 Hours	Falling	0.92 ft.	5.84 cfs
Jan/08/1991	16:00 Hours	Falling	0.67 ft.	2.93 cfs
Jan/16/1991	13:15 Hours	Falling	0.43 ft.	0.19 cfs

Spillway from Pond Downstream of Stone Springhouse Spring

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Dec/19/1990	17:30 Hours	Falling	No gage	0.91 cfs
Jan/08/1991	15:15 Hours	Falling	No gage	0.23 cfs
Jan/16/1991	12:45 Hours	Falling	No gage	0.05 cfs

MEASUREMENTS IN SINKING CREEK AT KEENE–SOUTH ELKHORN ROAD

Datum elevation not surveyed; topographic elevation 935 ft.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jun/15/1990	11:15 Hours	Falling	0.52 ft.	1.08 cfs
Jul/13/1990	12:00 Hours	Falling	0.40 ft.	0.39 cfs
Dec/19/1990	17:00 Hours	Falling	1.50 ft.	22.79 cfs
Jan/08/1991	17:15 Hours	Falling	1.00 ft.	13.84 cfs
Jan/16/1991	14:15 Hours	Falling	0.60 ft.	3.14 cfs

MEASUREMENTS IN SINKING CREEK AT DELANEY WOODS DRIVE

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jan/08/1991	10:44 Hours	Falling	No gage	17.53 cfs
Jan/16/1991	13:45 Hours	Falling	No gage	6.76 cfs

MEASUREMENTS AT TASHAMINGO SUBDIVISION GAGING STATION

Datum elevation 931.65 ft. at base of stilling well.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jan/22/1990	13:00 Hours	Falling	1.79 ft.	21.65 cfs
Jan/30/1990	10:45 Hours	Falling	2.04 ft.	32.21 cfs
Feb/06/1990	10:04 Hours	Falling	1.55 ft.	14.84 cfs
Feb/14/1990	14:02 Hours	Falling	1.41 ft.	10.29 cfs
Feb/22/1990	11:00 Hours	Falling	1.28 ft.	7.62 cfs
Mar/06/1990	10:00 Hours	Stable	0.97 ft.	1.89 cfs
Apr/10/1990	11:00 Hours	Stable	0.92 ft.	1.36 cfs
May/01/1990	16:00 Hours	Stable	1.06 ft.	2.96 cfs
May/04/1990	08:30 Hours	Stable	1.25 ft.	8.23 cfs
Jun/03/1990	08:30 Hours	Falling	1.87 ft.	30.10 cfs
Jun/07/1990	10:45 Hours	Stable	1.47 ft.	9.77 cfs
Jun/15/1990	10:45 Hours	Stable	0.98 ft.	2.81 cfs
Jul/13/1990	08:30 Hours	Falling	0.91 ft.	1.51 cfs
Jul/14/1990	08:30 Hours	Falling	1.22 ft.	6.49 cfs
Aug/22/1990	14:00 Hours	Rising	0.94 ft.	1.49 cfs
Aug/29/1990	07:00 Hours	Rising	1.36 ft.	8.03 cfs
Aug/29/1990	07:30 Hours	Rising	1.36 ft.	8.66 cfs
Aug/29/1990	07:45 Hours	Rising	1.38 ft.	8.80 cfs
Aug/29/1990	08:30 Hours	Rising	1.47 ft.	10.60 cfs
Aug/29/1990	09:15 Hours	Rising	1.52 ft.	12.56 cfs
Aug/29/1990	10:00 Hours	Rising	1.71 ft.	13.27 cfs

MEASUREMENTS AT TASHAMINGO SUBDIVISION GAGING STATION (Continued)

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Aug/29/1990	11:15 Hours	Rising	1.73 ft.	18.90 cfs
Aug/29/1990	11:30 Hours	Rising	1.73 ft.	17.72 cfs
Aug/29/1990	13:00 Hours	Rising	1.78 ft.	18.12 cfs
Aug/29/1990	13:45 Hours	Stable	1.78 ft.	18.68 cfs
Nov/06/1990	10:00 Hours	Falling	1.08 ft.	0.88 cfs
Dec/18/1990	10:15 Hours	Rising	4.11 ft.	223.50 cfs
Jan/08/1991	11:15 Hours	Stable	7.93 ft.	46.40 cfs
Jan/10/1991	14:30 Hours	Falling	7.46 ft.	40.30 cfs
Jan/14/1991	16:15 Hours	Falling	5.90 ft.	33.30 cfs
Jan/15/1991	12:45 Hours	Falling	5.34 ft.	29.85 cfs
Jan/16/1991	12:00 Hours	Falling	4.68 ft.	26.60 cfs
Jan/17/1991	14:00 Hours	Falling	3.75 ft.	21.10 cfs
Jan/18/1991	11:15 Hours	Falling	2.87 ft.	19.20 cfs
Feb/06/1991	15:15 Hours	Rising	1.94 ft.	42.53 cfs
Mar/06/1991	13:00 Hours	Stable	1.02 ft.	3.76 cfs
May/09/1991	10:00 Hours	Rising	1.19 ft.	4.33 cfs
Jun/28/1991	10:15 Hours	Falling	0.91 ft.	0.95 cfs
Aug/08/1991	11:30 Hours	Stable	0.51 ft.	0.15 cfs
Oct/09/1991	13:30 Hours	Stable	0.79 ft.	0.17 cfs
Jan/03/1992	11:15 Hours	Falling	2.69 ft.	50.45 cfs

MEASUREMENTS AT MYRA OWENS SPRING

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Jan/08/1991	12:00 Hours	Falling	No gage	0.88 cfs
Jan/16/1991	11:22 Hours	Falling	No gage	0.29 cfs
Feb/06/1991	14:30 Hours	Falling	No gage	0.69 cfs
Mar/06/1991	12:15 Hours	Falling	No gage	0.09 cfs
Aug/08/1991	12:15 Hours	Falling	No gage	0.01 cfs
Jan/01/1992	16:22 Hours	Falling	No gage	1.25 cfs

MEASUREMENTS OF SWALLOW HOLE CAPACITY AT SINKING CREEK GAGING STATION

Outflow Measured at Owens Karst Window

Datum elevation 905.54 ft. at base of staff gage upstream of distributary.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE*
Jan/08/1991	11:15 Hours	Stable	15.10 ft.	36 cfs
Jan/18/1991	11:15 Hours	Falling	10.10 ft.	34.5 cfs
Feb/06/1991	12:30 Hours	Rising	2.40 ft.	30.2 cfs
Jan/03/1992	15:00 Hours	Rising	6.13 ft.	30.1 cfs
Jan/06/1992	13:45 Hours	Falling	8.39 ft.	29.6 cfs
Jan/07/1992	12:00 Hours	Stable	7.48 ft.	29.5 cfs
Jan/08/1992	12:00 Hours	Stable	5.82 ft.	27.2 cfs
Jan/09/1992	10:30 Hours	Rising	1.53 ft.	12.5 cfs
Mar/19/1992	14:30 Hours	Stable	4.58 ft.	28.4 cfs

* Measured discharge multiplied by 1.18 to compensate for estimated underflow.

Inflow Measured Upstream of Swallow–Hole Distributary Divergence

Datum elevation 905.54 ft. at base of staff gage upstream of distributary.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
May/09/1991	10:00 Hours	Falling	1.13 ft.	3.23 cfs
Aug/08/1991	11:45 Hours	Falling	0.55 ft.	0.05 cfs
Oct/09/1991	12:30 Hours	Falling	0.68 ft.	0.18 cfs
Dec/02/1991	15:30 Hours	Rising	1.32 ft.	5.12 cfs
Dec/02/1991	16:30 Hours	Rising	1.44 ft.	7.63 cfs
Mar/18/1992	10:30 Hours	Rising	1.27 ft.	8.14 cfs
Mar/18/1992	13:00 Hours	Rising	1.53 ft.	12.98 cfs
Mar/18/1992	14:45 Hours	Rising	2.23 ft.	21.41 cfs

MEASUREMENTS AT OWENS KARST WINDOW GAGING STATION

Datum elevation 873.82 ft. at base of stilling well.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE*
Jan/22/1990	15:00 Hours	Falling	5.05 ft.	24.98 cfs
Feb/06/1990	13:15 Hours	Falling	3.40 ft.	14.50 cfs
Feb/14/1990	13:00 Hours	Falling	3.03 ft.	8.88 cfs
Feb/22/1990	12:30 Hours	Falling	2.66 ft.	5.33 cfs
Mar/06/1990	12:00 Hours	Falling	0.61 ft.	1.09 cfs
May/04/1990	13:00 Hours	Rising	2.54 ft.	6.50 cfs
Jun/07/1990	12:00 Hours	Stable	3.03 ft.	8.44 cfs
Jun/15/1990	11:45 Hours	Falling	0.65 ft.	2.81 cfs
Jul/13/1990	10:15 Hours	Falling	0.61 ft.	1.09 cfs
Nov/06/1990	14:10 Hours	Falling	0.61 ft.	0.85 cfs
Jan/18/1991	13:30 Hours	Falling	5.67 ft.	29.25 cfs
Feb/06/1991	12:30 Hours	Rising	4.07 ft.	25.66 cfs
Feb/06/1991	17:00 Hours	Stable	4.16 ft.	25.56 cfs
Feb/11/1991	11:45 Hours	Stable	2.95 ft.	10.36 cfs
Feb/11/1991	14:45 Hours	Falling	2.95 ft.	11.32 cfs
Mar/06/1991	10:45 Hours	Stable	0.63 ft.	2.72 cfs
Jun/28/1991	11:15 Hours	Falling	0.27 ft.	0.12 cfs
Jan/03/1992	15:00 Hours	Rising	5.00 ft.	30.16 cfs
Jan/06/1992	13:15 Hours	Stable	4.83 ft.	29.63 cfs
Jan/07/1992	12:30 Hours	Stable	4.42 ft.	25.02 cfs
Jan/08/1992	11:45 Hours	Stable	4.24 ft.	23.06 cfs
Jan/09/1992	10:30 Hours	Rising	2.59 ft.	10.56 cfs
Mar/18/1992	11:30 Hours	Rising	0.94 ft.	5.66 cfs
Mar/18/1992	13:45 Hours	Rising	2.32 ft.	10.15 cfs
Mar/19/1992	14:30 Hours	Stable	4.16 ft.	24.12 cfs

* Sum of sequential measurements at north, middle, and southern springs.

MEASUREMENTS AT GARRETTS SPRING GAGING STATION

DATE	TIME	CONDITIONS	STAGE	DISCHARGES*
Jan/04/1991	16:15 Hours	Falling	No gage	35.8 cfs
Jan/08/1991	12:30 Hours	Falling	No gage	58.6 cfs
Jan/16/1991	09:30 Hours	Falling	No gage	37.8 cfs
Jan/18/1991	15:30 Hours	Falling	No gage	35.7 cfs
Mar/06/1991	09:00 Hours	Falling	No gage	4.7 cfs
May/09/1991	13:00 Hours	Falling	No gage	5.2 cfs
Jun/28/1991	13:45 Hours	Falling	No gage	1.0 cfs
Aug/08/1991	14:45 Hours	Falling	No gage	0.04cfs
Oct/09/1991	11:45 Hours	Falling	No gage	0.1 cfs
Mar/19/1992	15:45 Hours	Rising	No gage	49.4 cfs

*Discharges below 5 cfs were measured with the flume. Discharges greater than 5 cfs were measured by wading with flow meter.

INFLOW MEASUREMENTS AT CHENAULT KARST WINDOW SWALLOW HOLES

Datum elevation 864.83 ft. at base of lowest staff gage.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Aug/24/1989	15:24 Hours	Falling	No gage	0.3 cfs
Jan/22/1990	15:25 Hours	Falling	5.7 ft.	4.04 cfs
Jan/30/1990	13:41 Hours	Falling	5.3 ft.	4.53 cfs
Feb/06/1990	14:06 Hours	Falling	4.4 ft.	0.95 cfs
Feb/14/1990	11:15 Hours	Stable	0.9 ft.	0.49 cfs
Mar/06/1990	13:45 Hours	Falling	0.9 ft.	0.36 cfs
Jun/07/1990	14:14 Hours	Falling	4.6 ft.	1.99 cfs

MEASUREMENTS AT CHENAULT KARST WINDOW GAGING STATION

Datum elevation 873.55 ft. at base of stilling well.

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Nov/14/1989	12:00 Hours	Stable	0.50 ft.	0.77 cfs
Jan/22/1990	16:00 Hours	Stable	0.98 ft.	6.85 cfs
Jan/30/1990	14:30 Hours	Falling	1.26 ft.	10.23 cfs
Feb/06/1990	15:15 Hours	Falling	0.89 ft.	4.74 cfs
Feb/14/1990	12:00 Hours	Stable	0.87 ft.	3.25 cfs
Feb/22/1990	14:00 Hours	Falling	0.73 ft.	2.44 cfs
May/04/1990	15:00 Hours	Falling	0.66 ft.	2.03 cfs
Jun/07/1990	13:30 Hours	Falling	0.88 ft.	5.04 cfs
Jun/15/1990	12:45 Hours	Falling	0.59 ft.	1.08 cfs
Jul/13/1990	09:30 Hours	Falling	0.59 ft.	1.26 cfs
Nov/06/1990	13:00 Hours	Stable	0.52 ft.	0.52 cfs
Jan/04/1991	11:30 Hours	Stable	0.83 ft.	4.37 cfs
Jan/07/1991	16:00 Hours	Stable	3.25 ft.	18.97 cfs
Jan/08/1991	14:00 Hours	Falling	1.22 ft.	11.52 cfs
Jan/16/1991	10:45 Hours	Stable	0.79 ft.	2.69 cfs
Jan/18/1991	16:45 Hours	Falling	0.72 ft.	1.26 cfs
Mar/06/1991	09:45 Hours	Falling	0.56 ft.	0.73 cfs
May/09/1991	11:00 Hours	Stable	0.56 ft.	0.45 cfs
Jun/28/1991	12:15 Hours	Stable	0.52 ft.	0.31 cfs
Aug/08/1991	15:00 Hours	Stable	0.45 ft.	0.10 cfs
Oct/09/1991	11:30 Hours	Stable	0.36 ft.	0.02 cfs
Jan/03/1992	15:45 Hours	Rising	1.92 ft.	16.41 cfs
Mar/19/1992	11:30 Hours	Stable	1.42 ft.	17.25 cfs

MEASUREMENTS IN DRY RIDGE CAVE

DATE	TIME	CONDITIONS	STAGE	DISCHARGE
Aug/24/1989	14:00 Hours	Falling	No gage	0.3 cfs

APPENDIX B:
Summary of Springs in the Vicinity of Garretts Spring Drainage Basin

Keene Quadrangle

Spring ID	*Spring or Resurgence Name*	*Spring Location*			*Formation or Member*	*Positive Dye Traces*
		Latitude North	*Longitude West*	*Elevation (ft.)*		
04143	Champions Green Springhouse	375832.62	843746.83	925.0	Grier	None
04144	Champions Stone Springhouse	375828.17	843811.86	945.0	Grier	None
04140	Mahin Spring	375659.00	843827.00	870.0	Grier	None
04136	Mount Pleasant Spring	375645.00	843748.00	910.0	Grier	5
04139	Garretts Spring	375937.00	843958.00	850.0	Grier	Multiple
04155	Owens Karst Window	375926.69	843912.49	880.0	Grier	Multiple
13771	Hoffmans Spring	375933.00	844002.00	845.0	Grier	2
None	Owens Spring	375908.00	843837.00	910.0	Tanglewood	1
None	Myra Owens Spring	375915.00	843825.00	940.0	Grier	None

Nicholasville Quadrangle

Spring ID	*Spring or Resurgence Name*	*Spring Location*			*Formation or Member*	*Positive Dye Traces*
		Latitude North	*Longitude West*	*Elevation*		
04793	Turner Power Pole Spring	375841.00	843435.00	920.0	Grier	None
04794	Turner Hawks Nest Spring	375844.00	843437.00	915.0	Grier	None
04795	Clemmons West Spring	375916.00	843448.00	900.0	Grier	None
04796	Clemmons Blue Hole	375918.00	843446.00	900.0	Grier	None
04810	Fosters Pond Spring	375839.00	843647.00	940.0	Grier	None
04142	Burriers Spring	375826.20	843639.96	930.0	Grier	None
04798	Fox Spring	375708.00	843639.00	970.0	Grier	None
04791	Berry Patch Spring	375824.00	843424.00	930.0	Grier	None
04790	Drive-In Spring	375859.00	843513.00	930.0	Grier	1
04799	McChesney Spring	375811.00	843626.00	945.0	Grier	1
04804	Keene Karst Window	375702.00	843727.00	950.0	Grier	2
04802	Wilkinson Karst Window	375704.00	843636.00	950.0	Grier	1
04803	Mathews (Jessamine) Spring	375611.00	843550.00	920.0	Grier	2
04808	Brownwood Karst Window	375746.00	843459.00	960.0	Grier	None
04805	Polley Spring	375813.00	843417.00	935.0	Grier	1
04807	Maddox Spring	375815.00	843409.00	935.0	Grier	None
04806	Oakes Spring	375813.00	843416.00	930.0	Grier	1

Versailles Quadrangle						
Spring ID	*Spring or Resurgence Name*	*Spring Location*			*Formation or Member*	*Positive Dye Traces*
		Latitude North	*Longitude West*	*Elevation*		
13042	Hills Lake Spring	380104.00	844138.00	910.0	Tanglewood	1
04785	Versailles (Big) Spring	380308.00	844354.00	855.0	Tanglewood	1
04784	Treatment Plant Spring	380324.00	844430.00	840.0	Grier	2
04153	Chenault Karst Window	380010.87	844003.12	870.0	Grier	Multiple
04154	Weber Farm Spring	380036.58	844207.50	880.0	Grier	1
04786	McConnell Karst Window	370250.00	844307.50	900.0	Tanglewood	None
None	Manley Spring	380013.00	843843.00	870.0	Grier	2
None	Sutherland Spring	380030.00	844209.00	870.0	Grier	2

APPENDIX C:

Summary of Qualitative Ground-Water Dye Traces in the Vicinity of Garretts Spring Karst Drainage Basin

KGS Study

Name of Injection Front	*Injection Point Location*			*Spring ID*	*Spring or Resurgence Name*	*Maximum Travel Time Days*
	Latitude North	*Longitude West*	*Elevation (ft.)*			
Equestrian Woods Swallow Hole	375840.00	843614.00	940.0	04790	Drive-In Spring	6
Stewarts Well	380130.00	844133.00	940.0	13042	Hills Lake Spring	7
Oriskany Swallow Hole	375757.50	843625.00	965.0	04799	McChesney Spring	5
Winning Ways Dry Well	375746.00	843737.00	955.0	04136	Mount Pleasant Spring	7
Moselys Sinkhole	375722.74	843653.68	950.0	04136	Mount Pleasant Spring	5
Moselys Well	375731.14	843727.47	940.0	04136	Mount Pleasant Spring	5
Fox Swallow Hole	375708.00	843640.50	970.0	04804	Keene Karst Window	4
Keene Karst Window	375700.00	843727.47	945.0	04136	Mount Pleasant Spring	5
Sinking Creek Swallow Holes	375926.69	843912.49	880.0	04155	Owens Karst Window	7
Brownwood Swallow Hole	375721.00	843514.00	1,010.0	04802	Wilkinson Karst Window	4
Wilkinson Karst Window	375704.00	843657.00	950.0	04803	Mathews Spring	3
Brownwood Karst Window	375745.00	843459.00	960.0	04806	Oakes Spring	6
Sycamore Cave	380037.07	844044.97	920.0	04153	Chenault Karst Window	3
Dry Ridge Cave	380033.61	844426.86	893.0	04153	Chenault Karst Window	3
Chenault Karst Window	375956.35	844002.50	864.7	04139	Garretts Spring	9
Chenault Karst Window	375956.35	844002.50	864.7	13771	Hoffmans Spring	3

Spangler* Study:

Name of Injection Front	*Injection Point Location*			*Spring ID*	*Spring or Resurgence Name*	*Maximum Travel Time Days*
	Latitude North	*Longitude West*	*Elevation (ft.)*			
Chenault Karst Window	375956.35	844002.50	864.7	04139	Garretts Spring	3
Owens Karst Window	375926.69	843912.49	880.0	04155	Garretts Spring	7
Sinking Creek Swallow Holes	375926.69	843912.49	905.0	04155	Owens Karst Window	7
Owens Swallow Hole	375912.00	843827.00	930.0	None	Owens Spring	3
Sycamore Swallow Hole	380047.00	844017.00	900.0	04153	Chenault Karst Window	3
Flora Swallow Hole	380032.00	844027.00	910.0	04153	Chenault Karst Window	3

* For additional information contact Lawrence E. Spangler, 4959 West Larkin Way, West Valley, UT 84120.

Spangler* Study:

Name of Injection Front	*Injection Point Location*			*Spring ID*	*Spring or Resurgence Name*	*Maximum Travel Time Days*
	Latitude North	*Longitude West*	*Elevation (ft.)*			
Prewitt Swallow Hole	375948.00	843933.00	900.0	04139	Garretts Spring	7
Prewitt Swallow Hole II	375937.00	843924.00	900.0	04139	Garretts Spring	6
Gilvin Swallow Hole	380050.00	844003.00	910.0	04153	Chenault Karst Window	7
Sycamore Cave	380037.07	844044.97	920.0	04153	Chenault Karst Window	5
Kelly Sinkhole	380025.00	844124.00	930.0	None	Sutherland Spring	5
Paint Road Swallow Hole	380014.00	844113.00	920.0	None	Sutherland Spring	7
Manley Swallow Hole	380053.00	843917.00	900.0	None	Manley Spring	6
Dairy Swallow Hole	380030.00	843927.00	920.0	None	Manley Spring	6

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Mission Statement

The Kentucky Geological Survey at the University of Kentucky is a State mandated organization whose mission is the collection, preservation, and dissemination of information about mineral and water resources and the geology of the Commonwealth. KGS has conducted research on the geology and mineral resources of Kentucky for more than 150 years, and has developed extensive public data bases for oil and gas, coal, water, and industrial minerals that are used by thousands of citizens each year. The Survey's efforts have resulted in topographic and geologic map coverage for Kentucky that has not been matched by any other state in the Nation.

One of the major goals of the Kentucky Geological Survey is to make the results of basic and applied research easily accessible to the public. This is accomplished through the publication of both technical and non-technical reports and maps, as well as providing information through open-file reports and public data bases.