1978

Hydrology and Water Quality in the Central Kentucky Karst: Phase II Part A: Preliminary Summary of the Hydrogeology of the Mill Hole Sub-Basin of the Turnhole Spring Groundwater Basin

James F. Quinlan
University of Kentucky

Donald R. Rowe
University of Kentucky

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Quinlan, James F. and Rowe, Donald R., "Hydrology and Water Quality in the Central Kentucky Karst: Phase II Part A: Preliminary Summary of the Hydrogeology of the Mill Hole Sub-Basin of the Turnhole Spring Groundwater Basin" (1978). *KWRRI Research Reports*. 203.
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Research Report No. 109

HYDROLOGY AND WATER QUALITY IN THE CENTRAL KENTUCKY KARST: PHASE II PART A: PRELIMINARY SUMMARY OF THE HYDROGEOLOGY OF THE MILL HOLE SUB-BASIN OF THE TURNHOLE SPRING GROUNDWATER BASIN

James F. Quinlan
Donald R. Rowe

Principal Investigators

Project Number:	A-066-KY (Completion Report)
Agreement Numbers:	14-34-0001-6018 (FY 1976) 14-34-0001-7037 (FY 1976T) 14-34-0001-7038 (FY 1977)
Period of Project:	February 1976 - July 1977

University of Kentucky
Water Resources Research Institute
Lexington, Kentucky

The work on which this report is based was supported in part by funds provided by the Office of Water Research and Technology, United States Department of the Interior, as authorized under the Water Resources Research Act of 1964.

March 1978

ABSTRACT

Water from upland areas flows to small ephemeral and perennial springs that feed sinking streams that are tributary to low-order cave streams. These cave streams, also recharged by diffuse percolation, are part of a dendritic network in which intermediate-order streams join high-order streams that flow to major trunk streams. The trunk in the Mill Hole Sub-basin flows across the bottom of a large karst window, Mill Hole, and joins the trunk of the Patoka Creek Sub-basin. Their combined discharge bifurcates, flows around the collapsed central core of a larger karst window, Cedar Sink, and re-joins to flow as one to Turnhole Spring, along the south bank of Green River. The location of the major trunk streams can be inferred from the position and orientation of well-defined troughs in the piezometric surface. Flow velocities over the same 5-mile distance, erroneously assuming a straight path from Parker Cave to Mill Hole, range from 60 to 1100 ft per hour -- depending upon whether discharge is at flood or base flow conditions. Actual velocity extremes are probably lower and higher.

Ten sinking streams have been traced to a high-order stream, Brown River, within Parker Cave. Flow routes within this cave system are highly variable and determined by changes in flood stage. An understanding of their variability, obtained by cave mapping and leveling, is essential for interpreting how water or pollutants can travel through limestone aquifers in seemingly erratic ways.

More than 200 tracer tests have been run. Fluorescein, Rhodamine WT, and other dyes have been used. Fourteen groundwater basins have been delineated; others are scheduled for study. Some of the traced flowpaths cross and bifurcate. Tracing results are being used for 201 and 208 planning and the preparation of an Environmental Impact Statement for a proposed regional sewage treatment plant for four towns plus Mammoth Cave National Park. The results are also applicable to planning for the protection of water supplies and cave biota.

New, inexpensive, practical techniques for groundwater tracing with optical brightener (fluorescent blue-white dye) and a similar fluorescent yellow dye that also exhausts onto cotton in cold water have been developed and successfully used.

DESCRIPTORS: Water Cycle, Water Quantity Management and Control, Water Quality Management and Protection

IDENTIFIERS: *Karst, *Kentucky, *Caves, *Limestone, *Tracers, *Dyes, Optical Brightener, Springs, Heavy Metals, Water Pollution, *Groundwater

ACKNOWLEDGEMENTS

It is difficult to properly acknowledge our appreciation to the many people whose help and cooperation in diverse ways has been essential to the success of this project. The resources of Western Kentucky University and the assistance of much of its staff, especially Dean L. E. Greely, has been essential for project planning and execution. Laboratory analyses for heavy metals were made by William M. Andrews (Kentucky Division of Water Quality). Data used in this report has been reciprocally shared with the following organizations and individuals: National Park Service at Mammoth Cave (Uplands Field Research Laboratory), U.S. Geological Survey (Louisville), Joseph Saunders, John Branstetter, Jack Hess, and George Deike. The following organizations have also provided financial or other material aid: Barren River Area Development District, International Business Machines Corporation, Western Kentucky University (Faculty Research Grant No. 13-451-101-10), Gannett Fleming Corddry and Carpenter, Inc., Southern Bell Telephone Co. and the following banks which demonstrated that they were interested in helping the people of the area they serve: American National Bank and Trust Company (Smiths Grove), Citizens Bank and Trust Company (Glasgow), Horse Cave State Bank (Horse Cave), and The Peoples Bank (Cave City). Ralph Ewers and the Cumberland Karst Research Laboratory assisted in many ways. Bolt, Beranak, and Newman, Inc. provided computer facilities for survey data reduction and plotting the map of Parker Cave; Will Crowther did this work.

Much of the arduous field work was completed by the following exceedingly capable assistants employed by the project: Tom Ahlers, James Borden, Bill Cobb, Rick Henriksen, Duke Hopper, George Huppert,

Steve Knutson, Phil O'Dell, Dan Quinlan, Joe Ray, John Schwartz, Mark Stock, Bob Taylor, and Gary Tinker. These individuals were the major part of the Western Kentucky University Karst Research Team. Analysis of spring and well waters during the summer of 1976 was done by Theresa Graham. The following Park Service employees did related work and some data was pooled in order to gain an understanding of the study area: John Branstetter, Carol Conroy, Myles Conway, Don Coons, Mark Elliot, Tom Gracanin, Steve Knutson, Mike McCann, Joe Ray, Rick Schwartz, Mark Stock, Bob Taylor, Gary Tinker, Joe Troester, Dave Walker, and George Wood. Perhaps most of all, we are indebted to the numerous hospitable landowners who graciously gave us access to their lands, springs, and caves.

CAUTIONARY NOTE

The springs and caves described herein are on privately-owned land. They should not be visited without the permission of the landowner.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF PLATES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

PROJECT OBJECTIVES

This project had three general objectives:

1. Obtain basic data relevant to an understanding of the hydrology of the Central Kentucky Karst.
2. Identify major present and potential sources of groundwater pollution, their flow paths, rate of movement, and the discharge point to where they go once they enter the ground.
3. Prepare a summary of the hydrology of the area which can be read, understood and used by federal, state, county, and local officials, as well as by professional engineers, geologists, and planners. This Phase II, Part A completion report is not that summary. Such a document will be prepared after a supplementary report is published and will be written in a completely different, non-technical style.

The first two objectives have been achieved; the last will be.

The most important content of this report is summarized in plate 1, and figures 2 and 5, and the interpretations thereof. They should be studied.

STATEMENT OF LIMITATIONS

It should be stressed that this is a summary completion report that is written while work continues under other funding. We are working on several sub-projects in which conclusions made just last week must be modified by new data collected even as this report is being written.

Several maps drafted for this report had to be redrafted. We know that next week's data may either force additional modification or "fill-in" a missing piece of the puzzle. Rather than write a report that will be largely out-of-date by the time it is published, we have elected to write one that describes a study that is largely complete and briefly discusses other work. More will be learned about the Mill Hole Sub-basin but the observations made will modify rather than negate conclusions we have drawn.

A moderate amount of compilation and other drafting remains to be done. We are confident of the reliability of the statements and conclusions of this report but discussion of many others, now considered to be tentative, is deferred until the next. The Phase II, Part B report on this project, a supplement to this final report, will have a different emphasis.

Many of the dye traces on which some conclusions are based were run by National Park Service personnel under the supervison of James F. Quinlan. The results, on open-file at National Park Service headquarters at Mammoth Cave National Park, have been incorporated into this report. All tests contributed to an understanding of the regional hydrology.

BACKGROUND INFORMATION

Numerous references will be made within this report to the Phase I report (Quinlan and Rowe, 1977a).

A description of the study area, a summary of major recognized and potential problems associated with groundwater pollution and aquifer management, and a review of the relevant geologic and hydrologic literature is given in our Phase I report and, more recently, by Quinlan

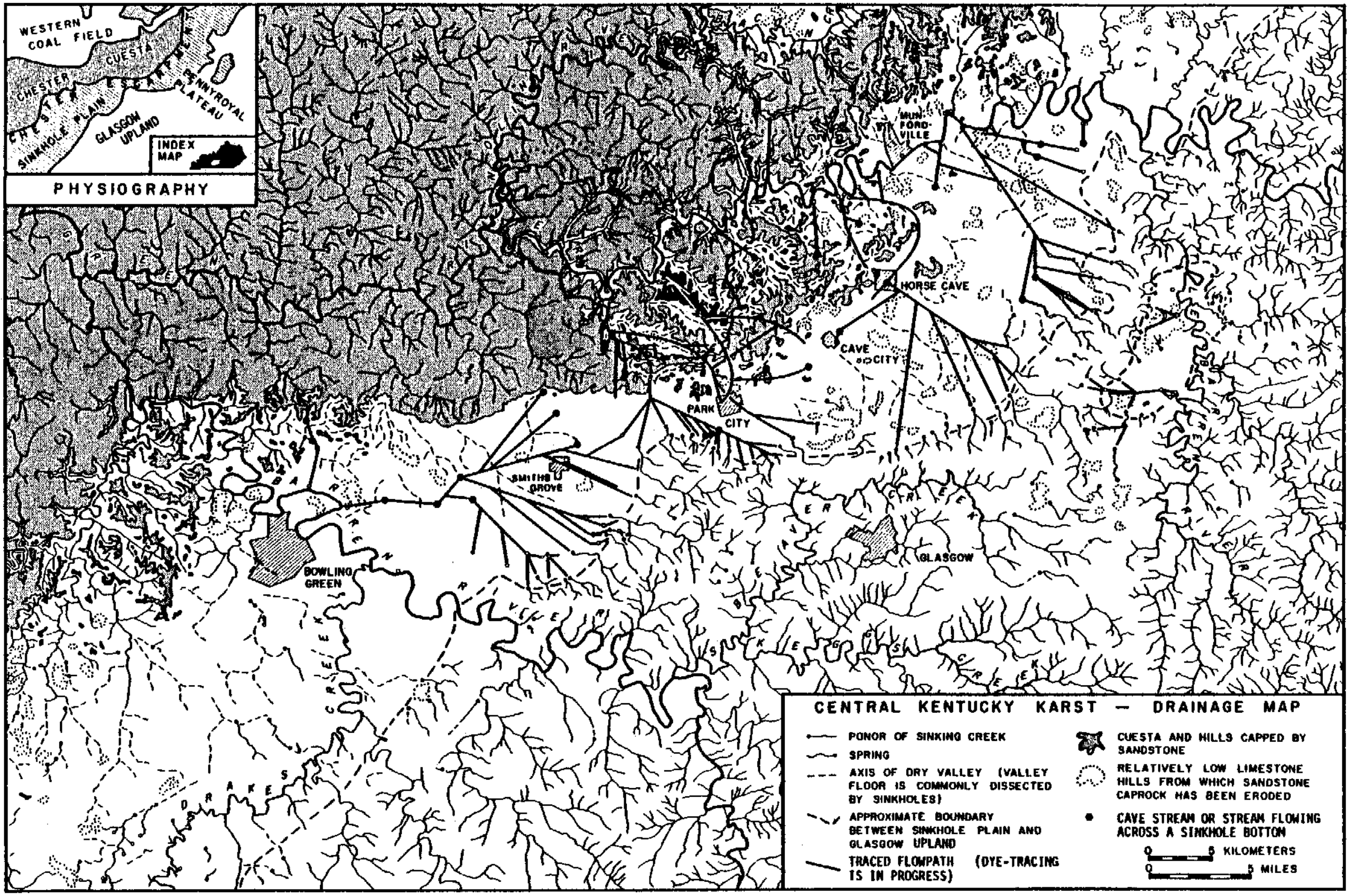
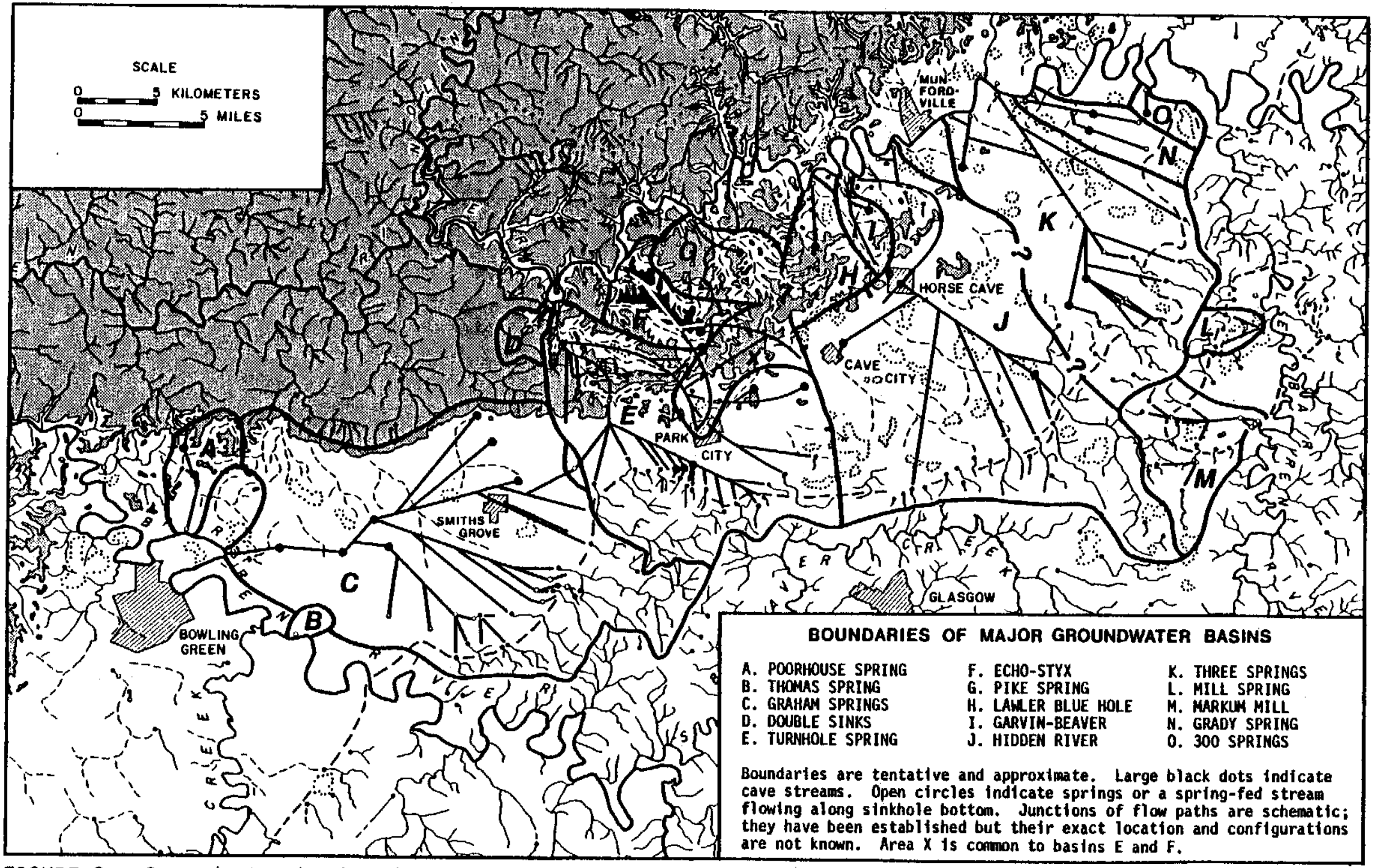


FIGURE 1 - Subsurface drainage as shown by dye traces. Mammoth Cave Ridge is shown in black. The boundaries of Mammoth Cave National Park are shown by long dashed lines.



BOUNDARIES OF MAJOR GROUNDWATER BASINS

A. POORHOUSE SPRING	F. ECHO-STYX	K. THREE SPRINGS
B. THOMAS SPRING	G. PIKE SPRING	L. MILL SPRING
C. GRAHAM SPRINGS	H. LAWLER BLUE HOLE	M. MARKUM MILL
D. DOUBLE SINKS	I. GARVIN-BEAVER	N. GRADY SPRING
E. TURNHOLE SPRING	J. HIDDEN RIVER	O. 300 SPRINGS

Boundaries are tentative and approximate. Large black dots indicate cave streams. Open circles indicate springs or a spring-fed stream flowing along sinkhole bottom. Junctions of flow paths are schematic; they have been established but their exact location and configurations are not known. Area X is common to basins E and F.

FIGURE 2 - Groundwater basins delineated as of February 1978. Traces are shown schematically by heavy lines. Note that area X is common to the Turnhole Spring and Echo-Styx groundwater basins (E and F). Other symbols are explained in the title block and caption for figure 1.

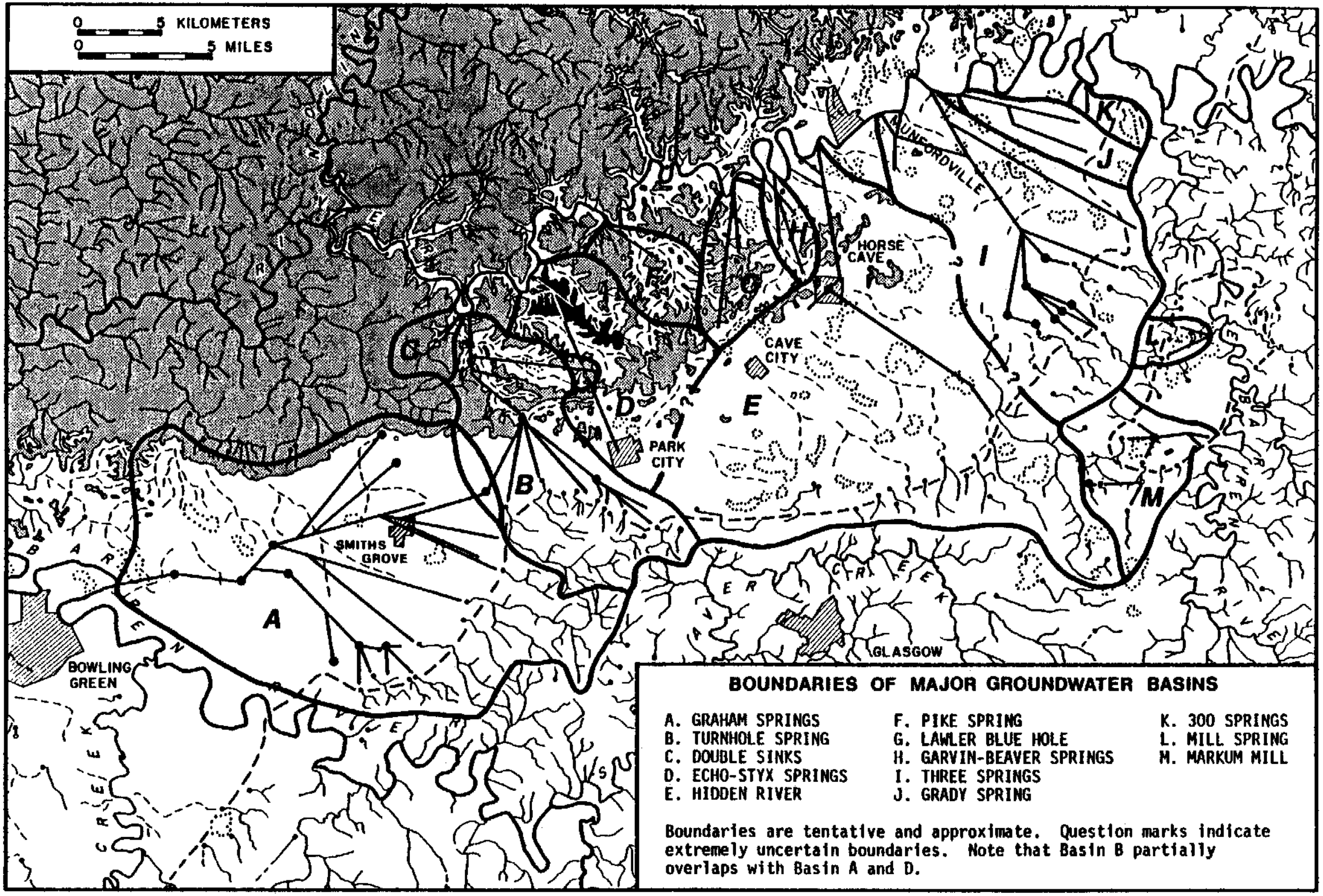
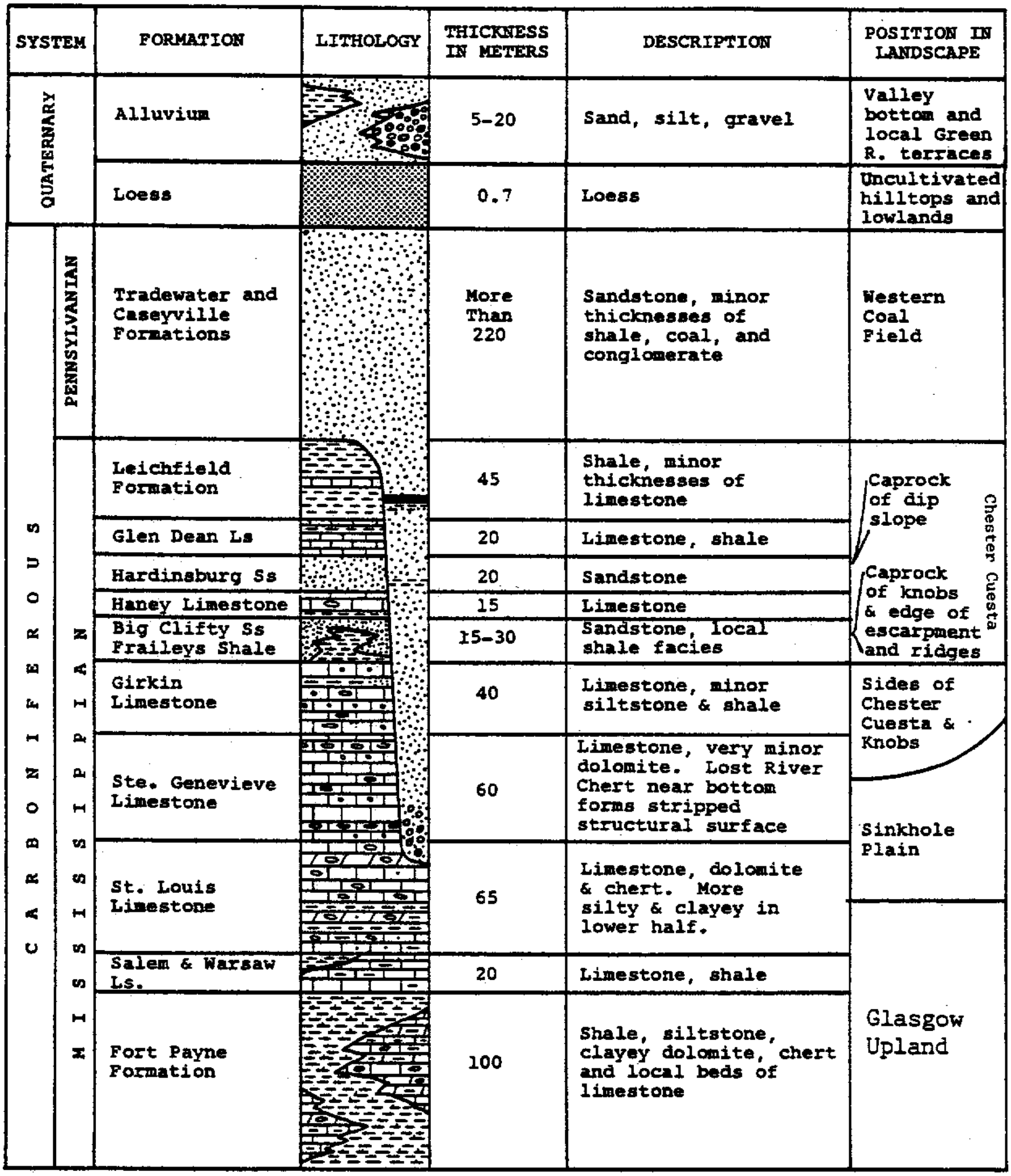


FIGURE 3 - Groundwater basins delineated as of June 1976. Compare with figure 2. (after Quinlan and Rowe 1977a).

(1977a), and Quinlan and Rowe (1977b). These discussions will not be repeated herein but the abstract of the Phase I report is included as Appendix A.

The study area is a 860 square mile (2200 km^2) terrain of nearly flat-lying limestone which is locally capped by sandstone and is bounded chiefly by the Green, Barren, and Little Barren Rivers and by Beaver Creek. It is shown in figures 1, 2, and 3. Figure 1 shows surface and subsurface drainage and the regional and local physiography. Figure 2, an enlargement of part of figure 1, shows the boundaries of major groundwater basins as determined by February 1978. Figure 3 is similar to figure 2 but shows these boundaries as they were interpreted in June 1976. Note the differences between these two maps.

All of the study area is depicted on 7.5-minute topographic and geologic maps published by the U.S. Geological Survey. The regional stratigraphy is shown in figure 4.



SYSTEM		FORMATION	LITHOLOGY	THICKNESS IN METERS	DESCRIPTION	POSITION IN LANDSCAPE
QUATERNARY		Alluvium		5-20	Sand, silt, gravel	Valley bottom and local Green R. terraces
		Loess		0.7	Loess	Uncultivated hilltops and lowlands
CARBONIFEROUS	PENNSYLVANIAN	Tradewater and Caseyville Formations		More Than 220	Sandstone, minor thicknesses of shale, coal, and conglomerate	Western Coal Field
	MISSISSIPPIAN	Leichfield Formation		45	Shale, minor thicknesses of limestone	Caprock of dip slope (Chester Cuesta)
		Glen Dean Ls		20	Limestone, shale	
		Hardinsburg Ss		20	Sandstone	Caprock of knobs & edge of escarpment and ridges (Chester Cuesta)
		Haney Limestone		15	Limestone	
		Big Clifty Ss Fraileys Shale		15-30	Sandstone, local shale facies	
		Girkin Limestone		40	Limestone, minor siltstone & shale	Sides of Chester Cuesta & Knobs
		Ste. Genevieve Limestone		60	Limestone, very minor dolomite. Lost River Chert near bottom forms stripped structural surface	Sinkhole Plain
		St. Louis Limestone		65	Limestone, dolomite & chert. More silty & clayey in lower half.	
		Salem & Warsaw Ls.		20	Limestone, shale	Glasgow Upland
		Fort Payne Formation		100	Shale, siltstone, clayey dolomite, chert and local beds of limestone	

FIGURE 4 - Generalized stratigraphy of the Central Kentucky Karst (after Quinlan, 1970).

CHAPTER II

RESEARCH PROCEDURES

Research procedures for the work summarized herein have been described on pages 9-20 of the Phase I report and by Quinlan (1977b, 1978). Other procedures, used for work to be described in the Phase II, Part B report, will be described in that supplementary report.

CHAPTER III

DATA AND RESULTS

INTRODUCTION

Most of our work has consisted of dye-tracing, cave mapping, piezometric surface measurement, and chemical analysis of waters. More than 200 traces have been made, more than 50 caves have been mapped, more than 3500 land-owners have been interviewed, water levels in more than 1000 wells have been measured, and more than 250 water samples have been analysed. The massive amounts of data acquired are not reproduced herein. The Phase I report was concerned chiefly with interpretation of some of these chemical analyses in the Hidden River Groundwater Basin, with dye-trace results, and with some of the cave mapping. The next report, a supplement to this and the Phase I report, will be concerned with dye-trace results, the function of certain caves in the hydrology of the aquifer, the piezometric surface, structural and stratigraphic controls on groundwater movement, and the interpretation of additional chemical analyses. This final report is a summary of the interpretations of some of the cave mapping and water tracing data in chiefly the Mill Hole Sub-basin of the Turnhole Spring Groundwater Basin; the latter is shown in figure 2 as basin E. There are two major confluent trunk streams in the Turnhole Basin, Mill Hole in the south and west, and Patoka Creek in the east and north. Their confluence, shown in figure 2, is upstream (south) from Cedar Sink, approximately 1 mile south of the Turnhole Spring along Green River, within Mammoth Cave National Park. Part of the Patoka Creek Sub-basin also drains to the Echo-Styx Groundwater Basin, basin F, as discussed subsequently.

Many of the other recent dye-traces shown in figure 2 are in the Hidden River Groundwater Basin, basin J. Most of this report is concerned with these four basins.

Throughout this report reference will be made to the following sites that are located on figure 2 but not specifically identified on it:

1. Parker Cave, the 3 adjacent black circles 1 mile southwest of Park City.
2. Mill Hole, a large karst window (sinkhole with a stream crossing its bottom) 1 mile west-northwest of the upper left corner of the E in Basin E, the Turnhole Spring Basin. It is the open circle (spring) adjacent to a closed circle (ponor) to which water in the southwest part of the basin flows.
3. Cedar Sink, a large karst window 2 miles almost due east of the D in figure 2 but in Basin E. It too is represented by adjacent open and closed circles.
4. Turnhole Spring, a large regional spring on the south bank of Green River, 1.1 miles north of Cedar Sink. It is shown by an open circle.
5. Little Sinking Creek, the long sinking stream at the southwest corner of the Turnhole Spring Basin.
6. Patoka Creek, the long sinking stream at the southeast corner of the Turnhole Spring Basin.

Sites 1 through 5 are identified by name in plate 1 of Quinlan (1977a). Sites 1 through 4 are shown in figure 3 of Quinlan and Rowe (1977a). Part of Site 6 is shown as surface drainage basin no. 14 on plate 1 of this report. Sites 3 and 5 are identified by name on the U.S. Geological Survey 7.5-minute Rhoda and Smiths Grove topographic maps. All can be identified on figure 2 of this report, as described. It will be assumed hereinafter that the reader knows where each of these sites is relative to the other.

TURNHOLE SPRING GROUNDWATER BASIN

Descriptive Hydrology

The purpose of this section is to summarize and update the hydrologic relations discussed in separate publications that are and will be, in part, a result of this project. The Turnhole Spring Groundwater Basin has two main trunk streams, the Mill Hole trunk (drainage through Mill Hole itself) and the Patoka Creek trunk -- both of which converge upstream from Cedar Sink. Boundaries of these sub-basins are known only approximately.

This discussion of the hydrology is predominantly qualitative. It represents what could be called the essential "second stage of knowledge." [The first stage is recognition of the problem.] The third stage of knowledge, a detailed quantitative study of the complex relations between rainfall, response to recharge, aquifer storage, changes in water quality, discharge, and stage, was not funded by this project but it is scheduled. The chemistry of the spring waters has been studied by Hess (1974) and a pioneering hydrographic analysis was published by Hess and White (1974).

Mill Hole Sub-basin

Mill Hole is a large collapse sinkhole, about 200 to 300 ft wide and 150 ft deep that functions as a karst window (Quinlan, 1977a). Eighteen sinking streams, several of which are ephemeral and most of which are spring-fed, contribute to the flow of the perennial stream that crosses the bottom of Mill Hole. Base flow of this stream is estimated to be 5 to 8 cfs. Flood flow is unknown but is several tens of cfs. After heavy rains the sink may flood to a depth of more than 60 ft; recession is rapid but related to the stage of Cedar Sink and Green River. Two major contributors to the discharge at Mill Hole will be briefly described and interpreted: the Parker Cave System and Little Sinking Creek.

PARKER CAVE SYSTEM

Study of the Parker Cave System, shown in plate 1 and figures 5, 6, and 9, has given a unique understanding of how water moves in the upper parts of the principal aquifer that underlies the Sinkhole Plain. The hydrology of this system is summarized after the major caves that comprise it are briefly described. The symbols used on the cave maps are explained in figure 7. The caves are mapped at BCRA (British Cave Research Group) Grade 6D, with backsights, as described in figure 8. All of the cave maps, including plate 1, were plotted and drawn at twice the size they are reproduced at. The relations of the nine caves in the system that are known and mapped are shown in plate 1 and figure 5. A brief description of only the larger of these, Parker, Gray's Water, Pandora's Box, and Deep Sink, is given herein. Passage dimensions and cross sections are accurately shown on the maps.

DESCRIPTION OF CAVES

Parker Cave

Parker Cave, the largest of the nine mapped caves known in the 7.2-mile system, consists of 4.17 miles of stream passage, overflow routes, and dry

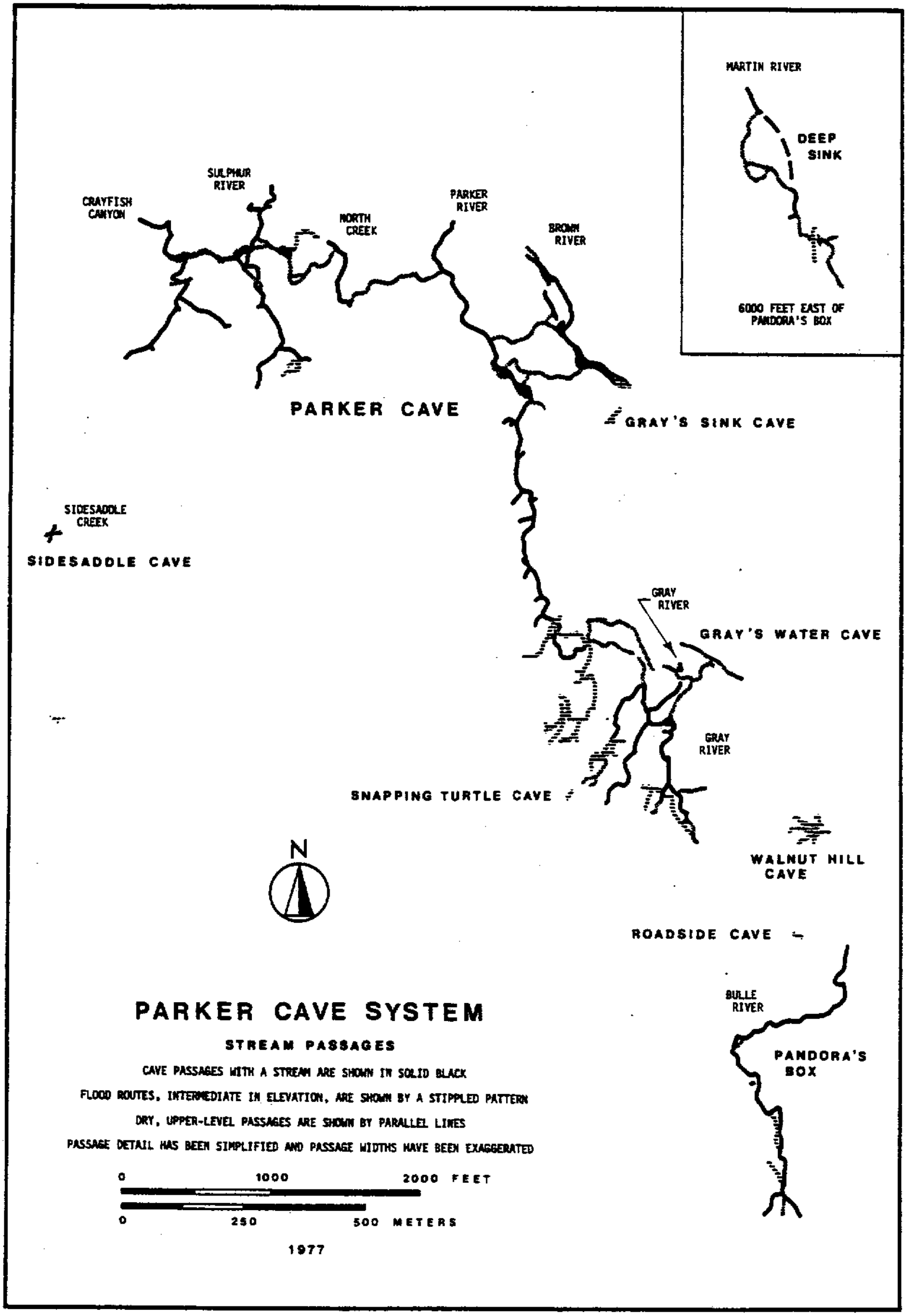
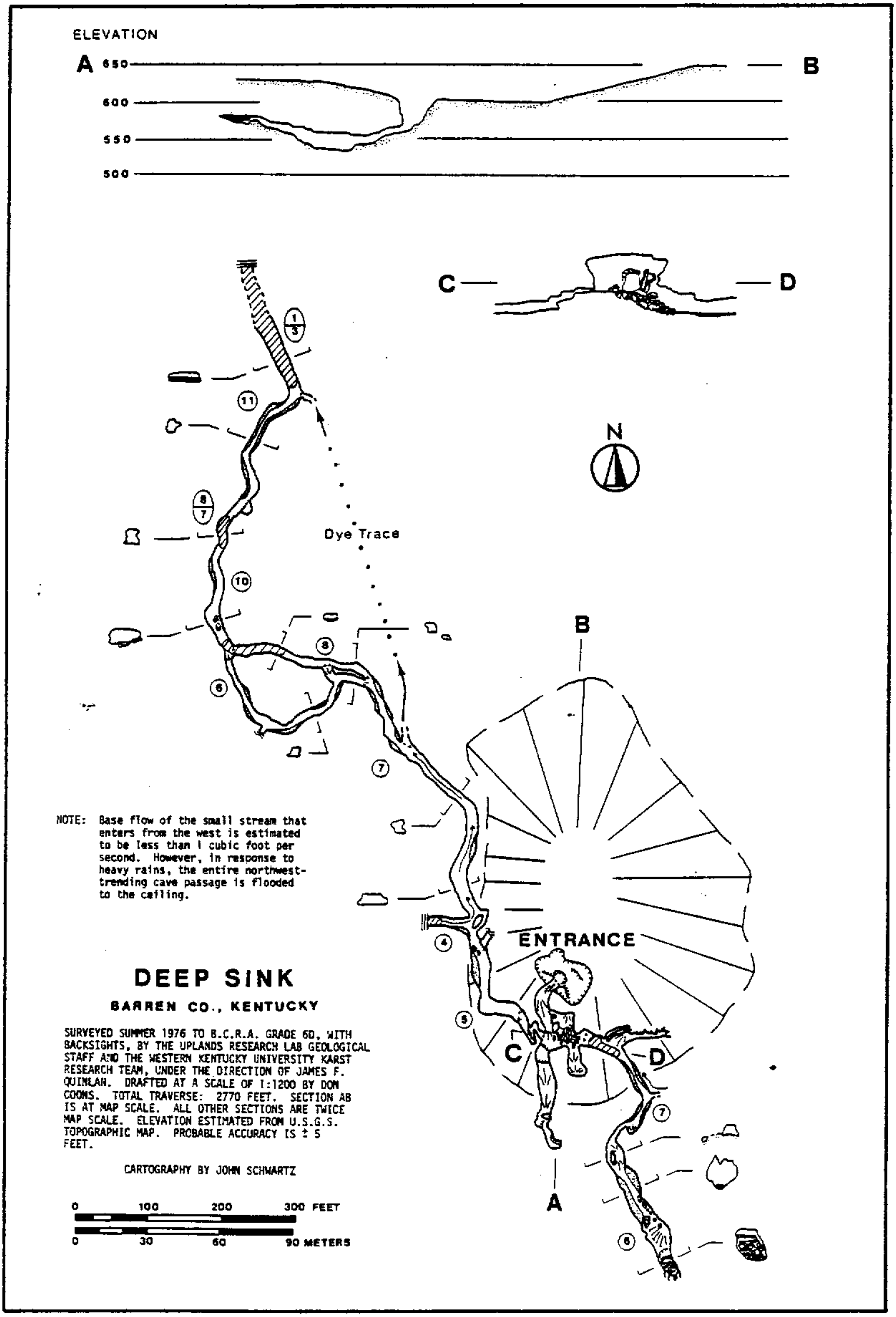


FIGURE 5 - Stream passages in the Parker Cave System.



NOTE: Base flow of the small stream that enters from the west is estimated to be less than 1 cubic foot per second. However, in response to heavy rains, the entire northwest-trending cave passage is flooded to the ceiling.

SURVEYED SUMMER 1976 TO B.C.R.A. GRADE 6D, WITH BACKSIGHTS, BY THE UPLANDS RESEARCH LAB GEOLOGICAL STAFF AND THE WESTERN KENTUCKY UNIVERSITY KARST RESEARCH TEAM, UNDER THE DIRECTION OF JAMES F. QUINLAN. DRAFTED AT A SCALE OF 1:1200 BY DON COONS. TOTAL TRAVERSE: 2770 FEET. SECTION AB IS AT MAP SCALE. ALL OTHER SECTIONS ARE TWICE MAP SCALE. ELEVATION ESTIMATED FROM U.S.G.S. TOPOGRAPHIC MAP. PROBABLE ACCURACY IS ± 5 FEET.

FIGURE 6 - Map of Deep Sink Cave. Symbols are explained on figure 7.

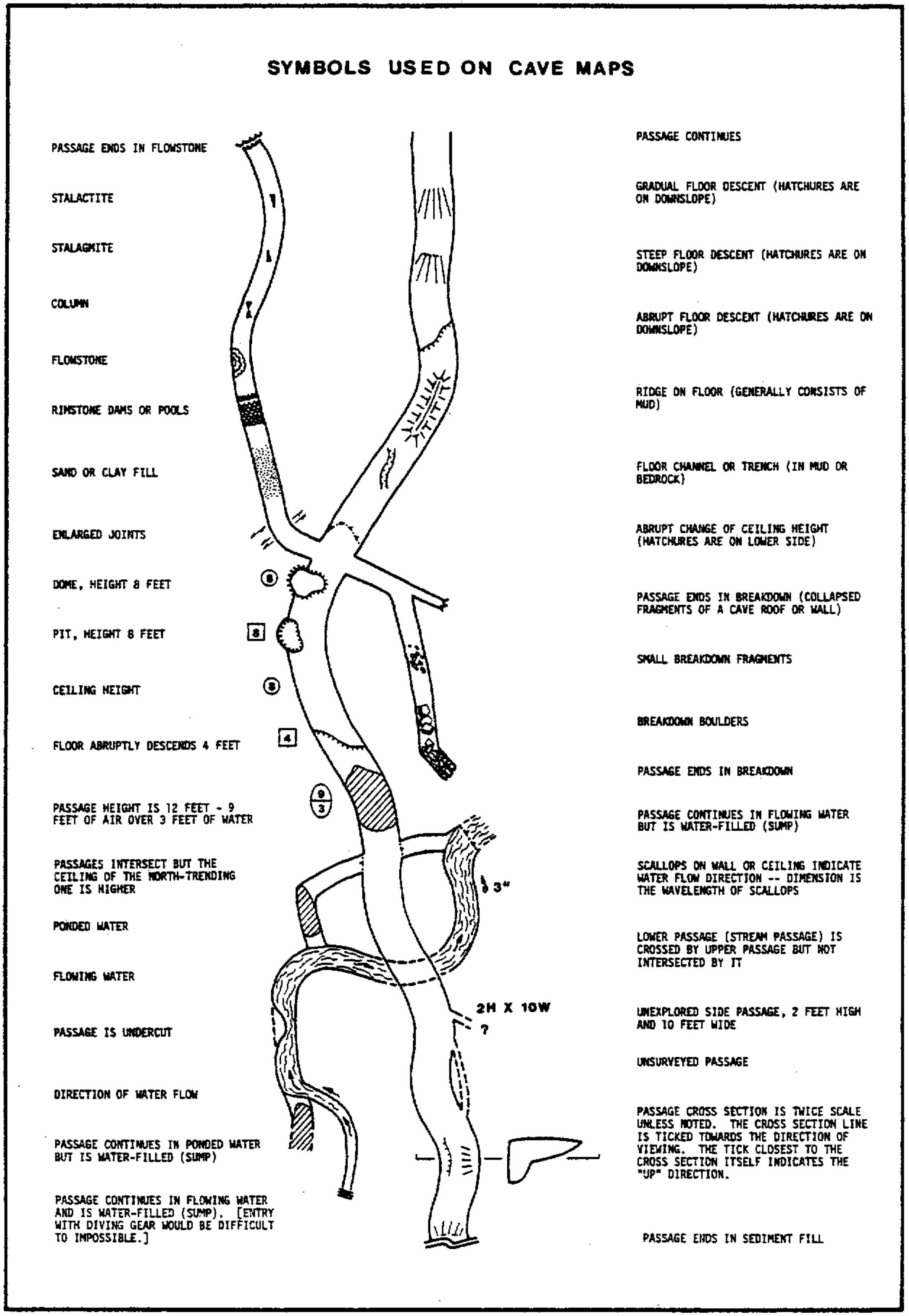
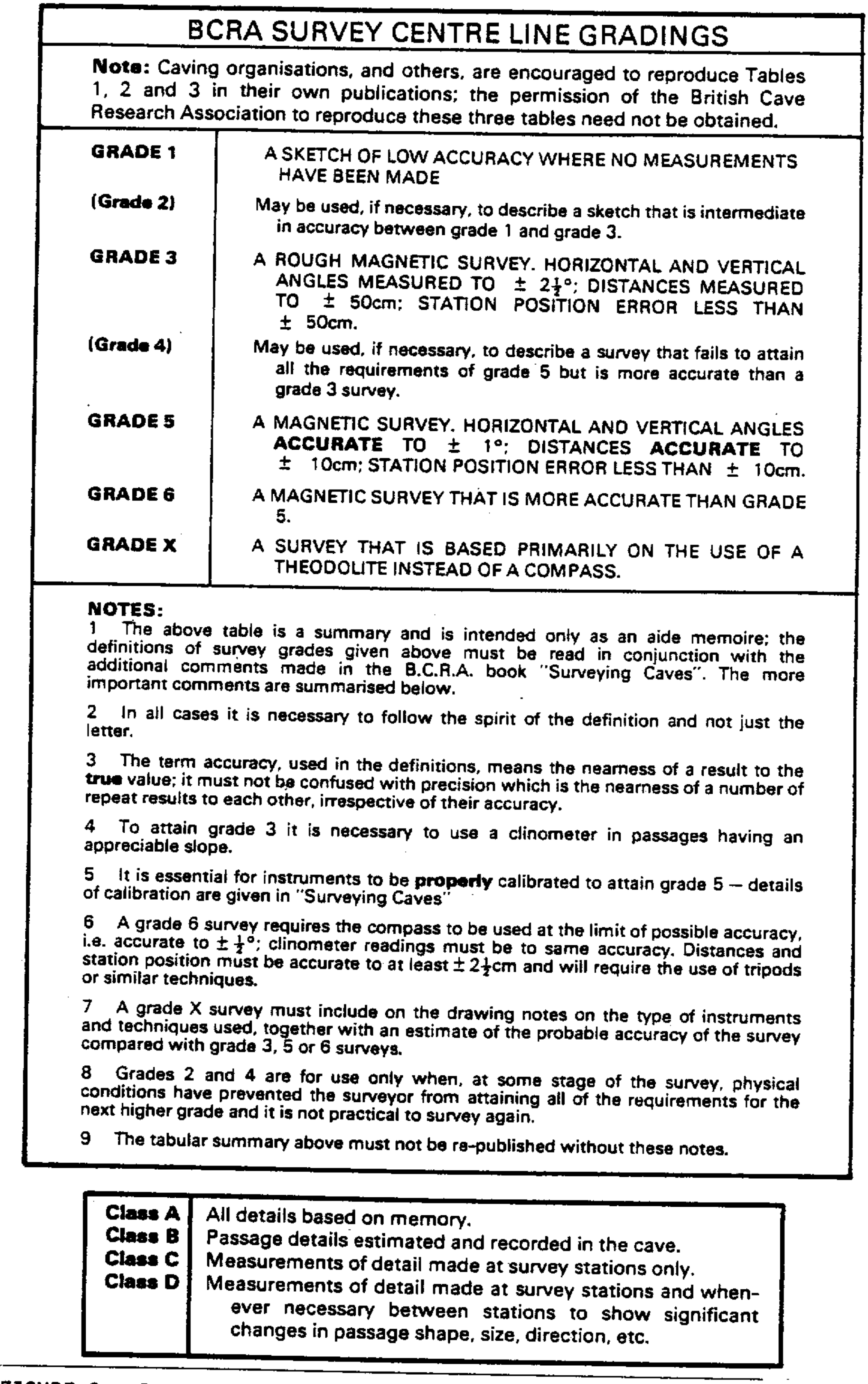


FIGURE 7 - Symbols used on cave maps.



BCRA SURVEY CENTRE LINE GRADINGS

Note: Caving organisations, and others, are encouraged to reproduce Tables 1, 2 and 3 in their own publications; the permission of the British Cave Research Association to reproduce these three tables need not be obtained.

GRADE 1	A SKETCH OF LOW ACCURACY WHERE NO MEASUREMENTS HAVE BEEN MADE
(Grade 2)	May be used, if necessary, to describe a sketch that is intermediate in accuracy between grade 1 and grade 3.
GRADE 3	A ROUGH MAGNETIC SURVEY. HORIZONTAL AND VERTICAL ANGLES MEASURED TO ± 2½°; DISTANCES MEASURED TO ± 50cm; STATION POSITION ERROR LESS THAN ± 50cm.
(Grade 4)	May be used, if necessary, to describe a survey that fails to attain all the requirements of grade 5 but is more accurate than a grade 3 survey.
GRADE 5	A MAGNETIC SURVEY. HORIZONTAL AND VERTICAL ANGLES **ACCURATE** TO ± 1°; DISTANCES **ACCURATE** TO ± 10cm; STATION POSITION ERROR LESS THAN ± 10cm.
GRADE 6	A MAGNETIC SURVEY THAT IS MORE ACCURATE THAN GRADE 5.
GRADE X	A SURVEY THAT IS BASED PRIMARILY ON THE USE OF A THEODOLITE INSTEAD OF A COMPASS.

NOTES:

1 The above table is a summary and is intended only as an aide memoire; the definitions of survey grades given above must be read in conjunction with the additional comments made in the B.C.R.A. book "Surveying Caves". The more important comments are summarised below.

2 In all cases it is necessary to follow the spirit of the definition and not just the letter.

3 The term accuracy, used in the definitions, means the nearness of a result to the **true** value; it must not be confused with precision which is the nearness of a number of repeat results to each other, irrespective of their accuracy.

4 To attain grade 3 it is necessary to use a clinometer in passages having an appreciable slope.

5 It is essential for instruments to be **properly** calibrated to attain grade 5 – details of calibration are given in "Surveying Caves"

6 A grade 6 survey requires the compass to be used at the limit of possible accuracy, i.e. accurate to ± ½°; clinometer readings must be to same accuracy. Distances and station position must be accurate to at least ± 2½cm and will require the use of tripods or similar techniques.

7 A grade X survey must include on the drawing notes on the type of instruments and techniques used, together with an estimate of the probable accuracy of the survey compared with grade 3, 5 or 6 surveys.

8 Grades 2 and 4 are for use only when, at some stage of the survey, physical conditions have prevented the surveyor from attaining all of the requirements for the next higher grade and it is not practical to survey again.

9 The tabular summary above must not be re-published without these notes.

Class A	All details based on memory.
Class B	Passage details estimated and recorded in the cave.
Class C	Measurements of detail made at survey stations only.
Class D	Measurements of detail made at survey stations and whenever necessary between stations to show significant changes in passage shape, size, direction, etc.

FIGURE 8 - Description of BCRA grades identifying the accuracy of cave surveys. All caves were surveyed at BCRA Grade 6D, with backsights (after Ellis, 1976).

upper-level passages, as shown in figure 5 and plate 1. Only one entrance is known. Deike (1967) had mapped it to a terminal breakdown that was traditionally considered to be the end of the cave. During the summer of 1974 Don Coons squeezed 60 ft through this breakdown, shown on plate 1 as Kulesza's Way, and discovered the route to the rest of the cave.

The most actively forming part of Parker Cave consists of 5 sub-parallel stream passages in which flow is down-dip, to the north-northwest. They are linked by flood routes that are sub-parallel to the strike of the beds. These relations are shown more clearly in figures 5 and 9 and their hydrology is discussed in a subsequent section. The largest of these streams, Brown River, is the easternmost stream. It is a fragment of a major trunk stream to which 10 different sinking streams have been traced and it is terminated at both ends by impenetrable breakdown. (See section A-B on plate 1 and the downstream continuation of this passage.) Base flow is estimated to be about 5 cfs.

The other stream passages range from canyons to tubes. The largest of the remaining streams is Parker River. About half of its 1 cfs base flow is from the perennial spring-fed stream in surface basin no. 3; the remainder of its discharge -- and the flow in Sulfur River and Crayfish Canyon is from a series of seeps and trickles from tributaries. The elevations of the various streams relative to one another are shown in figure 9; the hydrologic relations between them are summarized in a subsequent section.

Gray's Water Cave

Gray's Water Cave, a 1.43 mile upstream fragment of Parker Cave, has 4 entrances. The two caves have been surveyed to within about 75 ft of one another in two different areas but breakdown truncates one of the connecting passages and lack of air space over a pool impedes travel in another. Both of these streamless connecting passages function as floodwater routes.

A trickle of water that is a shaft drain in the upper levels of this cave flows to a tank west of the Water Pump Entrance and has been used as a domestic water supply. Only about 1200 feet of passage was known before 1976. This water supply trickle drains to a very tight, arduous canyon passage that had been partially explored in the early days of the project. A dye test subsequently showed that this water went to Brown River. This nasty canyon was, therefore, a potential access to the huge Brown River trunk that had been so elusive. In 1975 a group from McMaster University explored this drain canyon but not far enough. The following year, Don Coons went about 150 ft farther and discovered more than a mile of passage. Determined exploration and mapping of this new section showed that the most actively forming part of the cave consisted of Gray River which is fed by ephemeral surface streams in basins no. 4 and 5 and by diffuse, percolating waters. The flow of Gray River is augmented by the water supply trickle, a seep between them, and a shaft drain southeast of the Easy Way In.

Pandora's Box

This cave consists of eight tenths of a mile of stream-floored canyon that is subject to flooding. No surface streams can be traced to it; recharge is interpreted to be from diffuse percolation.

Deep Sink

This cave, shown in figure 5 and on the topographic map of plate 1, was discovered after a sinkhole collapse created an entrance a few years ago. It consists of a fragment of a high-level streamless passage and a low-level stream conduit with a base flow estimated to be about .2 cfs. After heavy rains the entire lower conduit is flooded.

Other Caves

Five other caves, each consisting of fragments of a once-integrated system, are known: Walnut Hill, Sidesaddle, Gray's Sink, Roadside, and Snapping Turtle. The traces from Walnut Hill and Sidesaddle are shown on plate 1.

HYDROLOGY

The highest recharge area for the Parker Cave system -- and for the Sinkhole Plain in general -- is the topographic divide at its southern flank. Where the beds are nearly flat-lying this divide is characterized by a series of swamps, one of which is shown in basin no. 9, just east of Highway 255. The beds in the map area dip north to north-west. Most of the streams shown are fed by perennial and ephemeral springs. Ten of these sinking streams, in basins 4 through 13, all flow to Brown River. Study of the cave maps implies that most water flow is to the north, sub-parallel to the dip, but evaluation of the dye-traces to Brown River that are shown schematically compels one to infer that most of upstream Brown River is oriented sub-parallel to the strike.

Careful leveling was done to determine the elevation of streams and divides in Parker Cave relative to base flow in Brown River. The

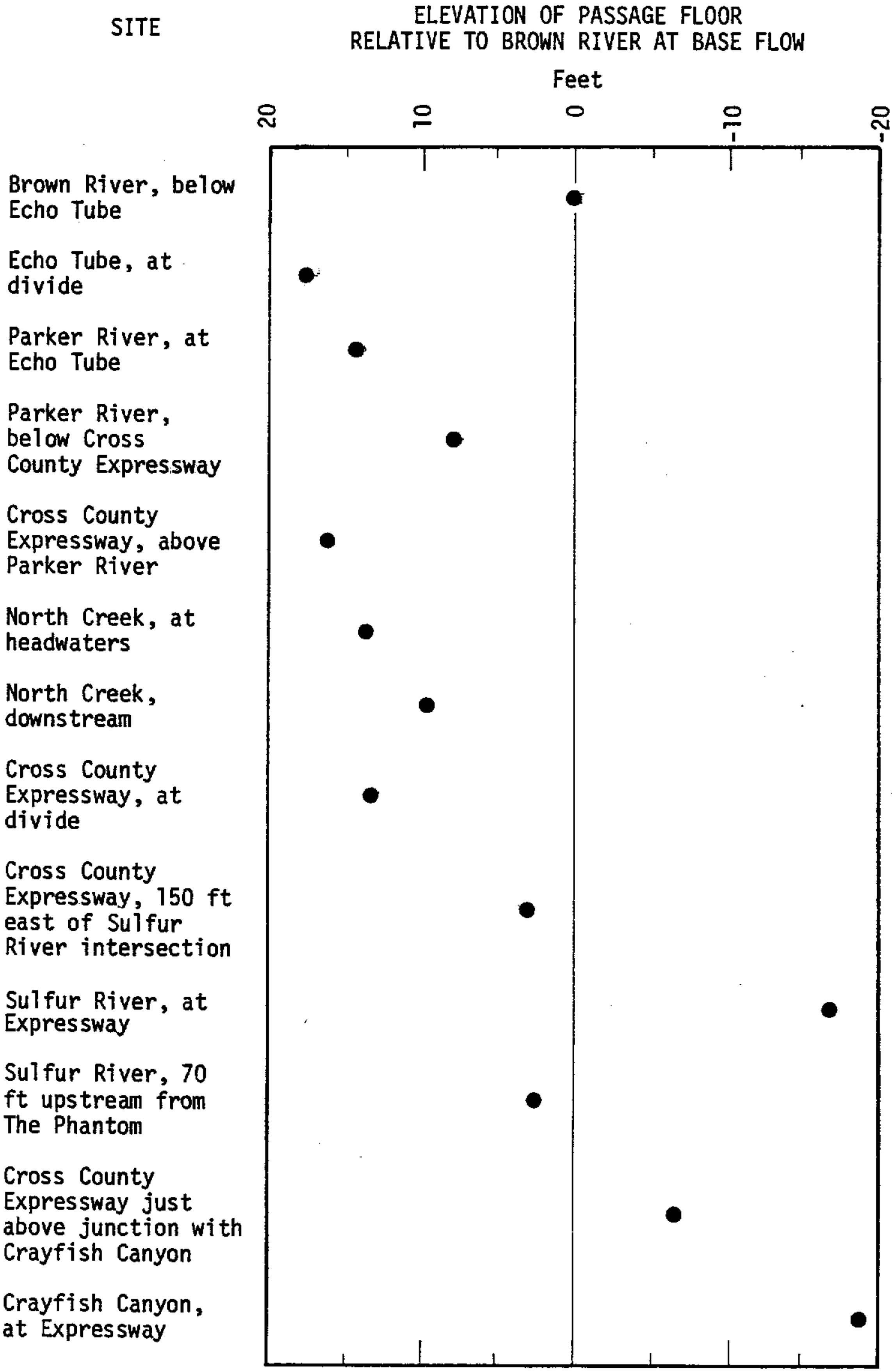


FIGURE 9 - Elevations relative to Brown River of passage floors in Parker Cave. Locations are shown in plate 1 and figure 5. Horizontal distances are not to scale. Brown River is known to backflood to a height of 80 ft. Most of the cave becomes water-filled.

results are shown schematically in figures 5 and 9. In response to heavy rains, the following happens:

1. After Brown River rises 18 ft its flow crosses a divide in the Echo Tube between it and Parker River. This overflow contributes to the discharge of Parker River, 4 ft below the divide and 14 ft above Brown River. A similar high-level flood route is 300 to 400 feet south of the Echo Tube but it has not been leveled. The divide in it may be slightly lower or higher than the one in the Echo Tube.
2. When Parker River rises 8 ft, part of its discharge is diverted west, along the strike, into the Cross County Expressway. The Parker River passage downstream from this intersection has approximately half the cross section it has upstream from it.
3. The water from the Cross County Expressway contributes to the flow of North Creek, 14 to 10 ft above Brown River, and to Sulfur River and Crayfish Canyon, 17 and 19 ft below the level of Brown River.
4. Water from one or more of the streams in Gray's Water Cave flows to upstream Parker River. During base flow the discharge of the westernmost stream in Gray's Water Cave and all the other streams is to Brown River.

Before the stage of Brown River rises the 18 ft necessary to flow westward and contribute to the discharge of Parker River, the stage of Parker River may rise 4 ft and send water east to Brown River. Flow in the Echo Tube can be east or west but it is predominantly to the west. It is possible that the flow of water in the Cross County Expressway could occasionally be to the east, towards Parker River, but the predominant flood-flow direction is from Brown River and Parker River, to the west. Well-developed, unequivocal scallops in bedrock confirm this. So too do the sedimentary structures.

The accumulation of mud that has settled from suspension on the breakdown mountain at the upstream end of Brown River show that it backfloods to a height of 80 ft. (See section A-B on plate 1.) Under such flood conditions all but the highest level passages in Parker Cave are flooded and totally water-filled.

The gradient of Parker River between the Echo Tube and the Cross County Expressway, and that of North Creek is between one-half and one percent. The gradient of Sulfur River, where leveled, is about 4 percent. Leveling of the rest of Parker River, Sulfur River, and Brown River remains to be done.

As discussed in the next section, the chemistry of each of the streams in Parker Cave is distinctive. The flow in a given stream, for example, Parker River, may switch from one route to another. The flow pattern described above and known to operate could, in another setting, explain abrupt increases or decreases in the concentration of pollutants in a carbonate aquifer.

A more detailed description of the Parker Cave System and a comprehensive discussion of the origin of its passages is in preparation by Quinlan and Coons.

Dye tests have shown that the time of travel for streams in the Parker Cave System, between it and Mill Hole, approximately 5 miles away, ranges from less than 24 hours to as much as 18 days. Erroneously assuming a straightline flowpath, these travel times give velocities of 1100 to 60 ft per hour. It is extremely likely that the maximum and minimum flow velocities are significantly greater and lower than these figures. A reasonable speculation about the extreme values is 2500 and 25 ft per hour.

WATER AND AIR QUALITY

Water quality in the Parker Cave system has been studied only in reconnaissance fashion -- in order to identify possible problems rather than to solve them. The water in each of the five streams of Parker Cave is chemically distinctive. For example, as measured just by the sulphate content of the streams during base flow: Brown River = 5 mg/l; Parker River = 250 mg/l (with locally higher inputs); North Creek = 2 mg/l; Sulfur River = 44 mg/l (upstream), 2750 mg/l (from The Phantom), and 660 (downstream from The Phantom); and Crayfish Canyon = 4 mg/l.

Most of the sulphate in the Parker Cave streams, as well as the saline character of the Sulfur River and Parker River waters shown in table 1, is interpreted to be derived from oil field waters that are artesian and mixed with meteoric waters. During the 1920's approximately 100 shallow oil wells were drilled within a several mile radius of Parker Cave. Perhaps 30 to 40 of them produced oil then; less than 10 do now. Casing was rarely set and some that was set was allegedly pulled during the 1930's. The result has been local contamination of groundwater. To drill a water well has been to gamble on the results. The most reliable source of potable water has been the perennial springs that fed some of the sinking streams. Seven families, for example, pump water from the spring in the downstream reaches of basin no. 6. In 1977, after water lines were laid along some of the highways, some of the springs were abandoned as a domestic source, and water was piped from Glasgow.

Table 1 also shows that the CO_2 content of Parker Cave is locally as high as 2.8% and that the H_2S in air at The Phantom is as high as 55 ppm. Parts of Parker Cave are semi-noxious, not at all pleasant, and now recognized as not safe for exposures of more than a few hours, if that

TABLE 1 - Analyses of waters and air in Parker Cave

CONSTITUENT	SULFUR RIVER, Phantom (Waterfall) mg/l	SULFUR RIVER, 600 ft Downstream from Phantom mg/l	NORTH CREEK, Headwaters mg/l	PARKER RIVER, 100 ft Downstream from Echo Tube mg/l
Ca^{++}	1450	-	84	157
Mg^{++}	360	-	17.0	38.5
Ca/Mg	2.45	-	3.00	2.48
Na^+	4200	-	6.10	400
K^+	36.0	-	1.10	5.70
Cl^-	8170	2620	-	400
$SO_4^=$	2750	660	1.0	310
HCO_3^-	-	-	-	-
$S^=$	50	0.0	-	-
H_2S (water)	13	0.0	-	-
DO	0.00	7.0	-	-
Zn	.152	-	.186	.192
Cr	.010	-	.002	.004
Cd	.039	-	.003	.005
Cu	.017	-	.003	.007
Ni	.169	-	.001	.005
Pb	.136	-	.014	.025
Fe	.110	-	.035	.041
Mn	.060	-	.036	.009
SpC (@ 25°C)	>26000 µmhos	9200 µmhos	-	(1800 µmhos)
pH	7.2	6.95	-	-
T (°F)	54	54	(54)	(54)
H_2S (air)	55 (50)	(0.0)	-	-
CO_2 (air)	1.4% (2.8%)	(2.8%)	(2.8%)	-
SO_2 (air)	0.0	0.0	-	-

Determinations of DO, SpC, pH, T, H_2S, $S^=$, CO_2 and SO_2 are by J. F. Quinlan. All others are by W. M. Andrews. Dashes - not determined.

Samples collected August 21, 1974 are in parentheses; all others were collected on November 12, 1974.

much. Radon concentration as high as 8 Working Levels have also been recorded.

The Phantom alluded to above, and shown on plate 1, is a white mass of gypsum, other sulphate minerals, and probably sulphide minerals that are being deposited as a fetid flowstone mass. Discharge at the tributary that forms The Phantom is estimated to be one tenth of a cfs and it comprises about half the base flow discharge of Sulfur River. Filamentous white sulfur bacteria flourish downstream from it. Study of this area has not been completed.

The chromium, lead, and cadmium content of water from The Phantom exceed the current criteria levels for domestic water supplies and the cadmium content exceeds criteria levels for aquatic life (Environmental Protection Agency, 1976) but its chloride, sulphide, and sulphate content make it not likely to be drunk. Nevertheless, if a larger quantity of oil field waters were to be intercepted by a shallow domestic well or if they intercept a cave stream there could be adverse effects on cave fish and crayfish.

OTHER RECHARGE AREAS

The surface of approximately 90% of the Sinkhole Plain area that drains to Mill Hole has been carefully walked and all sinkholes and caves have been checked. All significant caves have been mapped. Two with active streams have been and are being mapped but description of them is deferred until the Phase II, Part B report.

As discussed by Quinlan (1977a, p. 12 and plate 1) and as shown in figure 2, water from an ephemeral spring at the bottom of a sinkhole north of Rocky Hill flows both north to Mill Hole (thence to Green River) and west to the Barren River. An undefined area in the vicinity of this sinkhole is shown in figure 2 to be draining to both the Turnhole Spring Groundwater Basin (Basin E) and the Graham Springs Groundwater Basin (Basin C).

LITTLE SINKING CREEK

The westernmost stream draining to Mill Hole is Little Sinking Creek, shown in figure 2, and discussed in detail by Quinlan (1977a). There are two northwest-trending branches of this creek. The southern branch once continued to the west, sank, and flowed west to Graham Springs, but it has been captured by headward erosion of a fork of the northern branch. During major floods, however, Little Sinking Creek overflows its banks and, about two or three times a year, sends as much as 6 ft of water west along the relict valley floor, thus forming a lake as much as 800 ft wide. It too sinks, and flows to the Barren River. Thus, although Little Sinking Creek normally flows north to Mill Hole and the Green River, during floods part of its surface discharge is diverted west to a different sinkhole and to the Barren River at Graham Springs. The subsurface hydrology of the latter basin is summarized by Quinlan and Rowe (1977a and b) and, with new data, will be described in detail in the Phase II, Part B report that will be published as a supplement to this one.

Little Sinking Creek loses water at several places along the last quarter-mile of its course. After heavy rains, when the normal sinking points are unable to accept all of the floodwater, a lake almost 1000 ft wide is formed. Alternative, higher-level flood routes into the subsurface are then used. The base flow and complex flood water hydrology of caves associated with the downstream terminus of Little Sinking Creek will also be discussed in our Phase II, Part B report. More than 1.6 miles of passage has been mapped, at least half a mile remains to be completed during low flow conditions.

MILL HOLE

Mill Hole itself has already been described herein. It is along the axis of a well-defined north-trending trough in the piezometric surface. The relations of this surface to the flow paths delineated by cave mapping and dye tests will be discussed in our Phase II, Part B report.

Patoka Creek Sub-basin

Patoka Creek, named for an Indian tribe that once occupied part of the Sinkhole Plain (Edgar King, verbal communication, 1976), is partially shown on plate 1 as basin no. 14. It is the southeasternmost stream shown in the Turnhole Spring Basin in figure 2 and it drains a large swamp that is not shown on plate 1. This stream has the third largest base flow of any stream on the Sinkhole Plain between the Barren and Little Barren Rivers. Estimated base flow discharge is 5 cfs. Water from Patoka Creek bypasses Mill Hole and flows directly to Cedar Sink. The configuration of a northwest-trending trough on the piezometric surface, just north of Park City, strongly suggests that the flow path is approximately as shown on plate 1.

Dye tests from a sinking stream and two caves north of Patoka Creek itself have begun to delineate the boundary between the Turnhole Spring Groundwater Basin and the Hidden River Groundwater Basin, shown in figure 2. As discussed below, area X is part of the Patoka Creek

Sub-basin that drains both to Cedar Sink and to Echo River.

PARK CITY AREA

As shown schematically on plate 1 and figure 2, dye traces in the northern part of Park City show that surface runoff flows both to Echo River, within Mammoth Cave, and to Cedar Sink, thence to Turnhole Spring. The straight-line distance from Park City to these two discharge points along Green River is about the same but slightly greater to Cedar Sink. Dye first appears at Cedar Sink.

The piezometric surface north of the Park City area suggests flow to the west, towards Cedar Sink and Turnhole Spring. Flow to Echo River was unexpected but may be a result of:

1. Perching of cave streams on the relatively impermeable Lost River Chert and diversion of part of the perched water downward and westward to Cedar Sink.
2. Flow to Echo River only when water is diverted there during flood-flow conditions.
3. Conditions not yet known.

These three hypotheses are not mutually exclusive. More dye tests are planned.

Park City, a community with approximately 600 people, lacks a municipal sewage treatment plant. Septic tanks are used. Their effluent undoubtedly takes the same flow routes as surface runoff when it sinks into the ground. An understanding of the subsurface drainage of the Park City area is relevant to planning for possible subsurface disposal of effluent from any municipal sewage treatment plant that might be proposed.

CAVE CITY AREA

Figure 2 schmatically shows the curious results of a dye test run from the I-65 interchange at Cave City, about a mile west of town. Dye traveled approximately 14 miles to Turnhole Spring via Cedar Sink -- and one to three days later also arrived at Echo River, only 8.5 miles from the interchange. The relatively small amount of dye recovered on 2 consecutive days at Echo River, when compared with the larger concentration recovered at Cedar Sink on each of 6 days over an 8-day period, strongly suggests that flow from this interchange is chiefly to Cedar Sink. Only during moderate flow and flood flow stages does water (or dye) go to Echo River. The correctness of this last interpretation is being verified by additional dye tests. Study continues.

Water in area X is known to flow both to Echo River and to Cedar Sink. The size of area X, and how its probably interdigitate boundaries with 5 adjacent groundwater basins (E, F, G, H, and J) shift in response to rainfall and stage is not yet known. The shifting of boundaries could occur by mechanisms similar to those shown to operate in Parker Cave -- and the shifting could be different at different flood stages and in response to different rains. The mind boggles at the possible complexities -- many of which could only be understood by careful mapping of caves that one might be lucky enough to find and a series of dye tests at various flow stages.

It is to be stressed that resolution of the subsurface drainage patterns in the area between Park City, Horse Cave, and the Green River, has not yet been achieved. The first approximation that we now have, shown in figure 2, is informative and useful but not definitive.

Cedar Sink

Cedar Sink is a large collapse sink, about 300 x 600 ft wide and more than 100 ft deep. Its location in figure 2 is given on p. 10 and a detailed description of it has been published by Quinlan (1977a, p. 15-16). It is a karst window in which, depending upon the stage of the trunk streams and Green River, water can be sampled at from 1 to 7 places along its flanks. The Patoka Creek and Mill Hole subsurface trunks converge somewhere south of Cedar Sink, bifurcate and flow around its collapsed central core, and rejoin to flow as one to Turnhole Spring, a mile to the north.

Turnhole Spring

Turnhole Spring is one of the larger springs along the Green River. Its base flow has been estimated by Hess and White (1974, p. 27) to be 14 cfs. It is alluviated, about 60 ft deep and 130 ft wide. Turnhole Spring is the only major spring along the south bank of the Green River that is not part of a distributary system (Quinlan and Rowe, 1977a, p. 72-77.)

Summary of Hydrologic Relations

Water from upland areas that include small swamps (the distribution of which is structurally and stratigraphically controlled) flows to small ephemeral and perennial springs that feed short streams. These springs flow because interbedded siltstone and shale perches the water and prevents significant infiltration. The beds dip generally north to northwest at an angle slightly steeper than the topographic slope. The streams sink at a series of swallets downdip from where the uppermost shaley and silty beds would crop out if they weren't mantled by soil. The line formed by the distribution of these swallets is sub-parallel to the strike of the beds. Water from these swallets flows to cave streams. These low-order tributary streams join intermediate-order streams such as Brown River within Parker Cave and finally high-order streams such as the Mill Hole trunk and the Patoka Creek trunk, both of which converge to form the Cedar Sink master trunk that flows to Turnhole Spring at Turnhole Bend.

As judged by the distribution of cave passages with streams in the Parker System -- five major streams, each fed by numerous tributaries, a minor stream, plus a trunk stream fed by 10 sinking streams -- cave passages are ubiquitous beneath the Sinkhole Plain. Flow routes within even the same cave are highly variable and determined by flood stages. These streams are also fed by runoff into sinkholes and diffuse infiltration. The streams that drain beneath the Chester Cuesta are also fed by runoff from ridgetops, infiltration from karst valleys, and spring discharge from an overlying perched aquifer, the Haney Limestone. The percentage of spring discharge that is transmitted by Darcian diffuse flow in fractures as contrasted with turbulent conduit flow is not yet known. (This problem has most recently been studied by Atkinson, 1977).

A piezometric map, made by compiling data on levels in domestic water wells during base flow conditions, indicates the approximate position of major trunk streams and the flow direction of groundwater. This map is drawn with a 20 ft contour interval and is 98% complete at the time of this writing. It will be published in the supplementary Phase II, Part B report and also separately by the Barren River Area Development District and by the U. S. Geological Survey. In the meantime, it is being used to select areas for dye tests and it is being revised where new data requires same.

Hidden River Groundwater Basin

Comparison of figures 2 and 3 shows that much has been learned about the Hidden River Groundwater Basin since the earlier map was compiled. Additional dye tests have helped to identify the boundaries of the basin. More important, however, is the discovery that the flow path from the town of Horse Cave to the distributary along Green River is curvilinear (See figure 3.), rather than straight, as shown in figure 2. Water level data, used to construct a piezometric map of the area between the Barren River and the Little Barren River, has shown that a major piezometric trough with 60 ft of relief plunges northeast from Cave City and swings north and northwest as shown. The axis of the trough is subparallel to Highway 31-W.

The hydrology and water quality of the Hidden River Groundwater Basin has been discussed in detail in our Phase I report (Quinlan and Rowe, 1977a). More data has been acquired; the Phase II, Part B report will include interpretation of it.

Applications of Research Funded by This Project

The numerous uses and applications of maps similar to figures 1 and 2 and plate 1 have been discussed in our Phase I report. It is sufficient to state here that the data in these illustrations -- plus data acquired after this report is published -- will be used in planning for regional sewage treatment and disposal for the towns of Munfordville, Horse Cave, Cave City, Park City and, most recently, Mammoth Cave

National Park. This planning and a related Environmental Impact Statement will be done in compliance with Sections 201 and 208 of the Water Pollution Control Act of 1972 (Public Law 92-500).

The dye trace results are also relevant to water supply protection, industrial and urban development of the region, and protection and interpretation of the resources of Mammoth Cave National Park.

Our most universally applicable research results are the following:

1. Development of simple procedures for routinely and inexpensively tracing groundwaters with optical brighteners and Direct Yellow 96 (Quinlan and Rowe, 1977a, p. 14-17; Quinlan 1977b).
2. Discovery and evaluation of a new dye suitable and practical for tracing groundwater -- Direct Yellow 96 (Quinlan and Rowe, 1977a, p. 14-17; Quinlan, 1977b).

No tracer yet known is without advantages and disadvantages. There have been several discussions in the semi-technical literature during 1977 and 1978 about neutron activation analysis for bromine and iodine as a significant new tracing technique that was made practical as a result of research funded by the Office of Water Research, U.S.D.I., at the Institute for Research on Land and Water Resources -- the water resources research institute for the state of Pennsylvania. This technique, described by Jester & Uhler (1974) and Schmotzer et al. (1973), is indeed a significant one. But, assuming the availability of a nuclear reactor, an activation analysis facility, and automatic water samplers -- and neglecting the more than moderate costs thereof -- the sample processing cost for tracer tests using neutron activation analysis is approximately 100 times greater than those developed by our research and using optical brighteners and/or Direct Yellow 96 or the standard tracing techniques that employ Fluorescein or Rhodamine WT.

As a result of our work with optical brighteners and Direct Yellow 96, these dyes have been used in thesis investigations of limestone hydrology in the Lexington area that have been supervised by J.R. Thrailkill of the University of Kentucky Geology Department. These theses, as yet unfinished, are by Mike McCann and Joe Troester, field assistants formerly employed for some of the research described herein. Thrailkill has started a project in which he has begun to quantify some of the variables associated with tests using these dyes; more work is planned.

The data on groundwater basin boundaries, plumbing geometry, and routing of flood flows are necessary if computer simulations of aquifer behavior are to accurately model what they purport to.

Work in Progress

Continuation of the following work, sponsored in part by the Water Resources Research Institute, is in progress. All or most of it will be discussed in our Phase II, Part B supplementary report:

1. Mapping and interpretation of the piezometric surface.
2. Demonstration of structural, stratigraphic, and base level controls on regional groundwater movement and quality.
3. Hydrology and water quality of the following groundwater basins:
   - A. Poorhouse Spring
   - B. Thomas Spring
   - C. Graham Springs
   - E. Turnhole Spring
   - F. Echo-Styx
   - G. Pike Spring
   - J. Hidden River
   - K. Three Springs
   - N. Grady Spring

4. Role of caves in groundwater movement.
5. Sequential evolution of groundwater basins and the age of the relict topography.

CHAPTER IV

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The most important content of this report is summarized in plate 1 and figures 2 and 5 and the interpretations thereof.

1. An unusual mechanism by which underground streams can be diverted from site to site during various stages of flow has been discovered, mapped, and explained. A hydrologic flow regime similar to that in the Parker Cave System can explain how pollutants in a limestone terrane can be seemingly erratic in their distribution -- because of switching to different flow paths.
2. The Sinkhole Plain is underlain by a dendritic underground drainage system in which low-order streams flow to intermediate-order streams and thence to high-order streams. A fragment of one of these high-order streams have been traced to this major underground trunk. Brown River and five sinking streams west of it all flow to Mill Hole, a higher order trunk stream that joins another named for Patoka Creek. Both flow to Cedar Sink and thence to Turnhole Spring, at Green River.
3. The great range in water quality of cave streams in the area south of Park City is probably caused by contamination from oil field brines from wells that randomly intersected cave passages or fissures tributary to them.
4. From the passage density per unit area of plate 1 where caves are accessible, it can be inferred that most of the Sinkhole Plain in the area south of Park City is underlain by a prodigious number of cave passages that are hydrologically linked to one another.
5. Most sinkholes in the study area are underlain by collapsed cave

passages. The continued development and enlargement of the sinks is aided by subsoil solution of bedrock and by inwashing and slumpage of soil and colluvium. Many collapses within the caves do not have surface expression as sinkholes.

6. During floods, a significant part of the surface flow of Little Sinking Creek is diverted overland to a different drainage basin, from the Green River Basin to the Barren River Basin. The occurrence of such inter-basin flow affects the dispersion of possible pollutants and the accuracy of flood-routing calculations.
7. Much additional data on groundwater flowpaths has been acquired. It is summarized in figure 1 and plate 1 and interpreted in figure 2. Acquisition and interpretation of this data is relevant to 201 planning and EIS preparation for the site location and design of a proposed regional sewage treatment plant for the towns of Park City, Cave City, Horse Cave and, as recently announced, also for Mammoth Cave National Park. More tracing is needed. Work is in progress.
8. Surface runoff from the I-65 Interchange at both Park City and Cave City flows most rapidly to Cedar Sink and thence to Turnhole Spring in the western part of Mammoth Cave National Park -- and at a slower rate <u>over a shorter distance</u> to Echo River, within Mammoth Cave itself. There is a zone of as yet undetermined extent (tentatively shown as area X in figure 2) in which surface runoff -- and therefore possible pollutants or sewage effluent -- goes both to Turnhole Bend and to the Echo River-Styx springs. We believe that this unusual bifurcation of flow may be a result of perching of waters by the relatively impermeable Lost River Chert, partial

breaching of this generally impermeable zone, and more efficient flow in subjacent conduits. The upper-level flow routes from Cave City function only during moderate and flood conditions. It has not yet been determined whether flow routes from Park City also vary in response to changes in stage. The hypotheses of flow bifurcation by: 1) perching and piracy, 2) utilization of high-level routes only at moderate and high stages, and 3) unknown causes, are not mutually exclusive. All three could be operative. Delineation of this zone is important for planning decisions, siting of proposed new industries, and protection of the resources of Mammoth Cave National Park.

9. More than 200 traces have been run with Fluorescein, optical brightener, Direct Yellow 96, and Rhodamine WT. The procedures developed are extremely efficient and give reliable tracing results at a cost far lower than most other methods.
10. In an area where a tracer dye can go to so many different places, and where there is a shortage of manpower and funds, it is much more efficient to run qualitative tests -- to be followed by quantitative tests.
11. A piezometric map, drawn from water level data of 1200 wells, delineates major groundwater basins and indicates flow paths. This map, now in the final stages of preparation, is being used to select sites for future dye tests and will be included in the Phase II, Part B report.

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APPENDIX A

Abstract of Kentucky Water Resources Research Institute Research Report 101 -- Hydrology and Water Quality in the Central Kentucky Karst, Phase I (Quinlan and Rowe, 1977a).

Study of springs and cave streams has shown that heavy metal-rich effluent from a wastewater treatment plant can be traced to Hidden River Cave (beneath the city of Horse Cave) and thence 4 to 5 miles north to a group of 39 springs at 14 locations along a 5-mile reach of Green River. Nickel, chromium, copper and zinc in these effluent-bearing springs are in concentrations of as much as 30 times greater than other springs upstream and downstream from this reach, 20 times greater than the Green River, and 60 times greater than in shallow domestic wells between Horse Cave and the river. Mean concentration ratios, based on samples taken during moderate to flood flow, are considerably lower. Although the heavy metal content of the effluent-bearing stream in Hidden River Cave greatly exceeds various maximum concentrations set by current standards, the concentrations in the effluent-bearing springs do not exceed current maximums allowed for public water supplies. None of the domestic shallow wells between the cave and the river intercept this effluent-rich water.

The distributary system that was postulated to feed the 39 springs was entered by digging in June 1975; 14.6 miles of this flood-water maze has been mapped. [15.75 miles as of February 1978.]

Water tracing over distances of as much as 15 miles has made it possible to delineate thirteen groundwater basins, eleven of them characterized by distributary flow. Study of the water quality of five adjacent groundwater basins showed that they could be geochemically differentiated. One of these, the Three Springs Groundwater Basin, has a distributary complex that is 2.4 miles wide and its discharge is believed to be affected by drilling.

Dendritic flow paths, identified by dye-traces to and from caves (and mapping of these caves), have been recognized in the Turnhole Spring Groundwater Basin (Quinlan, 1976) and the Graham Springs Groundwater Basin. Flow converges to trunk streams as much as 40 ft wide that may rise and fall as much as 100 ft in response to heavy rains. Groundwater velocities in the upper part of the principal aquifer range from 30 ft per hour to 1300 ft per hour, depending upon the duration and intensity of rains.

Recommendations are made for: 1) the use of drainage basin maps for regional planning and protection of water supplies, 2) protection of other water supplies, and 3) development of specific springs as potential public water supplies.