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Hydrology and Water Quality in the Central Kentucky Karst: Phase 1

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Research Report No. 101

HYDROLOGY AND WATER QUALITY IN THE CENTRAL KENTUCKY KARST:
PHASE I

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University of Kentucky
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January 1977

ABSTRACT

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 floodwater maze has been mapped.

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 brines released 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.

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

IDENTIFIERS: *Karst, *Kentucky, *Caves, *Limestone, *Tracers, *Dyes, Optical Brighteners, 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 a project. The resources of Western Kentucky University and the assistance of much of its staff, especially Dean Lynn Greely, has been essential for project planning and execution. Laboratory analyses were made by William M. Andrews (Kentucky Division of Water Quality). Data has been reciprocally shared with the following organizations and individuals: National Park Service at Mammoth Cave (Uplands Research Laboratory), U.S. Geological Survey (Louisville), Joseph Saunders, John Branstetter, Angelo George, Gary Tinker, Jack Hess, Les Calaway, Lawrence and Lario Yerino, Clarence Dillon, Stephen Maegerlein, George Deike and Steve Wells. 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), 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). The mayor of Horse Cave, James K. Palmore, graciously gave permission for the collection of samples at the Horse Cave wastewater treatment plant. 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 the Hidden River Complex and 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 Henrikson, Duke Hopper, George Huppert, Steve Knutson, Phil O'Dell, Dan Quinlan, Joe Ray, John Schwartz and Gary Tinker. These individuals were the major part of the Western Kentucky University Karst Research Team. Analysis of well waters during the summer of 1976 was done by Theresa Graham. Robert Dunlap, Theodore Fox, and Joel Roberts assisted with data analysis and compilation. 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, Don Coons, Mark Elliot, Tom Gracnin, Mike McCann, Joe Ray, Rick Schwartz, Bob Taylor, Gary Tinker, and Joe Troester. 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.

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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 may 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 I completion report is not that summary. Such a document will be prepared after the next (and last) completion report and will be written in a completely different style.

Statement of Limitations

It should be stressed that this is an interim report that is written while work is in progress -- much map compilation and other drafting remains to be done. We are confident of the accuracy of the statements and conclusions of this report but discussion of many others, now considered to be tentative, is deferred until the next report. The Phase II report on this project will be more comprehensive but 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, have been incorporated into this report. All tests contributed to an understanding of the regional hydrology.

Background Information

Description of Study Area

The study area is shown in Fig. 1. It is a 1125 square mile (2915 km^2) area (15 square miles of which is not shown in the map) of Central Kentucky in which most of the terrain is gently rolling and pitted with sinkholes. It is arbitrarily bounded by the banks of the rivers, creeks, and branches shown. Most of our work, however, has been done in the 860 square miles (2200 km^2) area south of the Green River.

All of the Central Kentucky Karst is underlain by various limestones of Mississippian age that dip very gently (generally 40-100 ft per mile) to the north, northwest, and west. The stratigraphy of the area is summarized in Fig. 2. Most of the waters studied occur in the St. Louis and Ste. Genevieve Limestones. The U.S. Geological Survey has published geological maps (with structural contours) of each of the 7 1/2 minute quadrangles that include the study area. Reviews of the geology and hydrology have been published by White et al (1970), Quinlan (1970), and Quinlan and Rowe (1977). Except as relevant elsewhere within this report no attempt will be made to discuss the regional geology or review the voluminous literature concerning the karst. It has most recently been summarized by Lambert (1976), Quinlan (1976), Miotke (1975 & 1976), Miotke & Palmer (1972), and Palmer & Palmer (1975). This report is concerned with the results of new research.

General reports on the resources of the area, its water quality and sewage treatment problems, and basic data on the area, have been

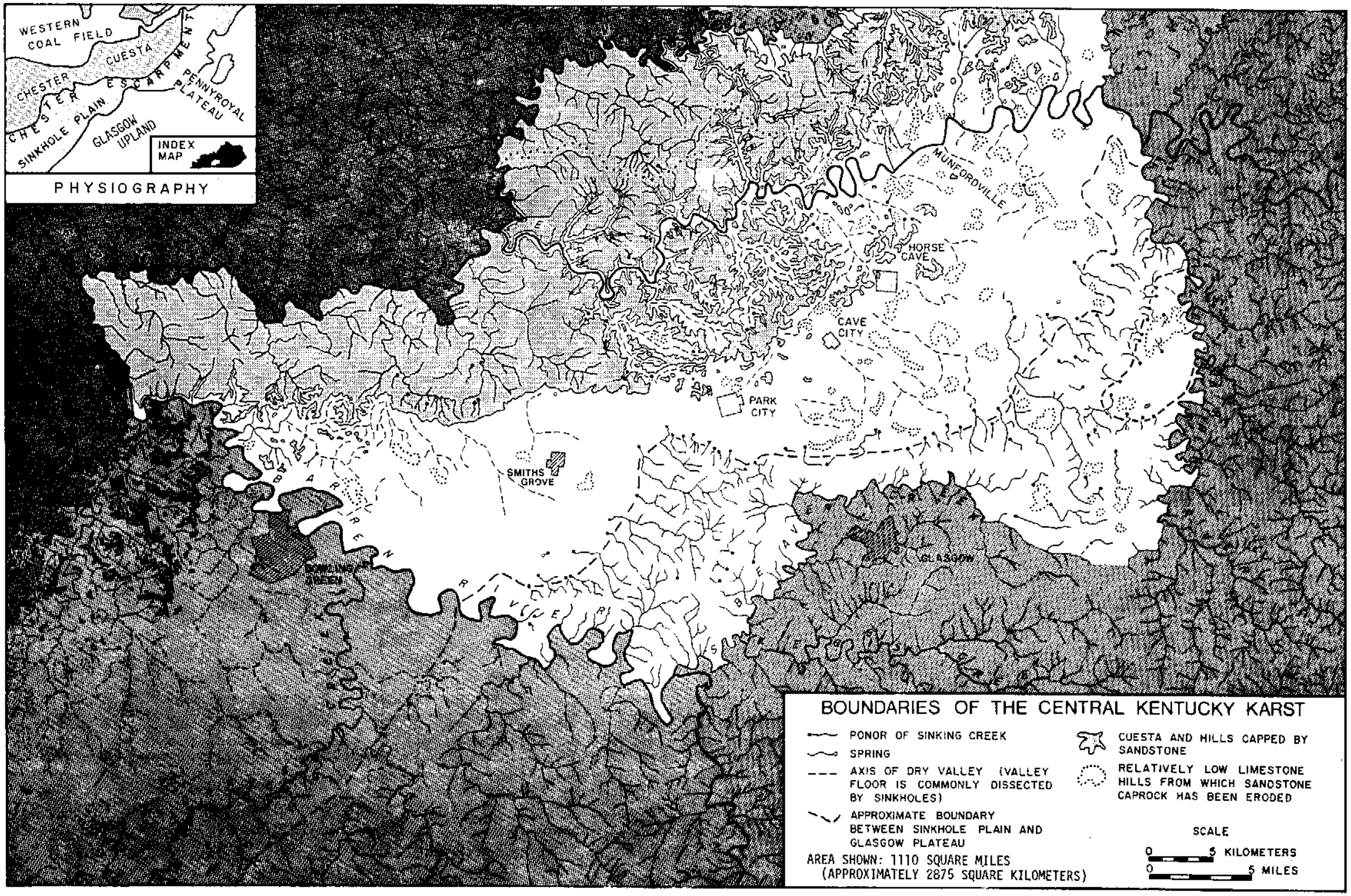
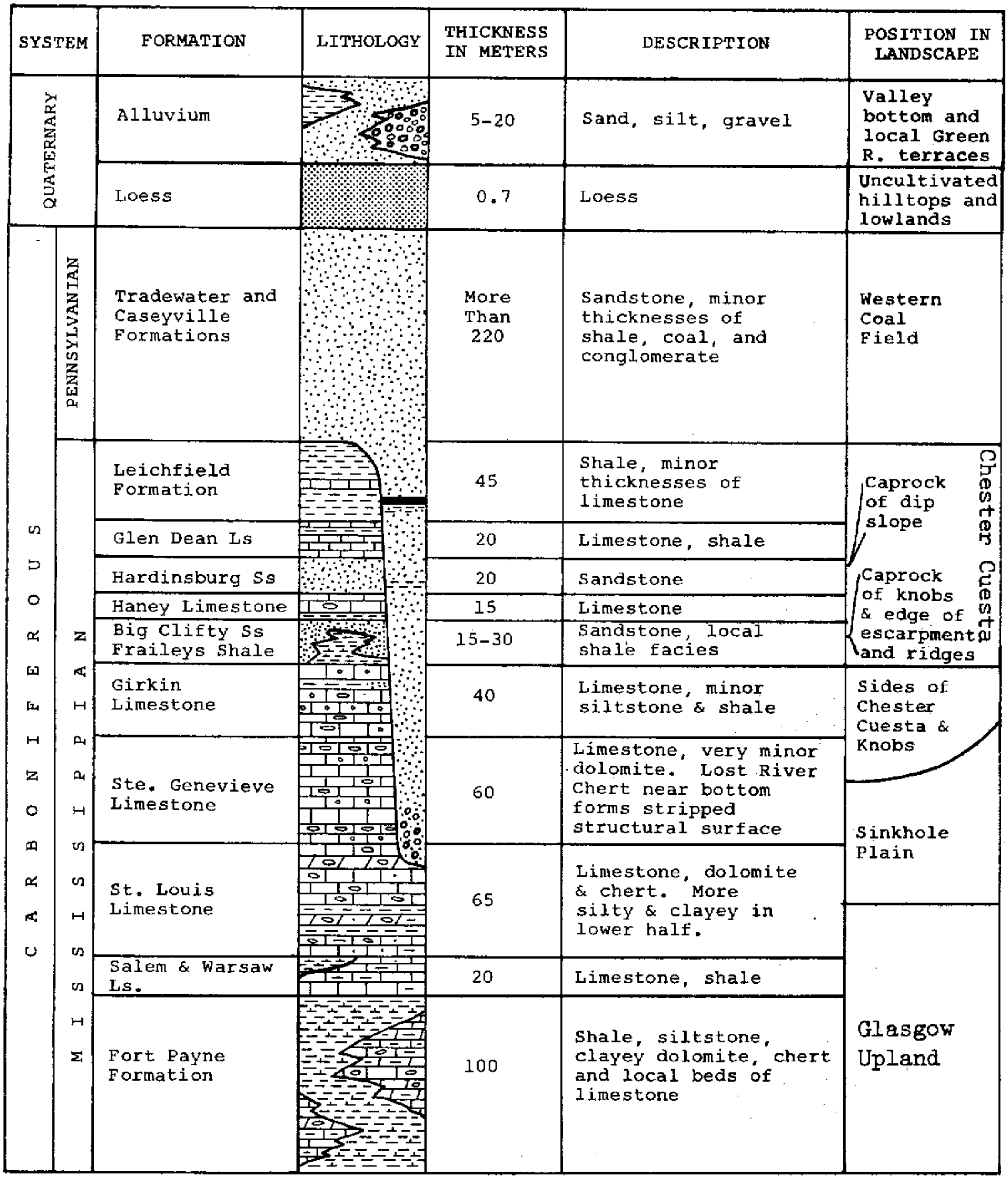


FIGURE 1 - Boundaries of the Central Kentucky Karst.



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	Chester Cuesta Caprock of dip slope
		Glen Dean Ls		20	Limestone, shale	
		Hardinsburg Ss		20	Sandstone	Caprock of knobs & edge of escarpment and ridges
		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 2 - Generalized statigraphy of the Central Kentucky Karst (after Quinlan, 1970).

summarized and published by: Weston (1976), Hensley-Schmidt (1973), U.S. Army Engineer District, Louisville (1975), U.S.D.A. River Basin Planning Staff (1975), and the Barren River Area Development District (1976).

Fig. 1 shows a broad streamless area, the Sinkhole Plain, that has been the principal area of study. More than 40 streams along its south and east border sink into the ground -- to ultimately resurge at springs along the Green, Barren and Little Barren Rivers. We have studied the subsurface of the area between where they sink and where they resurge, how they get there and the nature of waters in the aquifer.

Major Recognized Problems

The flow of water in limestone terrains is notoriously plagued with problems. The flow is different from that in other rocks because caves in limestone may transmit water as much as six or more orders of magnitude faster than most other rocks -- and in unpredictable directions. Yield of water wells is also unpredictable. As a consequence, pollutants move rapidly -- before they have time to biodegrade, break down, die, or be neutralized or sorbed by the rock or sediment through which they move.

Three recognized examples of pollution-related problems in the Central Kentucky Karst will be cited:

1. Horse Cave area (summarized chiefly from Payton, 1932, and Branstetter, 1974). Until 1912 this city obtained its water from Hidden River Cave, beneath its center. Municipal water was then obtained from wells but during the drought of 1930 and for several years thereafter the cave stream was again used. Several cases of typhoid fever occurred and a cholorinator was installed in 1932. Within a few years wells again became the sole source of groundwater but there

were problems of quality and quantity available for a growing town. Supply problems were alleviated by the creation of the Green River Valley Water District that developed Rio Springs (Site #3 on Fig. 5) on the north side of Green River. Today these springs supply water for Horse Cave, Cave City, and much of the area between these cities and the Green River.

Until the Horse Cave wastewater treatment plant went into operation in 1964 individual residences and businesses disposed of sewage and other waste by means of septic tank and tile field or direct discharge into wells or sinkholes. During 1931 oil refinery waste that was dumped into a sinkhole south of Hidden River Cave and near the city limits, appeared in wells and in the cave. Payton (1932) cites several other examples of how the municipal wells were commonly affected by waste disposal. Hidden River Cave had been operated as a commercial tourist attraction from 1916 until 1944 but by then, in spite of lawsuits and countersuits, the cave was forced to close because of malodorous and aesthetic problems caused by fecal waste and, beginning in 1944, whey from a local creamery (W. T. Austin, verbal communication, 1974).

The wastewater treatment plant, approximately 1 mile southwest of the entrance of Hidden River Cave, uses a trickling filter for secondary treatment. At first its effluent was discharged into an adjacent sinkhole but, when this became clogged, two disposal wells were drilled. All three disposal sites drain to the South Branch of Hidden River Cave. The effluent from the plant was unusually septic because much of it consisted of creamery waste. This problem was partially "solved" by dilution when a metal-plating plant went into operation in 1970. This plating plant discharges approximately 60-70% of the 10,000,000 gallons per month of effluent discharged by the treatment plant. Unfortunately this effluent also includes nickel, chromium, zinc, and copper that are present in Hidden River Cave in concentrations of as much as 8.90 mg/l chromium, 19.4 mg/l nickel, 2.1 mg/l zinc and 1.2 mg/l copper -- most definitely toxic to animal life and far above the maximum allowable for drinking water. Higher concentrations are present in the influent. These concentrations and their implications will be discussed in the body of this report.

A 24-hour composite sample of plant effluent in a May 1975 survey of it included the following characteristics:

Biochemical Oxygen Demand (BOD_5)	445 mg/l
Chemical Oxygen Demand (COD)	786 mg/l
Suspended Solids (SS)	153 mg/l

These figures and other data were supplied by Robert Ware, Sanitary Engineering Associate, Kentucky Division of Natural Resources and Environmental Protection (verbal communication to D.R. Rowe, December 1976).

For comparison, and to indicate how the treatment plant should be operating, the Water Pollution Control Act of 1972 (Public Law 92-500) requires that the monthly average of the maximum levels in the discharge of municipal wastewater receiving secondary treatment be:

Biochemical Oxygen Demand (BOD)	30 mg/l
Suspended Solids (SS)	30 mg/l

These figures are cited by the Izaak Walton League (1973, p. 24).

Part of the report on the May survey of the treatment plant by the Division of Natural Resources and Environmental Protection was quoted in the Hart County Herald of July 10, 1975. The survey "showed that the plant is 'all practically non-functional under the present operating conditions.'" The conclusions quoted in part include:

> "'1. The plant, which has a design capacity for a 4,000 population is receiving a waste load which is organically equivalent to a population of 13,556.'" [The 1970 population of Horse Cave was 2068.]
>
> "'2. . . . the appearance of the incoming wastes was indicative of milk and/or cheese plant wastes.
>
> "'3. The concentrations of certain metals indicate that Ken-Dec controls are ineffective. These metals can not be reduced to an acceptable level by conventional treatment means. Further, these are toxic to the biological life that must be present in order that the treatment plant can perform its function.
>
> "'4. The plant efficiency is considerably less than the design expectancy of 85 percent. (The survey showed the plant operating at 55 to 59 percent efficency.) The plant is so grossly overloaded that about 92 to 98 percent reduction would be required in order that effluent concentration limits be complied with.'"

The State of Kentucky, the City of Horse Cave, officials of the metal-plating plant and officials of the cheese and whey plants have been involved in trying to solve these problems of alleged pollution but no attempt will be made herein to summarize these efforts, or the various accounts of them published in the Hart County Herald during the past few years, but the issues for May 8 and July 17, 1975 (Matera, 1975) are also relevant.

Hidden River Cave is the type locality for the Horse Cave Blind Fish, _Typhlichtys osborni_ which was described in 1905 and later shown to be synonymous with _Typhlichtys subterraneous_. According to Branstetter (1974, p. 30, 32) the blindfish were once so abundant in the stream that they had come through the faucets of a house near the cave's entrance. With increased pollution, however, "the fish population decreased and eventually disappeared." Today it is no more.

2. Horse Cave area. An estimated 4000 gallons of gasoline was lost by leakage from an underground steel tank from February 1975 until November 1975 when it was discovered and the tank replaced. Gasoline fumes were detected in the basement of certain nearby buildings. These fumes could have been accidently exploded underground by cave explorers or by water well pumps. Both types of catastrophic accidents have occurred elsewhere in the U.S. and have been described in detail.

3. Smiths Grove area. According to Warren County court records, in 1970 a company was responsible for dumping an estimated 340 tons of whey into a sinkhole. No adverse effect was intended or anticipated but the water supply of Smiths Grove, approximately 5 miles to the northwest, became foul and unfit to drink for more than a month. This is described in issues of the Park City Daily News issues of September 4, 10, 16, 25, and October 1, 8, and 15, 1970. The dumping ceased and the water supply was restored to its former quality.

   Research described in this report indicates that if the whey had been dumped a mile or two north or east of where it was, it would have entered part of Mammoth Cave National Park -- with consequent destruction of the fauna of cave rivers and streams.

Some Potential Problems of Wastewater Disposal, Water Supply, and Industrial Development

The above-cited examples raise strong questions about the health, safety and economic welfare of the people in the Central Kentucky Karst --

and about the protection of the subterranean fauna of Mammoth Cave National Park, as well as that of other caves in the area. Some of these questions are:

1. Where does the heavy metal-rich, effluent-laden stream in Hidden River cave go? Does it affect the water quality of any of the domestic wells between the city and Green River? Might some of this water be going to Mammoth Cave National Park?
2. What might be the environmental consequences of locating an effluent-producing new industry or a sewage treatment plant that would dispose of its effluent into the ground at various places in the Central Kentucky Karst, specifically in or near the Sinkhole Plain? What towns and water supplies might be affected by any such new activity? Would industrial growth have to be curtailed?
3. Is Mammoth Cave National Park affected or potentially affected by present-day waste disposal practices at Horse Cave, Cave City, and Park City? If so, to what extent?
4. How and where does water move through the ground in limestone terrains? How fast? What controls this movement?

The reported research provides answers for many of these questions.

CHAPTER II

RESEARCH PROCEDURES

Water Analysis

For this first phase of the project only partial chemical analyses were run. Interest was primarily in the heavy metals, alkalai metals and chloride content of the waters. Analyses made during Phase II of the project, as part of a study of regional variation in the quality of well waters, are relatively complete analyses.

Specific conductance was measured in the field with a Beckman RB3-338 Solu Bridge conductivity meter. It corrects the reading to 25°C when the temperature dial is set at the sample temperature. Specific conductances below 600 micromhos/cm were recorded to the nearest micromho/cm. Specific conductance measurements were reproducible to within ±0.4%.

Samples were collected in 1-quart plastic cubitainers into which 4 ml of concentrated nitric acid had been previously added as a preservative. Cubitainers are routinely used by the Kentucky Division of Water Quality for the collection of samples to be analysed for heavy metals and have been shown to be contaminant-free. (W.M. Andrews, verbal communication, 1975). Because of leakage problems, however, a different type of bottle, also allegedly water-tight, was then used in May and June 1975. But the nitric acid leached heavy metals from their red plastic caps and these analyses for heavy metals had to be discarded.

All metals were analysed by atomic absorption with a Perkin-Elmer Model 403 Flame Atomic Absorption Spectrophotometer by W.M. Andrews of the Kentucky Division of Water Quality. Depending upon sample site and elements to be analysed, a portion of many samples was concentrated by slow evaporation. Specifically, a 500 ml portion of all spring, river, well, and Hidden River Cave-East Branch samples were concentrated 10:1 and analysed for heavy metals. A 250 ml portion of Hidden River Cave-South Branch samples was concentrated 5:1. Heavy metals in sewage plant influent and effluent samples were analysed after digestion, but without concentration. Alkalai metals were analysed without concentration. Certified standards were repeatedly run for the purposes of calibration and re-calibration. Blanks, consisting of distilled water with a similar amount of nitric acid, were concentrated to the same proportion as the samples, analysed before and after each sample, averaged as background, and added or subtracted from the reading for each sample.

The following are the limits of detection for the elements analysed:

Metal	Detection Limit before 10:1 Concentration (mg/l)	Analysis of 10:1 Concentrations Recorded to (mg/l)
Chromium	.003	.0001
Copper	.003	.0001
Nickel	.01	.001
Zinc	.003	.0001

Metal	Detection Limit (mg/l)	Analyses Recorded to (mg/l)
Calcium	.01	.1 or 1.0
Magnesium	.01	.01 or 0.1
Potassium	.01	.01 or 0.1
Sodium	.01	.01 or 0.1

Metals that were recorded to the nearest 0.0001 mg/l had this last digit retained in all calculations but means were rounded off to the nearest 0.001. Ratios between comparable samples were calculated to the nearest 0.01 but later rounded off to the nearest 0.1.

Chloride was determined by the mercurimetric method, as discussed in Standard Methods and recorded to the nearest 0.1 for values less than 10 and nearest unit for values greater than 10.

Some samples were analysed for mercury, cadmium, lithium, iron, and manganese. Mercury was analysed by flameless cold vapor atomic absorption spectrophotometry. Cadmium, lithium, iron and manganese were analysed by flame atomic absorption spectrophotometry. Mercury, cadmium, lithium, and manganese were present in trace concentrations that showed no significant systematic variation and analyses for them ceased. These results will not be discussed further.

Iron in Green River water averages less than twice the old, but no longer existing maximum allowable limit of 0.3 mg/l in drinking water (U.S. Public Health Service, 1962). The iron content of the Green River and of spring water increases directly with suspended sediment, but this is to be expected. The concentration of iron would have been much less if the samples had been filtered.

It can be argued that all samples should have been field-filtered. But the very low heavy metal content of the samples with by far the highest suspended solids content -- those from Green River -- is very similar to or less than that of the four groundwater basins other than the Hidden River Basin. Nevertheless, field filtration was tried for the June 1975 samples. Gelman GN-6 Metricel filters (pore size: 0.45 μm) were used but these had trace heavy metals that invalidated the heavy metal analyses.

Measurements were not made of the pH of samples collected but the wastewater treatment plant influent has been reported by the Hart County Herald (May 8, 1975) to be very acidic. The paper states that concrete in the manholes between the metal-plating plant and treatment plant ". . . has been eaten away 4 to 5 inches."

No attempt has been made herein to review the chemistry of carbonate waters, the various reactions involved, or to determine the saturation of the waters.

All chemical analyses used in this report have been carefully scrutinized. Unless otherwise cited, all analyses are based on samples collected specifically for this study since October 1974.

Standard deviations of element concentrations at individual sites were not calculated because of the small number of samples and the lack of evidence that concentration values are normally distributed. Specific conductance, for example, probably does not have a normal distribution. Nonparametric statistical tests could have been used but were not considered necessary.

Dye Tracing

The five dyes used are described in Table 1. Three of these five, Fluorescein, Rhodamine WT, and Rhodamine B, have been conventionally used for many years. The dye is recovered on detectors consisting of activated charcoal detectors and eluted with a mixture of 1-propanol (43%), ammonium hydroxide (33%) and distilled water (24%), as recommended by Smart (1972). Detector fluorescence, indicating a positive trace, was evaluated in sunlight. Dyes were used only after a literature search and evaluation had been made of their possible toxicity and data showed that they could be considered safe.

Optical brighteners are fluorescent dyes that absorb light in the ultra-violet region of the spectrum and are therefore colorless in solution. They have a strong affinity for cellulosic and various man-made fibers. Manufacturers add them to detergents in order to "make your whites whiter." They were first used for water-tracing by Crabtree (1970) and Glover (1972), in England. Their use in the United States was pioneered by James Quinlan on behalf of the National Park Service at Mammoth Cave beginning in August 1974. Since then, he and the staff of

TABLE 1 - Dyes used for water tracing

Brand Name	Common Name	Colour Index General Name	Colour Index Constitution Number	Supplier
Pyla-tel Fluorescent Yellow	Fluorescein	Acid Yellow 73	45350	Pylam Products Queens Village, N.Y.
Rhodamine WT	Rhodamine WT	not assigned	-----	DuPont Wilmington, Delaware
Pyla-tel Fluorescent Pink	Rhodamine B	Basic Violet 10	45170	Pylam Products Queens Village, N.Y.
Diphenyl Brilliant Flavine 7GFF	none	Direct Yellow 96	-----	Ciba-Geigy Corp. Greensboro, N.C.
Calcofluor White ST (Solution)	Optical Brightener	Fluorescent Brightener 28	40622	American Cyanamid Co. Bound Brook, N.J.

the Park Service's Uplands Research Laboratory have utilized brighteners in traces as long as 15 miles. Discussion of the results is included.

The several techniques for use of optical brighteners have most recently been described by Smart (1976), Quinlan (1977) and Quinlan and Rowe (1977). In brief, a piece of unbrightened cotton such as Johnson & Johnson Surgical Cotton is suspended in a stream or spring. If optical brightener is present in the water it reacts with the cotton and is retained. Detectors are changed every few days, washed under a high-speed jet of water, and examined under a long-wave ultra-violet lamp for the blue-white fluorescence of the brightener.

As a result of a systematic review of the properties of dyes, evaluation of desirable characteristics of dyes, an extensive correspondence with various manufacturers, and finally laboratory and field testing, Quinlan (1977) showed that Direct Yellow 96 is eminently suitable for water tracing. It is used like an optical brightener but it turns cotton a bright canary yellow.

The dye tests run were qualitative rather than quantitative because, with a limited number of personnel (1 assistant) during the winter and spring rainy season, rapid flow velocities, and the uncertainty as to which of ten or more springs dye from a test might go to, it was more practical to be qualitative. Quantitative tests are planned for the future.

Of the five dyes used, we highly recommend only fluorescein, optical brightener, and Direct Yellow 96 as groundwater tracers. Rhodamine WT is less efficient, and relatively expensive. Rhodamine B has been used for many years but it is too easily absorbed by clays. More importantly, in high concentrations, it can be toxic to fish (Little & Chillingworth, 1974). Although Rhodamine B is the safest of the basic dyes tested by others and its use in very low concentrations has been approved by the Public Health Service (Turner Associates, 1971), in our opinion no basic dyes should be used as water tracers. We had used small quantities Rhodamine B for three short-distance tests of less than a mile but, after reaching the above conclusion, we ceased using it -- even though we know of no strictures against its use.

A review of the chemistry and classification of dyes has been made by Allen (1971). A comprehensive and definitive review of dyes other than Direct Yellow 96 that are suitable for water tracing has been made by Smart and Laidlaw (1976).

Location of springs, wells, and caves and sampling of their waters

Springs were located by searching for them along river banks, consultation with landowners, and review of relevant literature. Springs sampled in the eastern two-thirds of the study area are shown in Fig. 3. Wells and caves were located by systematically talking with landowners and by plotting the position of these features on topographic maps.

Cave Mapping

Caves that are actively functioning as conduits in conveying water from the Sinkhole Plain to the Green or Barren Rivers were mapped so that an understanding could be obtained of the fluid mechanics of the aquifers.

Caves were mapped with Suunto KB-14 liquid-filled precision compasses, Suunto PM-5/360 PC clinometers, and fiberglass survey tapes. Backsights were used as a check on accuracy and closures made whenever possible. A four-man survey crew, generally in wetsuits, worked most

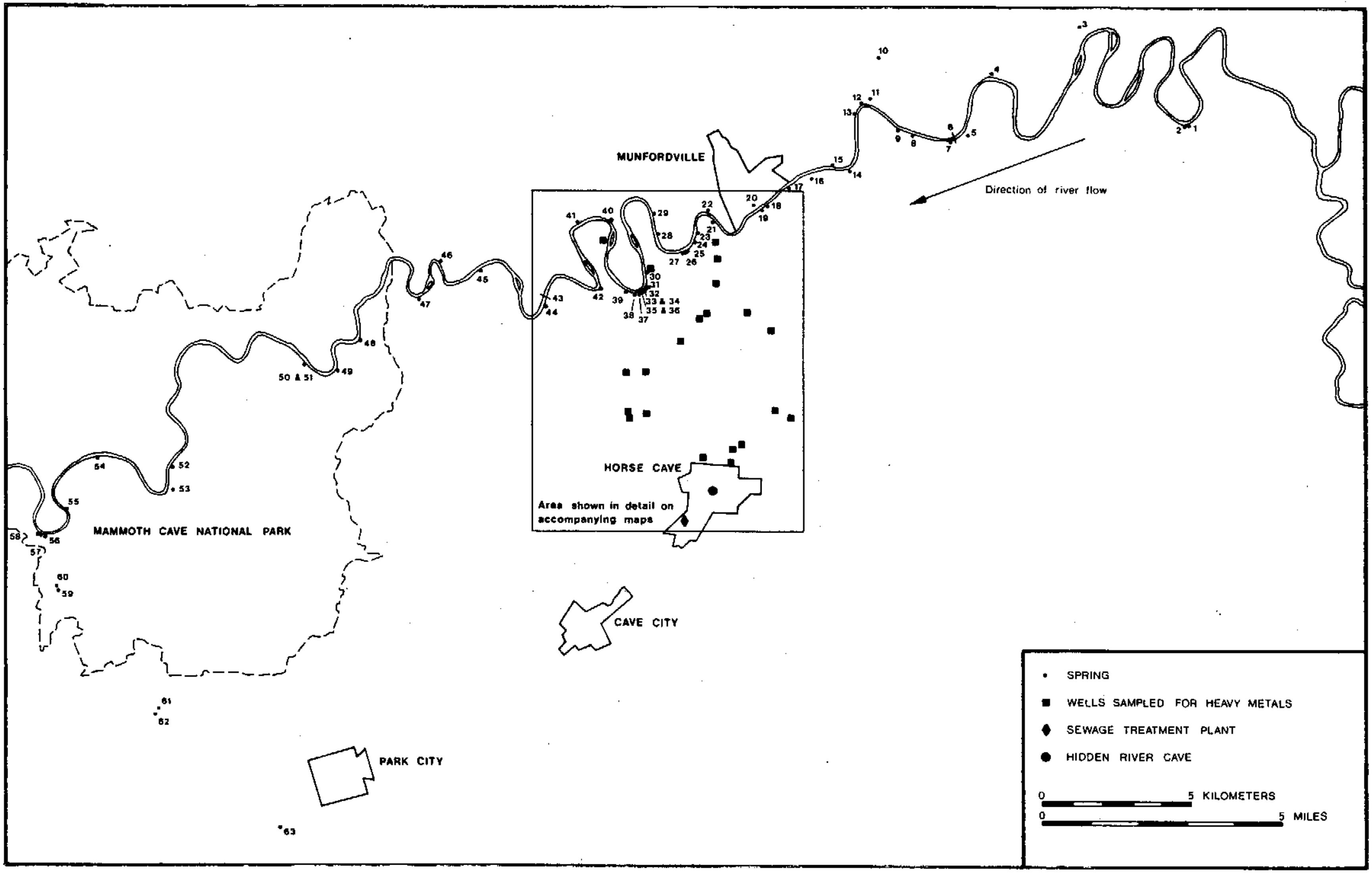


FIGURE 3 - Location of sites sampled for water analysis. See Table 2 for identification. See also Fig. 7.

TABLE 2 - Sampling and dye input sites. Locations are shown on Figs. 3 and 7.

MAJOR SPRINGS ALONG GREEN RIVER, CHIEFLY EAST OF MAMMOTH CAVE NATIONAL PARK, WELLS SAMPLED FOR HEAVY METALS BETWEEN THE TOWN OF HORSE CAVE AND GREEN RIVER, OTHER WATER SAMPLING SITES, AND DYE INPUT SITES

MAJOR SPRINGS, CAVES, AND SEWAGE TREATMENT PLANT

1	Cedar Spring
2	300 Springs
3	Rio Springs
4	Buckner Spring
5	Scott Spring
6	Green River
7	Grady Spring
8	Boyd Spring
9	New Spring
10	Boiling Spring
11	Major Johnson Springs
12	High Spring
13	Captain Spring
14	Blue Hole
15	"X" Spring
16	Dixon Spring
17	Perched Spring
18	31-W Bridge Spring
19	Woodsonville Spring
20	Munfordville Blue Hole
21	Big Tree Spring
22	#2 Spring
23	Gorin Mill Spring
24	Trough Spring
25	Spring Seat Spring
26	Summer Seat Spring
27	Fall Seat Spring
28	#8 Spring
29	#9 Spring
30	Hick Springs
31	5-Finger Springs
32	High & Dry Springs
33	Alcove High Spring (Cave)
34	Alcove Spring
35	Mike's Spring
36	Natural Tunnel Spring
37	Blow Hole East Spring
38	Blow Hole West Spring
39	Garvin Spring
40	#16 Spring
41	#17 Spring
42	Beaver Spring
43	Green River
44	Lawler Blue Hole
45	Williams Spring
46	McCoy Spring
47	Suds Spring
48	Mile 205.7 Spring
49	Grinstead Spring
50	Pike Spring East
51	Pike Spring West
52	Styx Spring
53	Echo River Spring
54	Cotton Gin Hollow Spring
55	Sand Cave Spring
56	Above Turnhole Spring
57	Turnhole Spring
58	Sandhouse Cave Spring
59	East Window Spring
60	Smith Valley Cave Spring
61	Mill Hole Spring
62	Mill Hole Cave Spring
63	Parker Cave, Sulphur River
HRC-S	Hidden River Cave, South Branch
HRC-E	Hidden River Cave, East Branch
STP-I	Sewage Treatment Plant, Influent
STP-E	Sewage Treatment Plant, Effluent

WELLS SAMPLED IN A STUDY FOR HEAVY METALS IN GROUNDWATER

W-1	Wells
W-2	H. Lively
W-3	Bennett
W-4	Rowe
W-5	England
W-6	Mears
W-7	Mears-Meredith
W-8	Martin
W-9	Ross-Dennison
W-10	Gilpin-Wallace
W-11	Smith
W-12	Houk
W-13	Wilson-Turner
W-14	J. Wilson
W-15	Stinson
W-16	Lane
W-17	Meador
W-18	Mansfield
W-19	Mammoth Onyx Cave
W-20	Minit-Burger
W-21	Marathon
W-22	Lawler

DYE INPUT SITES

D-1	Horse Track Sink
D-2	Marshall Collins Cave
D-3	Palmore Sink
HRC	Hidden River Cave

efficiently. The map of only one of the more than 20 caves surveyed is reproduced in this report. The Phase II report will include these maps with a discussion of the role of these caves in the regional hydrology.

Study of Surface Geomorphology

Terraces along the Green River were mapped in an effort to descriminate between base-level and stratigraphic controls on water movement. This work is still in progress and will be discussed in the Phase II report.

CHAPTER III

DATA AND RESULTS

Introduction

Dye tests by project personnel began in April 1975 from Horse Cave to the Green River and have been run in the Smiths Grove, Park City, and Grady Spring area. However almost all tracing tests since 1974 have been by the staff of the Uplands Research Laboratory (chiefly Bill Cobb and Don Coons), under the direction of James Quinlan. Many tests in the area east of Horse Cave were run in collaboration with Dr. Joseph Saunders of the University of Kentucky. Quinlan compiled this information on a base map first published in 1970, delineated groundwater basins on another copy of the first compilation, and placed both maps on open-file status in Park Service files at Mammoth Cave National Park. A copy of these syntheses is reproduced as Fig. 4 and 5. These maps are introduced here so that subsequent discussion can refer to the various groundwater basins.

Fig. 4 is similar to Fig. 1, but the boundaries of the study area are not shown. The streams that sink along the south and east margin of the Sinkhole Plain have been traced as shown to the Green, Barren, and Little Barren rivers. Much more water tracing is scheduled, particularly in the Hidden River Groundwater Basin.

Fig. 5 shows part of Fig. 4 at a different scale and tentative boundaries of thirteen groundwater basins are shown. These will be referred to in the following sections. The Western Kentucky University Karst Research Team has worked chiefly in caves of the Graham Springs Groundwater Basin (A), the Three-Springs Groundwater Basin (I), the Grady Spring Groundwater Basin (J), and Markum Mill Groundwater Basin (M).

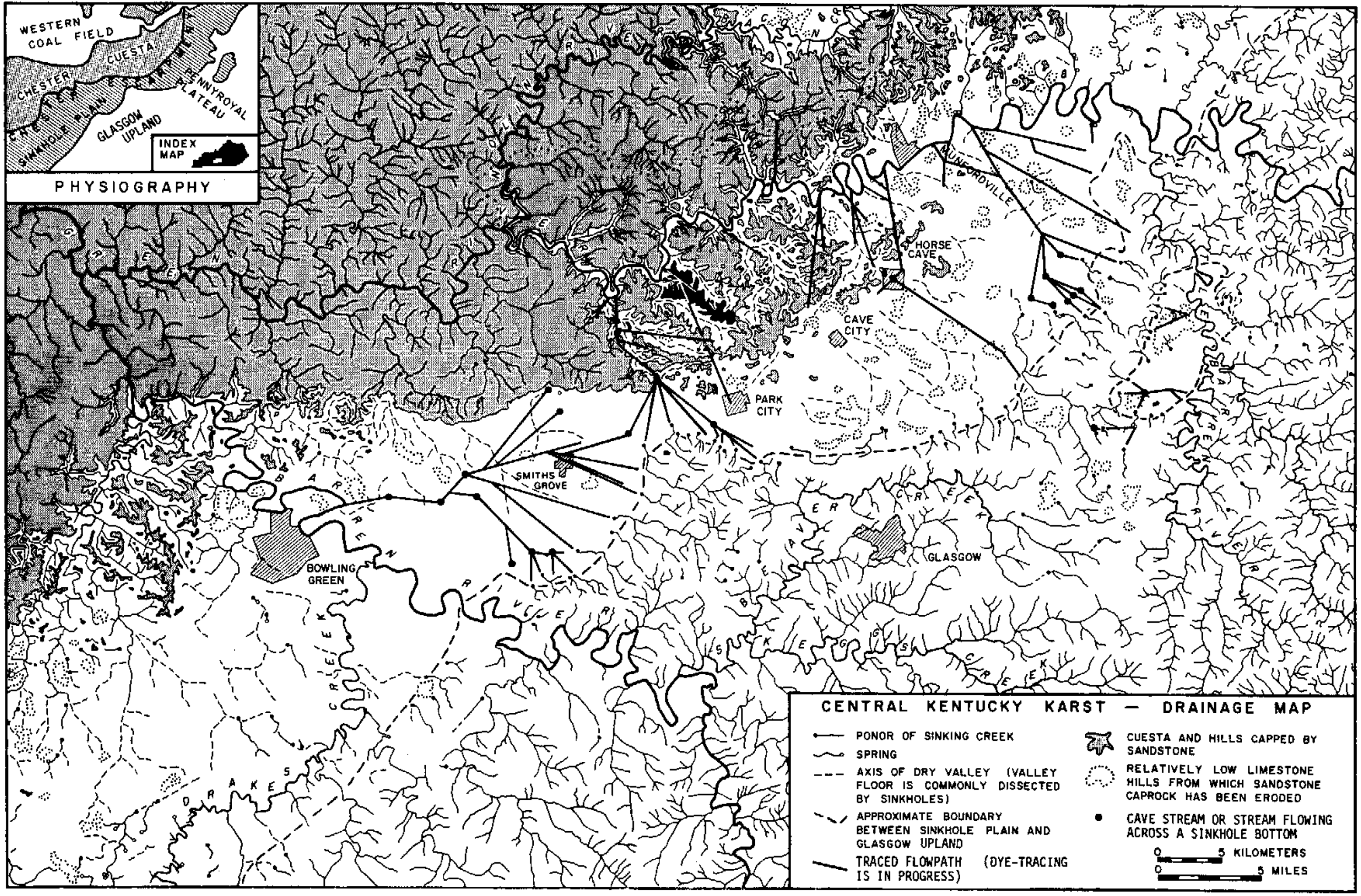
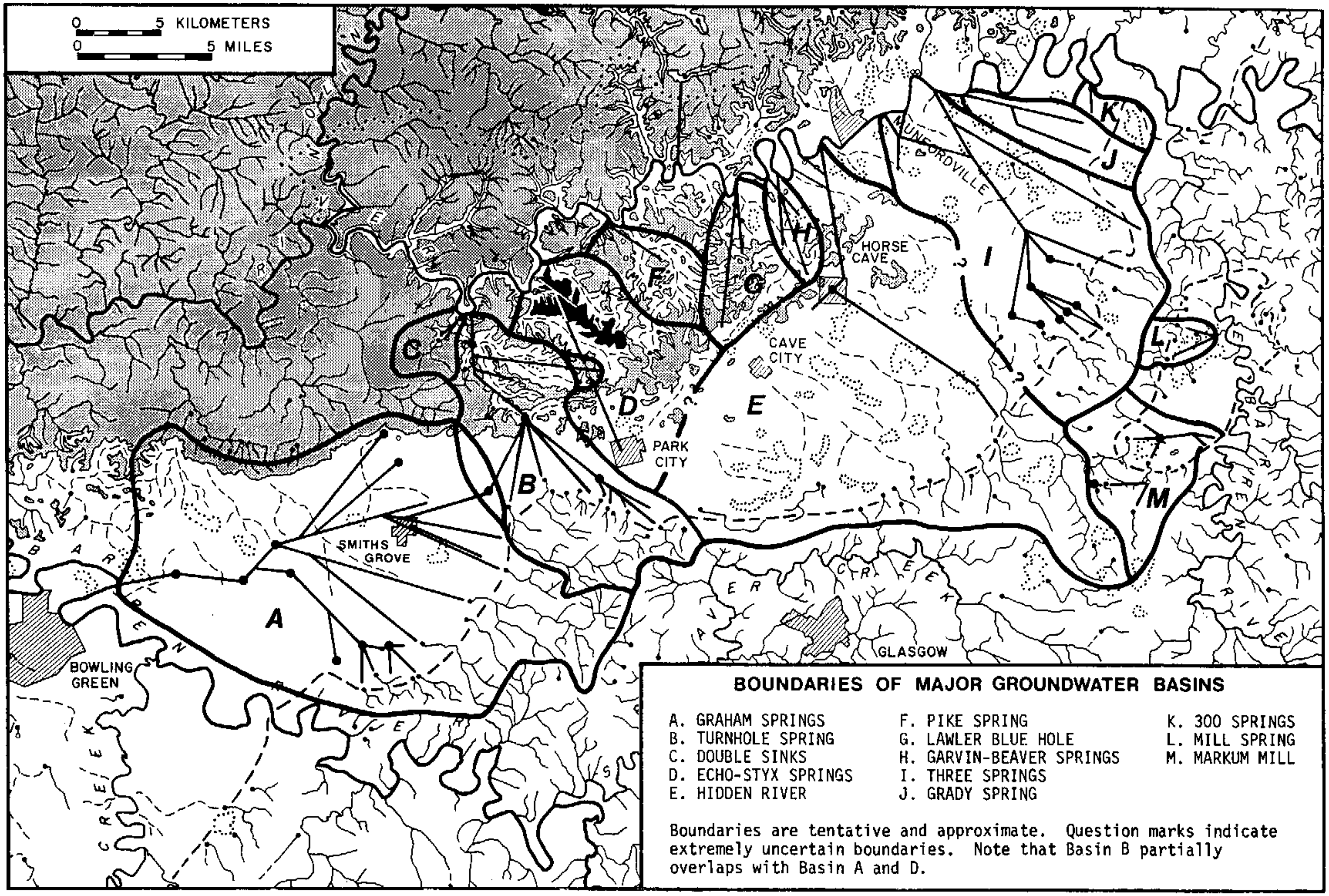


FIGURE 4 - Subsurface drainage as shown by dye traces. Mammoth Cave Ridge is shown in black.



BOUNDARIES OF MAJOR GROUNDWATER BASINS

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

Boundaries are tentative and approximate. Question marks indicate extremely uncertain boundaries. Note that Basin B partially overlaps with Basin A and D.

FIGURE 5 - Groundwater basins delineated as of June 1976. Traces are shown schematically with straight lines.

Uplands Research Lab personnel have worked chiefly in caves of the Turnhole Spring Basin (D) and Pike Spring Basin (F). Both groups have worked in caves of the Hidden River Groundwater Basin (E).

The significance of Fig. 5 and application of its data is discussed beginning on page 82.

In this report only two of the twelve groundwater basins will be discussed in detail -- Hidden River and Graham Springs. A preliminary description of the hydrology of the Turnhole Spring Groundwater Basin (B) has been published by Quinlan (1976).

A brief description of major perennial springs of the Hidden River Groundwater Basin and adjacent basins is given in Table 3.

Hidden River Groundwater Basin

General Description

The discharge point of the contaminated water in Hidden River Cave has long been a matter of speculation. In order to test the hypothesis that sewage effluent that contained optical brighteners (from laundry detergent) and heavy metals should be capable of detection at the spring (or springs) along Green River where it is discharged*, in October 1974 James Quinlan and Mike McCann (a volunteer assistant) sampled a series of nine springs along its south bank, north of Horse Cave. They also placed cotton detectors in the springs. The results

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*This heavy metal anomaly had been predicted by Quinlan. He had suggested to Rowe that a group of Western Kentucky University students doing a National Science Foundation SOS (Student Originated Studies) Project under the latter's supervision during the summer 1974 look for it. The analytical procedures they used were incapable of detecting heavy metals at the low concentrations subsequently found in October. After the anomaly was found, and before another set of data was acquired, Rowe and Quinlan decided to collaborate in this study and seek funding for it. Quinlan was appointed Adjunct Professor in the Department of Engineering Technology and Department of Geography and Geology at Western Kentucky University.

TABLE 3 - Brief description of major perennial springs in the Hidden River Groundwater Basin and adjacent basins

Site	Spring	Base Flow Discharge (cfs)
	Grady Spring Groundwater Basin	
7	Grady Spring. Issues from rubble and flows about 100 ft to Green River. Site of former mill. Fed by Grady Cave, more than 10 miles long.	5-8
	Three Springs Groundwater Basin	
8	Boyd Spring. A group of five springs along river bank, but only one flows perennially. Issues from rubble.	3-4
14	Blue Hole. Spectacular alluviated rise pit in large alcove 250 ft back from river. 30 ft deep.	5-8
16	Dixon Spring. Alluviated rise pit, 300 ft back from river. 30 ft deep (Steve Maegerlein & Clarence Dillon, verbal communication, 1976)	2-3
	Hidden River Groundwater Basin	
23	Gorin Mill Spring. Alluviated rise pit, at least 35 ft deep. 100 ft back from river. Has highest base flow discharge of any spring along south bank of Green River. Site of former mill.	25-30
26	Summer Seat Spring. Group of three springs in an alcove. Issues from rubble.	1
30	Hick Spring. Group of ten springs issuing from rubble at base of cliff. Only one flows perennially during low stages of the river.	.5
38	Blow Hole West Spring. A series of seeps along a 100 ft wide outcrop of bedrock and rubble.	.5
	Garvin-Beaver Groundwater Basin	
39	Garvin Spring. Cave passage at river level.	.5
42	Beaver Spring. Issues from rubble and alluvium along bank.	.25
	Lawler Blue Hole Groundwater Basin	
44	Lawler Blue Hole. Alluviated rise pit, 60 ft deep (Steve Maegerlein & Clarence Dillon, verbal communication, 1976), about 1000 ft from river bank. At least four other higher level springs are part of a distributary complex here.	1-2

were quite surprising. Five of the nine springs were positive for optical brighteners and only these five springs had heavy metals (nickel, chromium, copper and zinc) in concentrations significantly higher than those of the other four springs and the Green River.

The tests were repeated in November at more springs with similar results and one minor anomaly. Beaver Spring (Site 42) was slightly positive for optical brighteners but had no heavy metal anomaly. A comparison and discussion of the heavy metals in the springs and Green River is given in Table 4. The heavy metal anomaly had been shown to be significant and the springs that carried them were dubbed "effluent-bearing springs."

In December another series of samples was taken and a conductivity meter was again used. The heavy metal analyses are plotted on Fig. 6. Upstream from Gorin Mill Spring (Site 23) the specific conductance of the first six springs sampled ranged from 315 to 565 μmhos/cm. But the conductivity of the next seven springs along the south bank, measured beginning at Gorin Mill and travelling downstream, was 420, 420, 423, 420, 420, 419, and 420 μmhos/cm! The first six of these seven* had previously been identified as having heavy metal and optical brightener anomalies. The next five springs measured ranged from 216 to 414 μmhos/cm. Thus there was demonstrated a near-perfect correlation between the occurrance of heavy metal and optical brightener anomalies and uniform conductivities. The only flaw in the perfection was the very slight optical brightener anomaly at Beaver Spring (Site 42).

All operating domestic wells between Horse Cave and the effluent-

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*Previous and subsequent measurements of the conductivity of this seventh spring (Garvin Spring, Site 39) showed that its conductivity was usually significantly less than the group upstream from it.

TABLE 4 - Comparison of analyses for heavy metals present in effluent springs, other springs, and Green River during conditions of moderate spring flow and moderate river flow, November 15, 1974.

COMPARISON OF MEANS OF HEAVY METAL CONCENTRATIONS						
Sample Site	GROUNDWATER BASINS					
	Hidden River Effluent-Bearing Springs (ES)	Grady Spring (GS)	Three Springs (3S)	Garvin-Beaver (G-B)	Lawler Blue Hole (L)	Green River (GR)
	Analysis	RATIOS				
Metal	ES (mg/l)	$\frac{ES}{GS}$	$\frac{ES}{3S}$	$\frac{ES}{GB}$	$\frac{ES}{L}$	$\frac{ES}{GR}$
Nickel	.047	11.8	12.7	13.4	15.7	7.8
Chromium	.012	6.7	5.5	8.4	10.9	7.5
Copper	.009	4.5	2.4	4.5	4.5	3.0

INTERPRETATION: On November 15, 1974 the nickel content of effluent-bearing springs was 11.8 to 15.7 times greater than that of the two groundwater basins immediately upstream and downstream and 7.8 times greater than in the Green River. For chromium the range was 5.5 to 10.9; Green River was exceeded by 7.5. For copper the range was 2.4 to 4.5; Green River was exceeded by 3.0. The chromium content of the effluent-bearing springs is 24% of the allowable maximum of .05 mg/l for drinking water.

bearing springs were located and sampled. The lack of anomalous heavy metal concentrations and the very low Ca/Mg ratio of these shallow wells as well as the lack of bacterial contamination in them (Branstetter, 1974) indicated that they did not penetrate the conduit system conveying effluent to the Green River and suggested that there was no connection between the wells and the conduit system. Subsequent re-sampling and analysis of some of these wells confirmed this interpretation.

Springs were again sampled in December 1974. The results for nickel, chromium and copper are shown in Fig. 6 and discussed in the interpretation of it. The legend identifying the sample sites is given in Table 5.

The sites sampled at Horse Cave, the effluent-bearing springs along Green River, and the sampled wells in the area between are shown in Fig. 7. They are identified by name in Table 2. The large ridge just north of Horse Cave is uninhabited; there are no wells there. Most families are serviced by the Green River Valley Water District or they rely on rainwater stored in cisterns.

Field observations made during river stages ranging from low flow to high flood, chemical analyses, and specific conductance measurements made during the past 18 months have showed that the effluent-bearing water from Hidden River Cave emerges at Green River at 39 springs at 14 locations over a 5-mile reach of the river. Quinlan et al. (1975), in an abstract written in March, concluded that the conduit-flow system of the cave and springs is largely independent of the diffuse-flow system that is intercepted by the wells. They also predicted the existence of a cave system that included a complex of at least 34 distributary springs that is 3 km wide -- 3 times wider and much more complicated than any other known in the Central Kentucky Karst. This conjectured cave system -- to be discussed subsequently -- was thought to feed every spring along the Green River, from Gorin Mill to Blow Hole West! Another of the reasons for predicting its existence was the uniformity of heavy metal concentrations at each of the effluent-bearing springs on a given day.

In order to test this hypothesis and gain access to this cave, project personnel during June 1975, with the permission of a land-owner, excavated rocks from the orifice of an intermediate-level spring at Site 31 (Hick Spring) but were stopped by a pool of water. They then dug at a nearby high-level spring and worked their way down about 10 ft to a 6 x 6 ft passage with 2 ft of water. This led to a river passage 10 ft high and 20 ft wide. The saga of the mapping of this cave system will not be given here. From June until September 1975, 13.33 miles of passage were mapped; more than 100 passages remained to be checked and mapped. An outline map of the cave, subsequently named the Hidden River Complex, is included on Figs. 7 and 19 and the location of sampled wells relative to known cave passages can be seen. A brief description of this cave and its hydrology is given after the following discussion on the chemistry of the spring waters.

Fig. 8 summarizes distinctive chemical properties (exclusive of heavy metals) of springs in the Hidden River Groundwater Basin, adjacent groundwater basins, wells, and the Green River -- at two different flow conditions, low and moderate. Most of the discussion of it and other graphs will not be repeated within the body of this report.

Table 6 is a summary of the chemical analyses at various sites within the Hidden River Groundwater Basin and at relevant adjacent sites.

FIGURE 6 - Concentration of nickel, chromium, and copper in springs, cave streams, and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, and Green River, December 20, 1975. The location of the various sites is shown in Fig. 3. Some are also shown in Fig. 7. Explanation of sample site symbols is given in Table 5.

DESCRIPTION: Concomitantly with the study of water quality, dye-tracing and field observations have made it possible to differentiate between the various groundwater basins and demonstrate the existence of a distributary spring system in the Three-Springs, Hidden River, Garvin-Beaver, and Lawler Blue Hole basins. The tentative boundaries of the groundwater basins are shown in Fig. 5. The springs that discharge diluted effluent-bearing water derived from Hidden River Cave are hereafter referred to as "effluent-bearing springs."

INTERPRETATIONS: The effluent-bearing springs of the Hidden River Groundwater Basin have a nickel, chromium, and copper content that is significantly higher than that of other springs and the Green River. Specifically, for the day sampled, their mean nickel, chromium, and copper content was 5.0, 5.8, and 2.7 times greater than that of the mean of the four other groundwater basins and 3.0, 11.7, and 2.6 times that of the Green River (Sites 6 and 43). Effluent from the sewage treatment plant (Site STP-E) contributes to the flow of the South Branch of Hidden River Cave (Site HRC-S). It mixes with water from the East Branch (Site HRC-E) where the flow is estimated to be 10 to 40 times greater (depending upon stage), and ultimately discharged at the effluent-bearing springs along Green River, 4-5 miles away. The nickel and chromium content of the effluent-bearing springs is significantly higher than that of the wells but their copper content is slightly less than that of the wells. The slightly higher copper content of the wells might be related to copper in their plumbing. It is not significant.

NOTE: Each of the subsequent 11 graphs is accompanied by a separately written description and interpretation. Some are accompanied by a description that generally applies also to other graphs but the descriptions of the regional hydrology relevant to the interpretation of all graphs will not be repeated. Generally the interpretations will not be repeated within the body of the report.

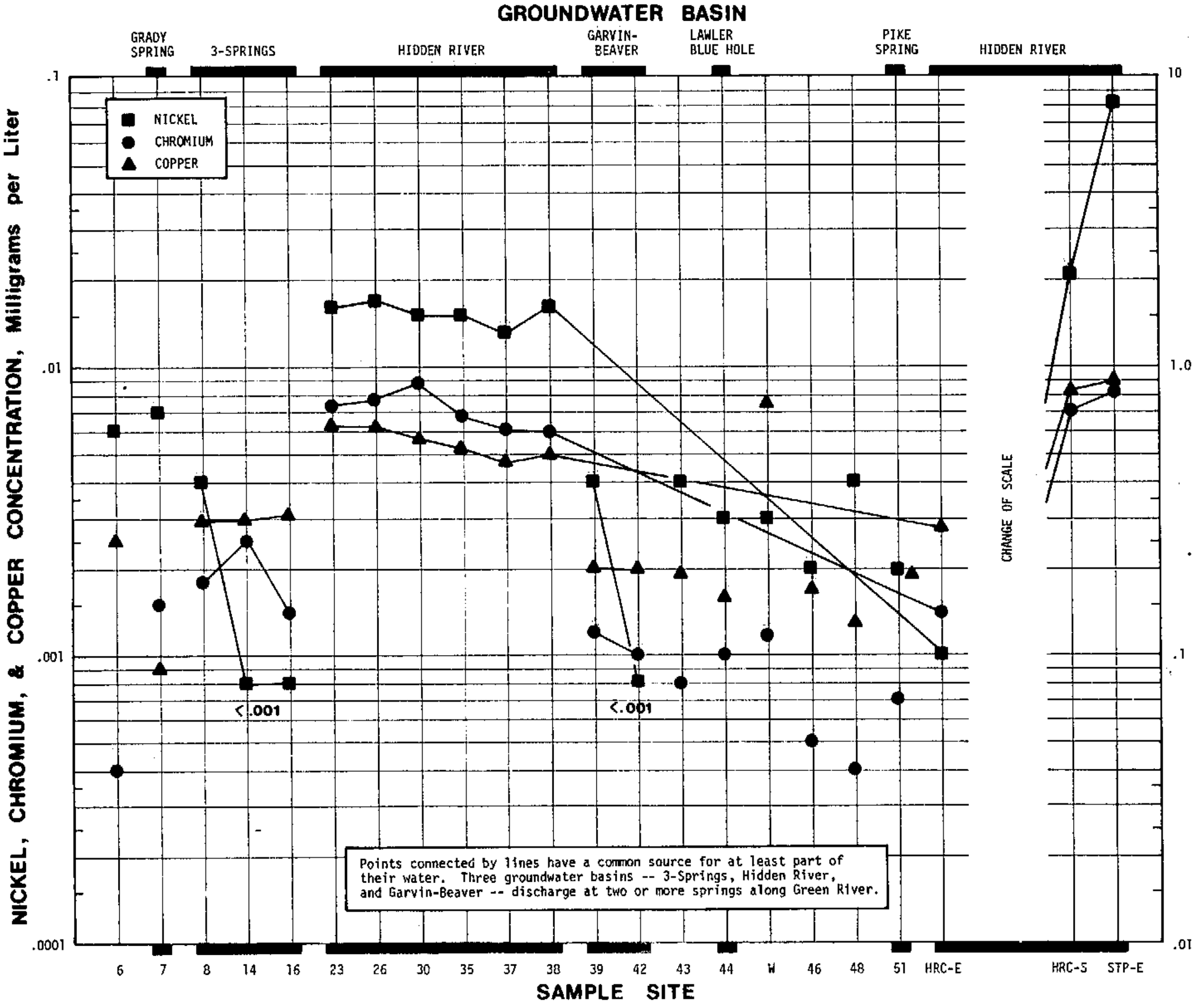

GROUNDWATER BASIN
GRADY SPRING
3-SPRINGS
HIDDEN RIVER
GARVIN-BEAVER
LAWLER BLUE HOLE
PIKE SPRING
HIDDEN RIVER
■ NICKEL
● CHROMIUM
▲ COPPER
NICKEL, CHROMIUM, & COPPER CONCENTRATION, Milligrams per Liter
.1
.01
.001
.0001
10
1.0
.1
.01
<.001
<.001
CHANGE OF SCALE
Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.
6
7
8
14
16
23
26
30
35
37
38
39
42
43
44
W
46
48
51
HRC-E
HRC-S
STP-E
SAMPLE SITE

TABLE 5 - Legend for site numbers, flow conditions, and symbols on Figs. 6 and 9 through 18. (Continued on next page)

	SELECTED SAMPLE SITES
Site #	Site Name
6	Green River, above Grady Spring
	GRADY SPRING GROUNDWATER BASIN
7	Grady Spring
	THREE SPRINGS GROUNDWATER BASIN
8	Boyd Spring
14	Blue Hole
16	Dixon Spring
	HIDDEN RIVER GROUNDWATER BASIN
23	Gorin Mill Spring
26	Summer Seat Spring
30	Hick Spring
31	Five-Finger Springs
34	Alcove Springs
36	Natural Tunnel Springs
37	Blow Hole East
38	Blow Hole West
	GARVIN-BEAVER GROUNDWATER BASIN
39	Garvin Spring
42	Beaver Spring
43	Green River, above Lawler Blue Hole
	LAWLER BLUE HOLE GROUNDWATER BASIN
44	Lawler Blue Hole
W	Shallow water wells within the Hidden River Groundwater Basin and adjacent basins
46	McCoy Spring
48	Mile 205.7 Spring
	PIKE SPRING BASIN
51	Pike Spring West
	HIDDEN RIVER GROUNDWATER BASIN
HRC-E	Hidden River Cave, East Branch
HRC-S	Hidden River Cave, South Branch
STP-E	Horse Cave Wastewater Treatment Plant, Effluent
STP-I	Horse Cave Wastewater Treatment Plant, Influent

TABLE 5 (Continued)

Symbol on Graphs	Date	Gage Reading @ Mammoth Cave Ferry (feet)	Discharge @ Munfordville (cfs)	Suspended Sediment (mg/l)	Flow Conditions of River
△	10/01/74	7.1	2,420 F	42	C
▲	11/15	5.7	4,760 C	37	C
⬭	12/20	6.1	2,710 F	15	C
⬬	12/25	9.5	4,650 R	133	D
◇	1/20/75	11.8	6,920 F	54	D
◆	2/26	12.2	5,850 F	57	D
○	3/29	24.5	18,900 R	340	E
●	4/17	13.6	7,070 F	57	D
□	5/03	12.5	5,720 F	51	D
■	5/21	6.8	2,100 F	41	C
⬯	6/19	2.7	718 C	34	B
◊	6/29	2.2	476 R	33	A

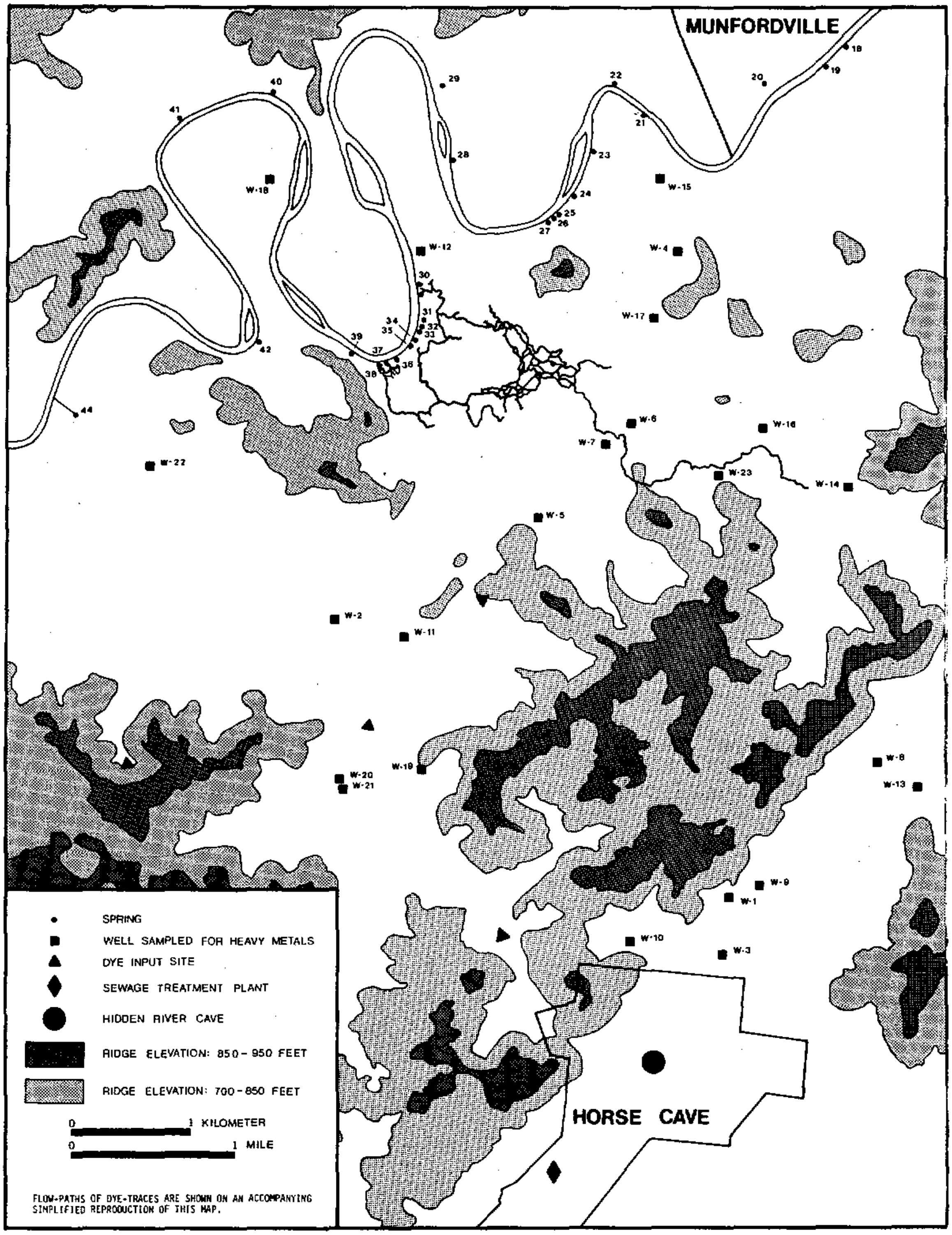
NOTES

1. Location of all sites is shown on Fig. 3. Many sites are also shown on Fig. 7.
2. Discharge and suspended sediment data is cited from U. S. Geological Survey Water Data Report Ky-75-1. F, C, and R indicate that the river was falling, cresting, or rising.
3. Flow conditions on Green River, indicated by letters, are based on the following arbitrary limits:

A	200- 699 cfs	Very Low
B	700- 1,999 cfs	Low
C	2,000- 4,499 cfs	Moderate
D	5,000- 9,999 cfs	Moderate Flood
E	10,000-24,999 cfs	High Flood
F	25,000+ cfs	Extreme Flood

Flow for individual springs is considerably less but may exceed 150-200 cfs. During floods, spring hydrographs are out of phase with that of the river and are complicated by the fact that all springs may be back-flooded by the river. The release of water from Green River Lake, 79 miles upstream from the USGS gaging station at Munfordville, creates a second flood pulse that may also cause back-flooding of springs for either the first of second time during a given flood.

4. Numerous samples from sites HRC and STP were taken on various other dates during the month indicated.
5. Sites 46, 48, and 51 are shown only on Fig. 6.



FLOW-PATHS OF DYE-TRACES ARE SHOWN ON AN ACCOMPANYING SIMPLIFIED REPRODUCTION OF THIS MAP.

FIGURE 7 - Detailed map of the area between Horse Cave and the Green River. Wells and springs are identified on Table 2.

Evaluation of it is made easier by study of Table 7, wherein the ratios between chemical properties are compared for various sites and basins. Figs. 9 through 18 graphically summarize the chemical analyses made for the period October 1974 through June 1975. Each graph is accompanied by a description and interpretation. Other analyses of samples collected since 1976 during low base flow of the springs, are being run. They will be discussed in the Phase II report. Table 8 summarizes bacterial quality and nitrate concentration of several sites along Green River. Table 9 summarises the extent to which wastewater treatment plant effluent and Hidden River Cave water exceeds maximum limits for heavy metals in public water supplies and fish habitats. Table 10 gives dilution ratios.

What do all these graphs and tables tell us? Many things, some obvious and some not so obvious. To summarize:

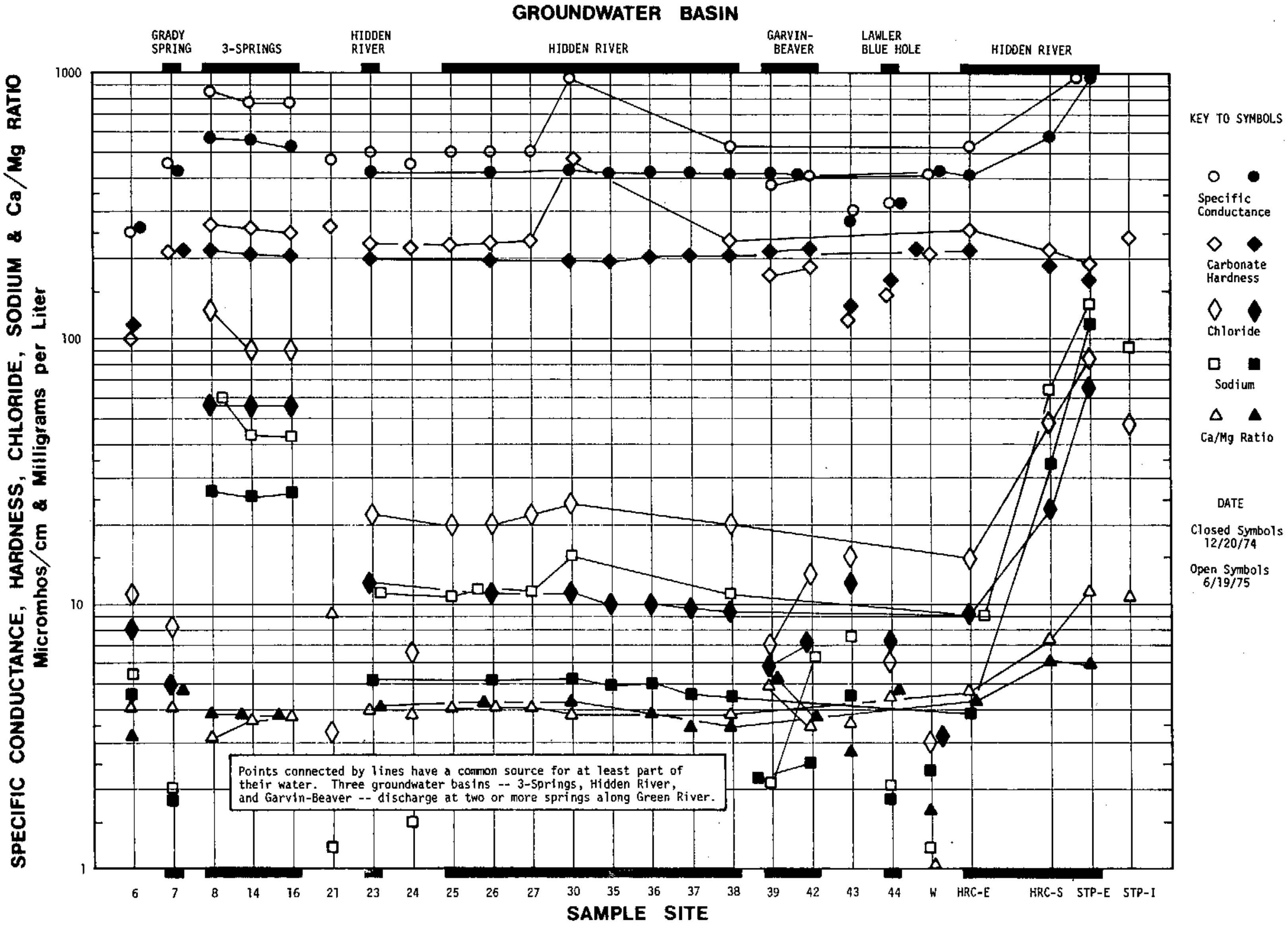
1. The chromium concentration of the effluent-bearing springs (those which discharge diluted wastewater effluent derived from Hidden River Cave) reaches a maximum of 0.015 mg/l but the mean is 0.005 mg/l. This mean is 4.0 times greater than that of the mean of four adjacent groundwater basins, 6.5 times that of the Green River and 3.7 times that of shallow domestic water wells, as shown in Tables 6 and 7.
2. The nickel concentration of the effluent-bearing springs reaches a maximum of 0.058 mg/l but the mean is 0.018 mg/l. This mean is 5.1 times greater than the mean of four adjacent groundwater basins, 4.2 times that of the Green River, and 9 times that of shallow domestic water wells, as summarized in Tables 6 and 7. Similar statements can be made about the concentrations of copper and zinc but their means

FIGURE 8 - Distinctive chemical properties (exclusive of heavy metals) characteristic of springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent. Site locations are shown in Fig. 3; many are also shown in Fig. 7. Symbols for sites are in Table 5.

DESCRIPTION: Same as that of Fig. 6. This shows values for specific conductance, carbonate hardness, chloride, sodium, and calcium/magnesium ratio during low river flow accompanied by low base flow of springs (June 19, 1975; open symbols) and moderate river flow accompanied by moderate base flow of springs) (December 20, 1974; closed symbols). The properties of water in the Hidden River Groundwater Basin are traced from where wastewater treatment plant effluent first enters the ground by a sinkhole (Site STP-E) to where it is discharged along Green River. The effluent-bearing springs are a mixture of flow from the South Branch and East Branch of Hidden River plus input from various other sources. Gaging of springs and Hidden River Cave during low base flow conditions has shown that the total discharge in Hidden River Cave (6.8 cfs) is only about 25% of the discharge of the effluent-bearing springs (28 cfs at Gorin Mill Spring (Site 23) and an estimated total of 1 cfs at all other effluent springs). It is impossible to measure discharge of the effluent-bearing springs during high flood stage but an aggregate discharge of 1000 to 1500 cfs is believed possible.

INTERPRETATIONS:

1. Specific conductance, carbonate hardness, chloride, and sodium of the Three-Springs Groundwater Basin is significantly higher than that of the others, Green River, and wells. (Sulphate was not determined.)
2. During moderate base flow of the effluent-bearing springs the chemical composition of their waters is surprisingly uniform; it is also different from that of the other groundwater basins and wells.
3. During low base flow conditions the composition of Hick Spring (Site 30) is remarkably different from that of the other effluent-bearing springs. Mapping of the distributary cave passages behind this and adjacent springs west of it has shown that Hick Spring is also fed by a small tributary passage that discharges less than .1 cfs of brine presumably derived by upward seepage from an old oil well about 200 ft away (Point D, Fig. 20). No complete analysis was made of this brine but it smelled of hydrogen sulphide and had a sulphate content of 760 mg/l (July 15, 1975). During low base flow of this spring, this brine significantly alters the composition of the distributary stream that feeds it.
4. The composition of the water in both springs of the Garvin-Beaver distributary is less uniform than the composition of water in springs of distributary systems in other groundwater basins, presumably because of local recharge that doesn't go to both springs.
5. The small spring (Site 21) immediately east of Gorin Mill Spring (Site 23) is clearly not part of the Hidden River Drainage Basin, as indicated by the significant differences between their chemical properties. Similarly, the composition of the small spring at Site 24 -- between the two effluent-bearing springs (Gorin Mill and Spring Seat) -- shows that it drains a separate (smaller) basin that is not part of the Hidden River Groundwater Basin but is within it.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

TABLE 6 - Summary of chemical analyses (mean, maximum and minimum) at relevant sites.

SAMPLE SITE / CHEMICAL PROPERTY & LIMITS**		GROUNDWATER				
		HIDDEN RIVER				
		Effluent-Bearing Springs	Hidden River Cave East Branch	Hidden River Cave South Branch	Horse Cave Wastewater Treatment Plant, Eff.	Grady Spring
Chromium 5.0 (.05)	Mg/l (Heavy metal values rounded off to nearest .001)	.015 .005 .001	.008 .003 .002	8.90 2.73 .202	4.75 3.48 .810	.002 .001 .001
Nickel 5.0		.057 .018 .008	.013 .007 .001	19.4 4.13 1.15	12.2 9.22 6.21	.007 .004 .002
Copper .02 (1.0)		.011 .005 .003	.007 .004 .002	1.17 .584 .130	4.72 2.28 .895	.005 .002 .001
Zinc .3 (5.0)		.020 .009 .001	.021 .009 .004	2.12 .841 .074	.952 .652 .396	.006 .005 .005
Chloride		24.0 11.5 3.6	15.0 10.0 6.6	48 26.2 11	110 81.8 .35	8.2 5.2 4.0
Sodium		15.0 5.79 1.50	9.00 4.81 2.70	197 54.6 28.0	480 165 70.0	2.00 1.71 1.22
Potassium		2.18 1.27 .92	1.74 1.15 .68	54.0 13.2 2.95	114 41.1 4.45	1.61 1.07 .67
Carbonate Hardness		463 206 121	255 214 180	288 200 179	200 163 110	226 200 159
Ca/Mg Ratio		5.86 4.63 3.18	5.49 4.68 4.23	8.13 6.34 3.86	11.17 6.31 .934	6.39 5.09 4.12
Specific Conductance		540* 420 210	520 422 379	670 522 299	1350 1166 960	458 395 330
No. of Sample Sites		13	1	1	1	1
Average total no. of samples		36	8	8	10	5

**The first figure in column 1 is the concentration fatal to some fish (Cheremisinoff et al. 1976). The figure in parentheses is the maximum allowed by State and/or Federal standards for public water supplies.

BASINS				Green River	Shallow Water Wells	Horse Cave Wastewater Treatment Plant, Influent
OTHER						
Three Springs	Garvin-Beaver	Lawler Blue Hole	Mean of 3 Basins other than 3-Springs			
.003 .002 .001	.002 .001 <.001	.002 .001 <.001	.002 .001 <.001	.002 <.001 <.001	.003 .001 <.001	21.7 7.33 .156
.005 .003 <.001	.005 .004 .003	.004 .003 .003	.007 .004 .001	.005 .004 <.001	.004 .002 <.001	27.2 12.9 .198
.006 .003 .002	.002 .002 .002	.004 .002 .001	.006 .002 .001	.003 .002 .001	.021 .007 .003	5.36 1.64 .090
.012 .005 .027	.003 .003 .003	.011 .005 .002	.011 .004 .002	.012 .006 .002	not analyzed	11.9 2.21 .220
128 49.9 13	13 5.8 3.2	7.6 5.6 2.9	13 5.6 2.9	15 9.2 6.1	5.6 3.81 2.5	216 94.2 35
76 29.0 4.6	6.36 2.57 1.56	2.65 1.65 1.00	636 2.0 1.00	7.5 3.89 2.4	3.25 1.68 .82	213 148 60.5
2.16 1.43 1.07	1.83 0.97 0.58	1.81 1.08 .60	1.83 1.0 .58	1.71 1.15 .70	1.27 .66 .39	59.0 32.1 10.6
325 213 147	248 189 166	183 151 129	----	.32 105 73	245 212 185	279 197 130
5.06 4.18 3.15	9.21 6.29 3.46	8.77 6.39 4.41	----	5.04 3.71 2.78	3.88 1.56 .86	10.68 7.49 4.25
865 543 320	420 381 328	355 303 252	----	300 250 173	490 426 360	8000+ 2434 715
3	2	1	7	2	14	1
17	11	7	23	18	17	13

*This maximum for Specific Conductance does not include the 945 value caused by local seepage of brine into a single spring (Hick).

TABLE 7 - Comparison of means of chemical analyses of effluent-bearing springs with those of other relevant sites

SAMPLE SITE CHEMICAL PROPERTY	Mean analysis of effluent-bearing springs in the Hidden River Groundwater Basin, along the South Bank of Green River (ES)	GROUNDWATER			
		HIDDEN RIVER			
		Hidden River Cave, East Branch (HRC-E)	Hidden River Cave, South Branch (HRC-S)	Hidden River Cave South Br. & East. Br. (HRC-S, HRC-E)	Horse Cave Wastewater Treatment Plant, Effluent (STP-E)
		RATIOS			
		ES / HRC-E	STP-E / HRC-S	HRC-S / HRC-E	STP-E / ES
Chromium	.005 mg/l	1.8	1.3	940	670
Nickel	.018 mg/l	2.6	2.2	590	512
Copper	.005 mg/l	1.2	3.9	140	450
Zinc	.009 mg/l	1.0	.78 (2.7)	98	77 (209)*
Chloride	11.6 mg/l	1.2	3.1	2.6	7.1
Sodium	5.8 mg/l	1.2	3.0	11.4	28
Potassium	1.3 mg/l	1.1	2.8	11.5	32
Carbonate Hardness	206 mg/l	1.0	Mean of all but zinc ratios is 2.7. This mean is assumed for zinc.	.9	.8
Ca/Mg Ratio	4.63	1.0		1.4	1.4
Specific Conductance	420 µmhos/cm	1.0		1.2	2.8

* Calculated from assumed STP-E/HRC-S ratio of column 4.

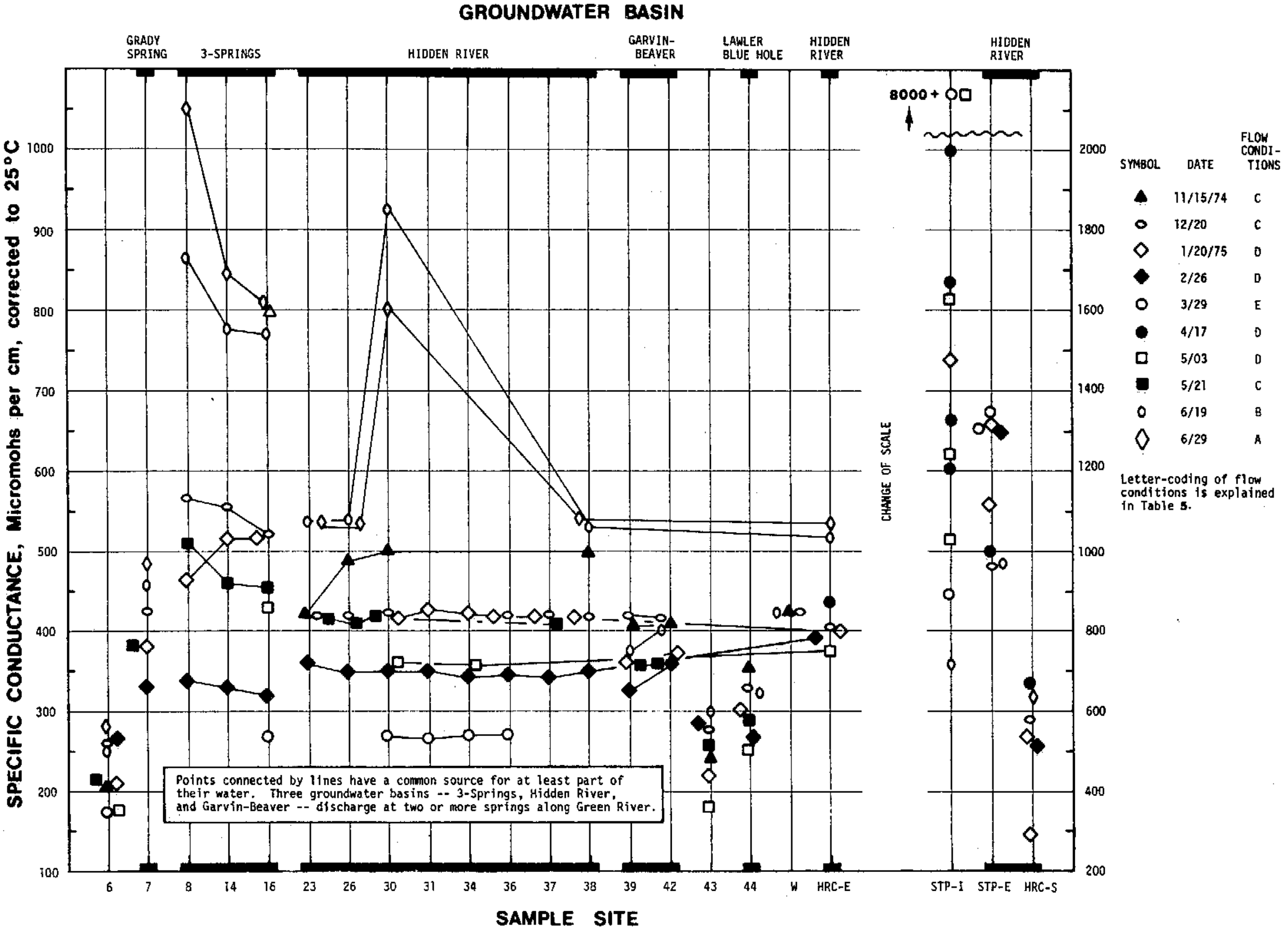
BASINS					Green River (GR)	Shallow Water Wells (W)
OTHER						
Grady Spring (GS)	Three Springs (3S)	Garvin-Beaver (GB)	Lawler Blue Hole (L)	Mean of 3 Basins other than 3-Springs (3B)		
(Rounded off, for Clarity)						
$\frac{ES}{GS}$	$\frac{ES}{3S}$	$\frac{ES}{GB}$	$\frac{ES}{L}$	$\frac{ES}{4B}$	$\frac{ES}{GR}$	$\frac{ES}{W}$
4.0	3.3	4.0	5.8	4.6	6.5	3.7
4.5	5.8	4.9	6.0	5.1	4.2	9.0
2.1	1.8	2.6	2.4	2.4	2.4	.8
1.6	1.6	3.0	1.8	2.1	1.4	--
2.2	1.1	2.0	2.1	2.1	1.3	3.0
3.4	.2	2.3	3.5	2.9	1.4	3.5
1.2	.9	1.3	1.2	1.3	1.1	1.9
1.0	1.0	1.1	1.4	--	2.0	1.0
.9	1.1	.7	.7	--	1.3	3.0
1.1	.8	1.1	1.4	--	1.7	1.0

FIGURE 9 - Specific conductance of water in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8. The general uniformity of conductivity of other effluent-bearing springs in the Hidden River Basin and anomalously high conductivity of Hick Spring (Site 30) during conditions of low flow has been discussed in Interpretation no. 2 of Fig. 8.

INTERPRETATIONS:

1. The relatively low specific conductance of Gorin Mill Spring (Site 23) in November may indicate local recharge from a local sub-basin east of the spring.
2. The specific conductance of springs in the distributary of the Three-Springs Groundwater Basin is not uniform, suggesting local inputs of chemically different waters, but it is usually higher than that of other springs. Boyd Spring (Site 8) generally has the highest specific conductance of any spring along the Green River. These high conductivities, the relatively high sodium and chloride content of these springs, and the dye tests shown in Fig. 5 suggest mixing with oil well brine from the LeGrande Field, other shallow oil and gas fields, and uncased exploration holes within the Three-Springs Groundwater Basin. Seepage from uncased water wells that penetrate rock with saline water could also be a cause.
3. The high specific conductance of water in the South Branch of Hidden River Cave is caused by partial dilution of the wastewater treatment plant effluent that is discharged into the ground at the plant.
4. As would be expected, there is much more variation in the character of the wastewater treatment plant influent than for the effluent.
5. The specific conductance in the East Branch of Hidden River Cave (Site HRC-E) in the February samples is slightly higher than in the effluent-bearing springs. This is because the cave stream samples were collected 2 days later and the flow was rapidly receding after a heavy rain 4 days before.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

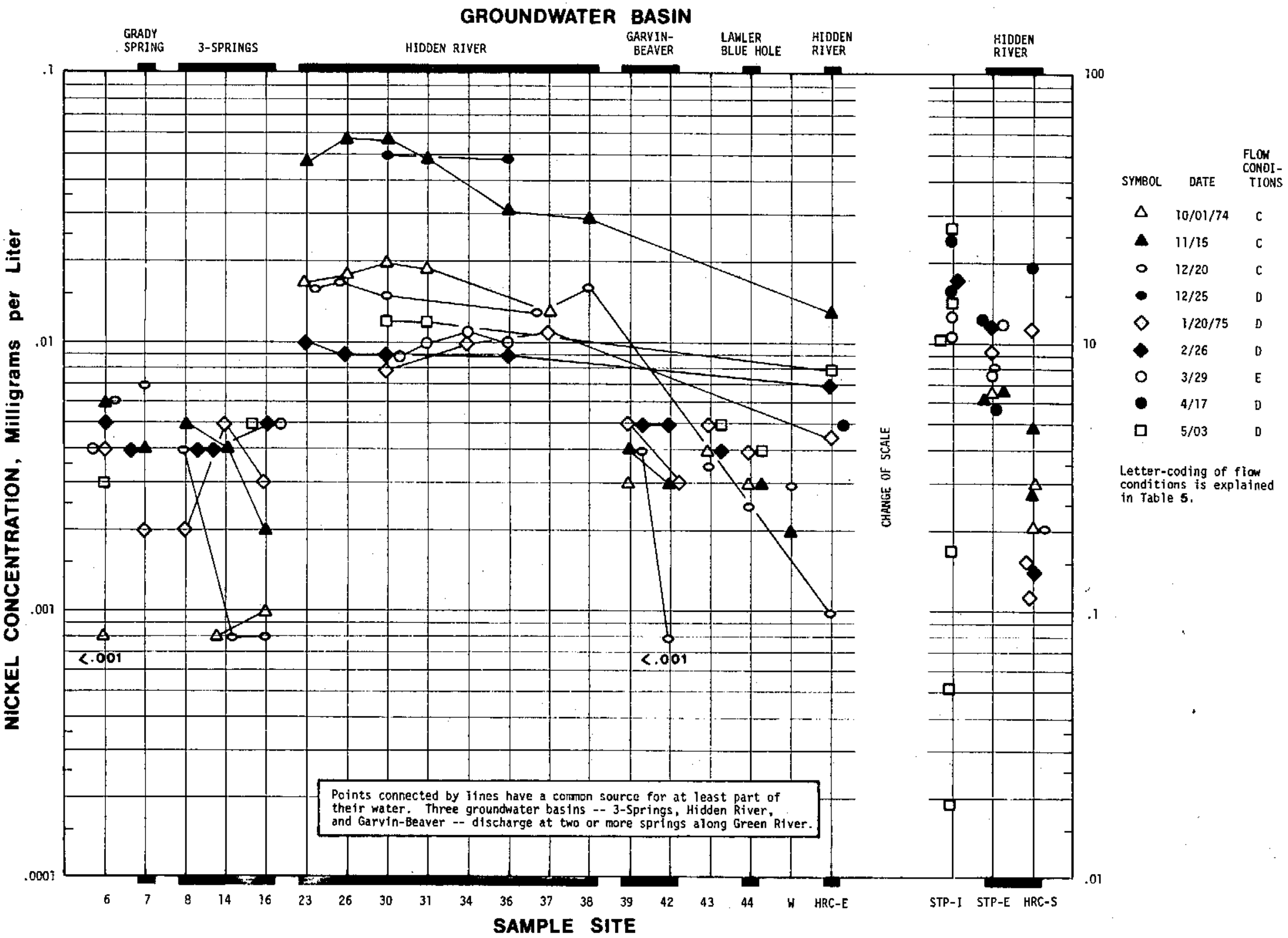
Letter-coding of flow conditions is explained in Table 5.

FIGURE 10 - Concentration of nickel in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8. There is no maximum limit for nickel in the current federal standards for public water supplies but the nickel content of wastewater effluent discharged into the ground at Site STP-E almost always exceeds the levels known to be toxic to some fish (5.0 mg/l). Such high levels are only occasionally achieved in the South Branch of Hidden River Cave. A graphic summary of how often the limits for various heavy metals are exceeded by treatment plant effluent and in the South Branch of Hidden River Cave, and the sources for these limits, is given in Table 9.

INTERPRETATIONS:

1. Nickel concentrations as high as those present in the wastewater treatment plant influent and effluent are usually derived from a metal-plating industry.
2. The nickel content of the effluent-bearing springs is significantly higher than that of springs in adjacent groundwater basins, wells, or the Green River.
3. The nickel content of the January, February and May samples from the East Branch of Hidden River Cave (Site HRC-E) is higher than that of springs in adjacent groundwater basins and wells but not very much lower than that of the effluent-bearing springs. There are several possible explanations for this but most likely it is due both to:
   A. Contamination of the East Branch by water in a slightly higher passage sub-parallel to the South Branch that is inaccessible to people because of collapse and aesthetic reasons.
   B. A smaller dilution factor when both branches are flowing with high discharges. A dye test has proven that contamination of the East Branch by the South Branch, by flow beneath the talus that separates them, occurs during very low stages.
4. The nickel content of springs outside of the Hidden River Basin is not significantly different from that of the Green River. It is slightly higher than that of water in shallow wells.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

Letter-coding of flow conditions is explained in Table 5.

FIGURE 11 - Concentration of chromium in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Fig. 6 and 8. The chromium content of wastewater effluent discharged into the ground at the treatment plant always exceeds the maximum allowed for public water supplies but doesn't exceed or rarely exceeds levels known to be toxic to some fish. See also the summary of metal toxicity that comprises Table 9 and the discussion of metal toxicity that begins on p. 65.

INTERPRETATIONS:

1. Chromium concentrations as high as those present in the wastewater treatment plant influent and effluent are usually derived from a metal-plating industry.
2. The chromium concentration is significantly higher in the effluent-bearing springs than in other springs, wells, and the Green River. The ratios between means of these different analyses at various sites are given in Table 7 and won't be summarized here.
3. The reasons for the suspicious similarity of the chromium concentrations in the effluent-bearing springs with those in the East Branch of Hidden River Cave are discussed in Interpretation no. 3 of Fig. 10. If the proposed explantion or a similar explanation were not correct one would be forced to conclude that the East Branch is also a major source of heavy metals -- even though there are no known probable sources for them in its recharge area.
4. The mean copper content of the wastewater treatment plant effluent is greater than that of its influent but this imbalance is attributed to greater variation in the quality of the influent and the statistical problems of adequately sampling for them. This lack of mass balance does not affect our conclusions about the flow to the effluent-bearing springs and their properties.

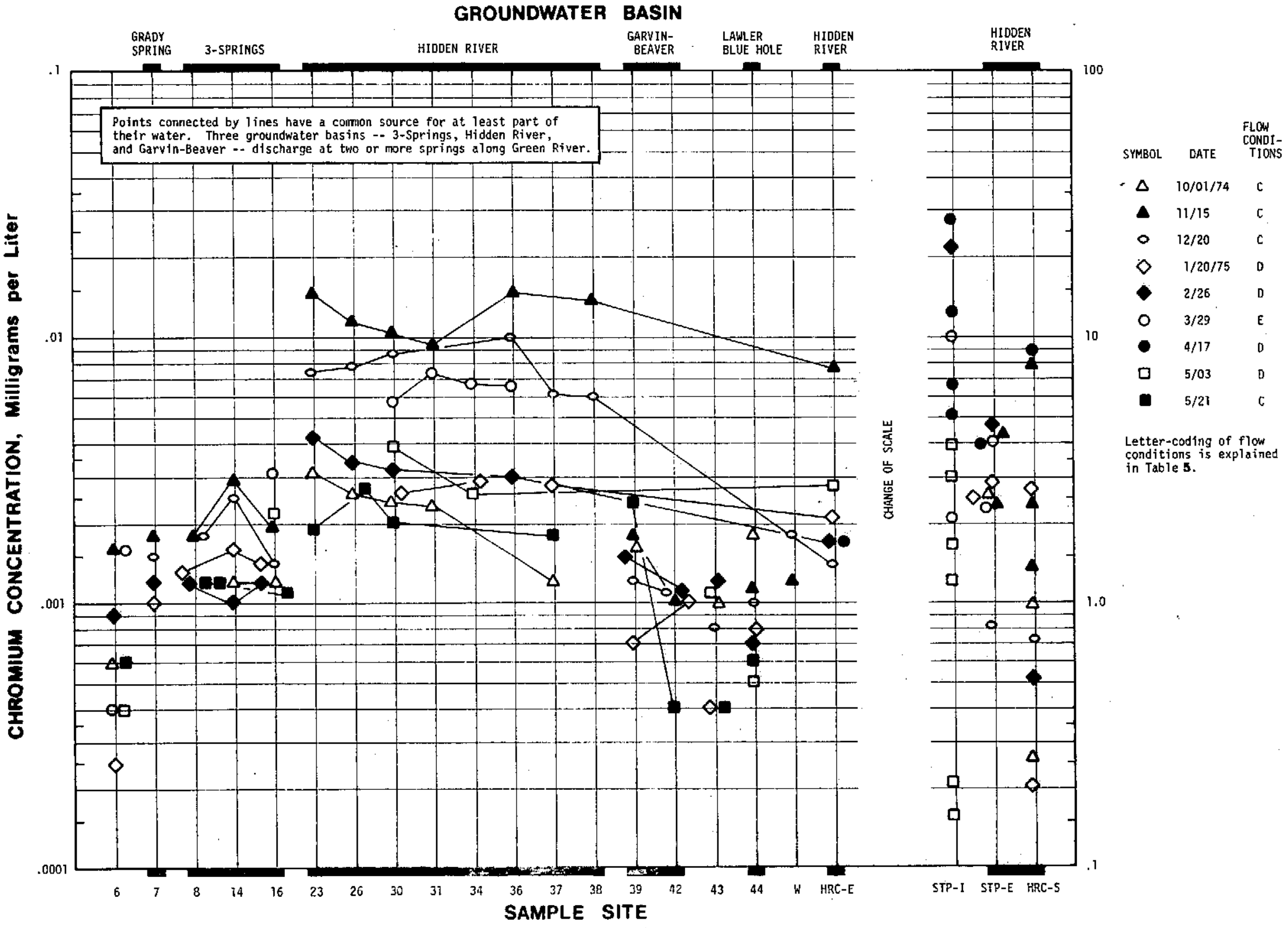
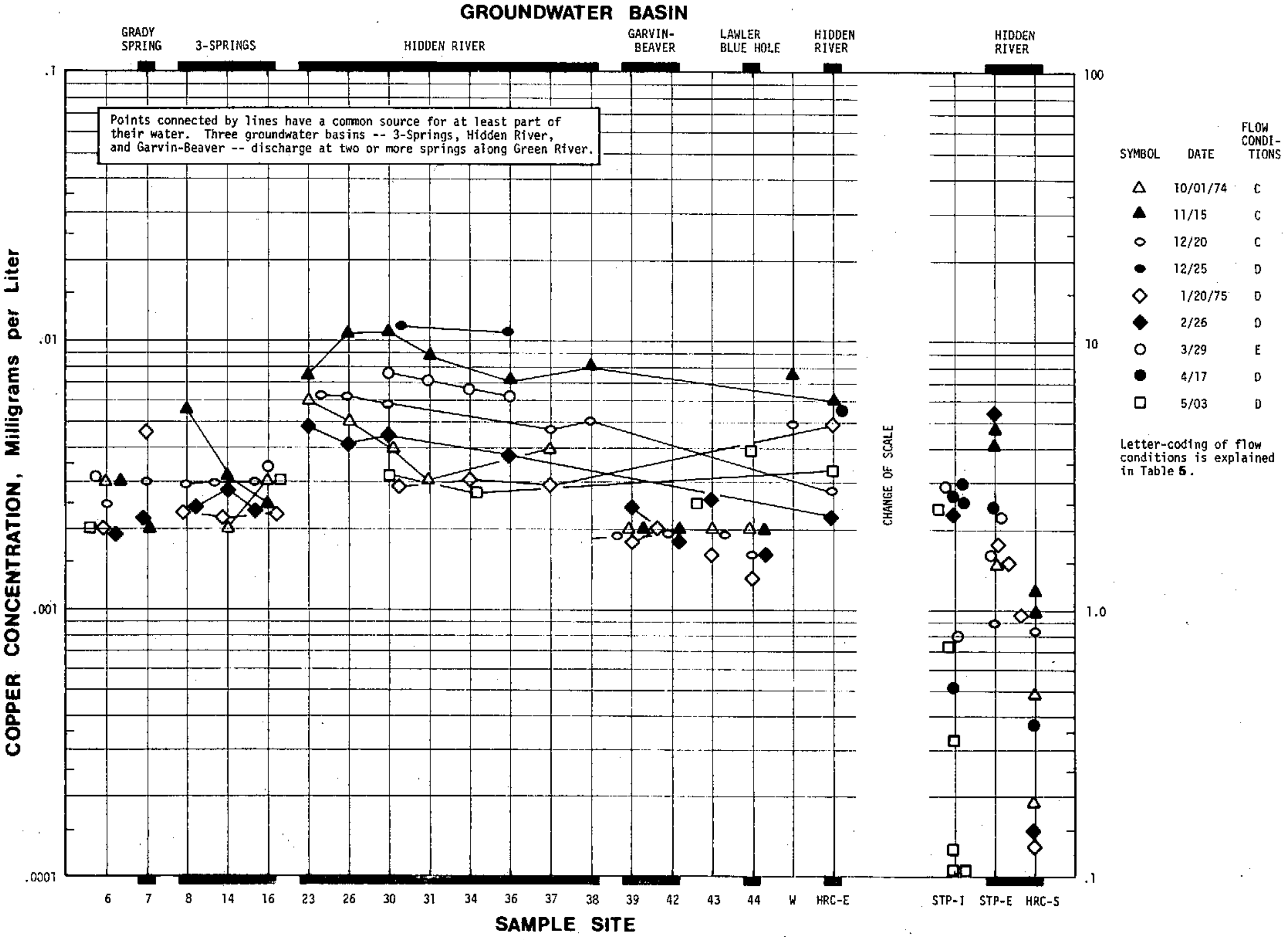

GROUNDWATER BASIN
GRADY SPRING
3-SPRINGS
HIDDEN RIVER
GARVIN-BEAVER
LAWLER BLUE HOLE
HIDDEN RIVER
HIDDEN RIVER
Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.
CHROMIUM CONCENTRATION, Milligrams per Liter
.1
.01
.001
.0001
100
10
1.0
.1
CHANGE OF SCALE
6
7
8
14
16
23
26
30
31
34
36
37
38
39
42
43
44
W
HRC-E
STP-I
STP-E
HRC-S
SAMPLE SITE
SYMBOL
DATE
FLOW CONDI-TIONS
△ 10/01/74 C
▲ 11/15 C
○ 12/20 C
◇ 1/20/75 D
◆ 2/26 D
○ 3/29 E
● 4/17 D
☐ 5/03 D
■ 5/21 C
Letter-coding of flow conditions is explained in Table 5.

FIGURE 12 - Concentration of copper in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8. The copper content of wastewater effluent discharged into the ground usually exceeds the maximum allowed for public water supplies (2.0 mg/l) and always exceeds levels known to be toxic to some fish (0.2 mg/l). The concentration of copper in the South Branch of Hidden River Cave usually exceeds levels known to be fatal to some fish. See also the summary of metal toxicity that comprises Table 9 and the discussion of metal toxicity that begins on p. 65.

INTERPRETATIONS:

1. Copper concentrations as high as those present in the wastewater treatment plant influent and effluent are commonly derived from a metal-plating industry.
2. Generally the copper content of the effluent-bearing springs is significantly higher than that of springs in adjacent groundwater basins and Green River. It is about the same as that of wells.
3. The reasons for the suspicious similarity of the copper concentrations in the effluent-bearing springs to that of the East Branch of Hidden River Cave are discussed as Interpretation no. 3 of Fig. 10.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

SYMBOL	DATE	FLOW CONDITIONS
△	10/01/74	C
▲	11/15	C
○	12/20	C
●	12/25	D
◇	1/20/75	D
◆	2/26	D
○	3/29	E
●	4/17	D
□	5/03	D

Letter-coding of flow conditions is explained in Table 5.

FIGURE 13 - Concentration of zinc in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8. The zinc content of wastewater treatment plant effluent discharged into the ground is always less than the maximum allowed in public water supplies. The concentration of zinc in the South Branch of Hidden River Cave commonly exceeds levels known to be fatal to some fish. See also the summary of metal toxicity that comprises Table 9 and the discussion of metal toxicity that begins on p. 65.

INTERPRETATIONS:

1. Zinc concentrations as high as those present in the wastewater treatment plant influent and effluent are commonly derived from a metal-plating industry.
2. The mean zinc content of the South Branch of Hidden River Cave (Site HRC-S) is greater than that of the effluent (Site STP-E) that was diluted by water in the South Branch. This apparent discrepancy is interpreted to be a statistical anomaly that would not exist if more samples had been taken. It does not seem likely that zinc in the effluent is reacting significantly with something between the two sample sites. Therefore an assumed mean value of 1.78 mg/l has been calculted as explained in Table 10.
3. The zinc content of the effluent-bearing springs is significantly higher than that of other springs, but the anomaly is less significant than those for nickel and chromium because less zinc is discharged into the system.
4. Other than chance, we have no satisfactory explanation for the low zinc concentration in October at Site 37 (Blow Hole East). The analysis was not re-run but the data was checked. Chromium and nickel in the sample are high like they are in other effluent-bearing springs.
5. The peculiar apparent decrease in zinc between the East Branch of Hidden River Cave and the effluent springs in the January samples -- as well as the similarity in the concentration of the May samples -- is explained in Interpretation no. 3 of Fig. 10. The difference could also be enhanced by the arrival of a zinc-rich pulse of contamination in the East Branch, or, more likely, dilution of the total Hidden River Cave discharge by water from elsewhere in the groundwater basin.

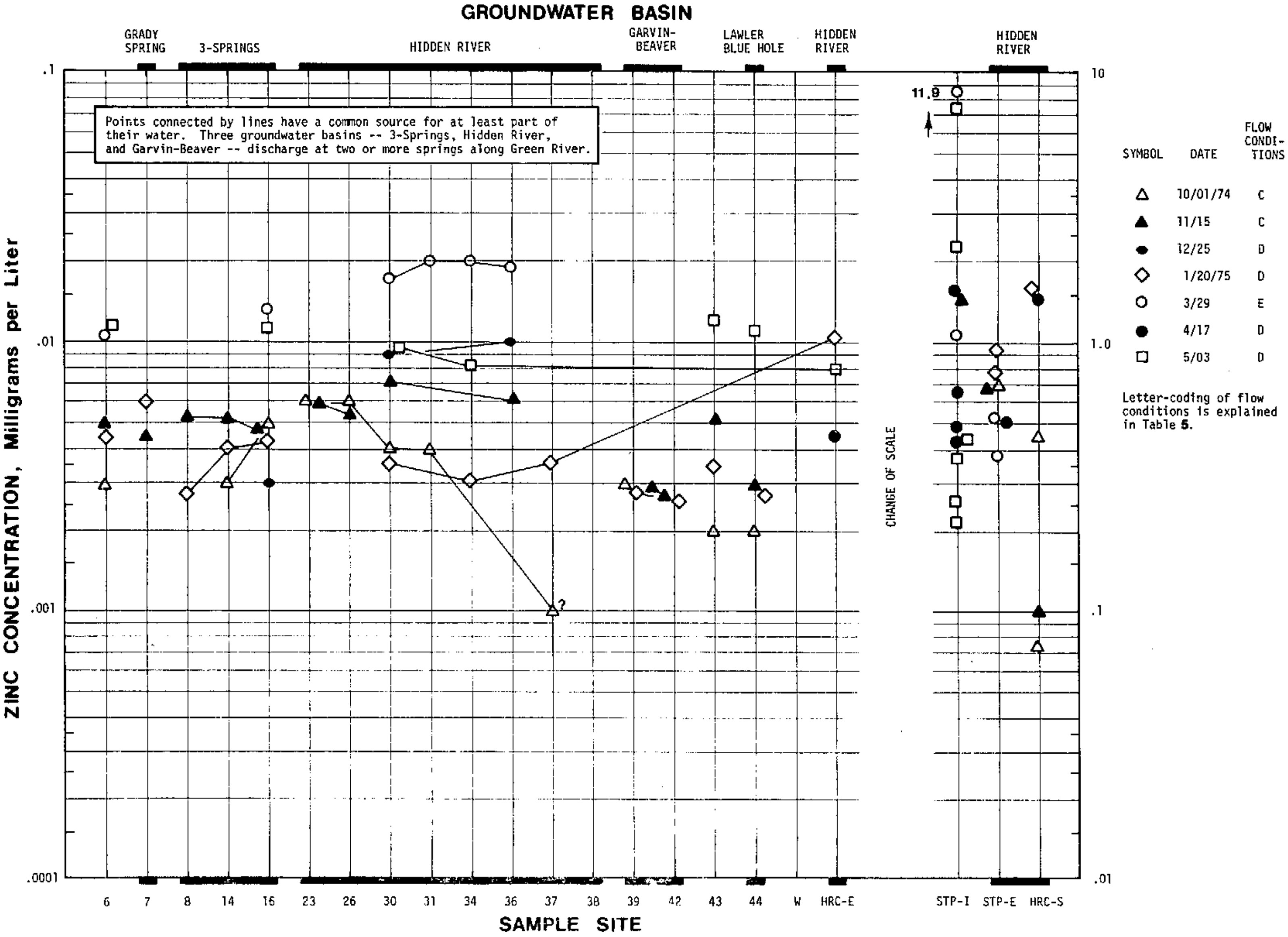
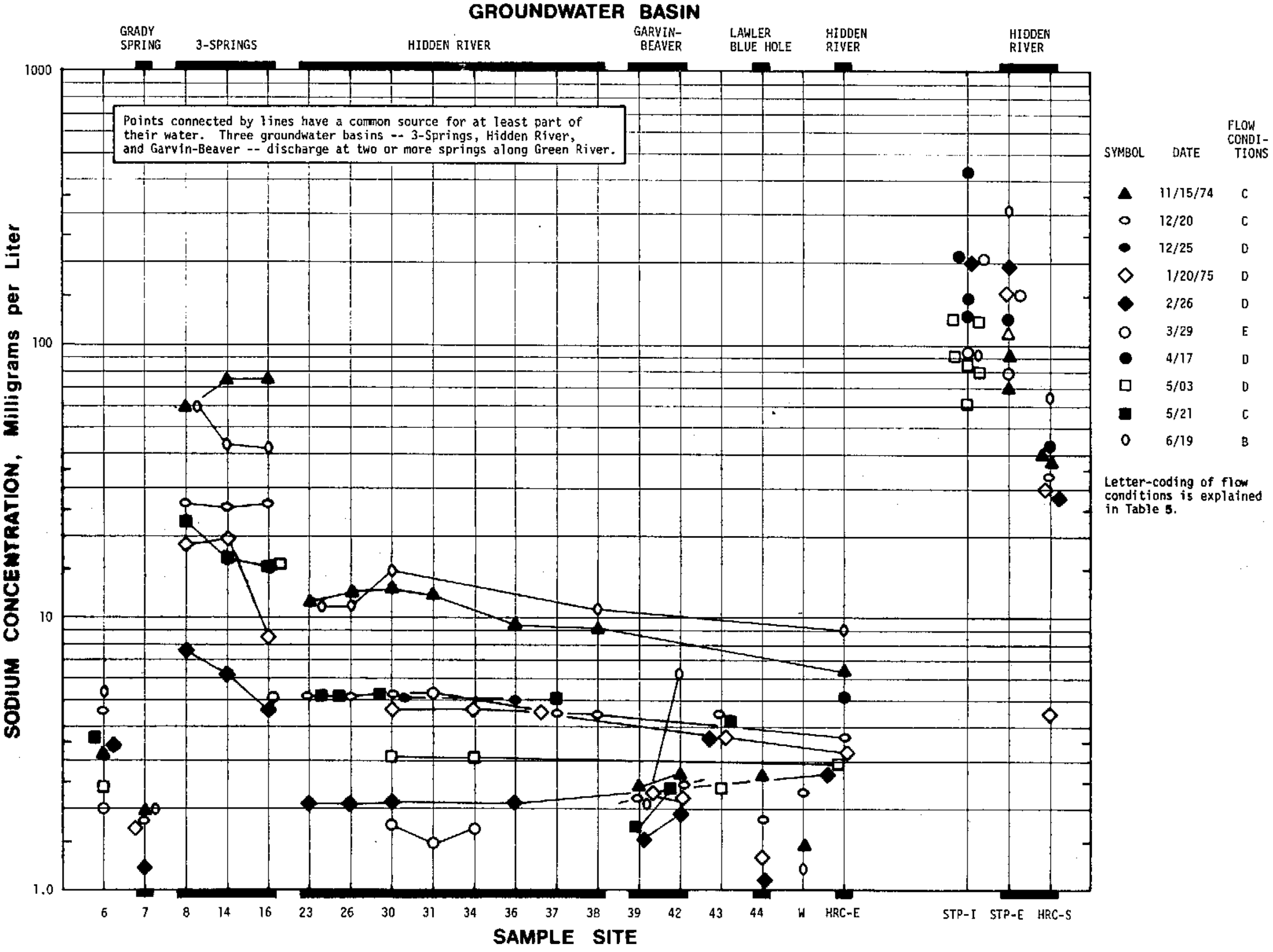

GROUNDWATER BASIN
GRADY SPRING
3-SPRINGS
HIDDEN RIVER
GARVIN-BEAVER
LAWLER BLUE HOLE
HIDDEN RIVER
HIDDEN RIVER
Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.
ZINC CONCENTRATION, Milligrams per Liter
.1
.01
.001
.0001
10
1.0
.1
.01
11.9
?
CHANGE OF SCALE
6
7
8
14
16
23
26
30
31
34
36
37
38
39
42
43
44
W
HRC-E
STP-I
STP-E
HRC-S
SAMPLE SITE
SYMBOL
DATE
FLOW CONDI- TIONS
△ 10/01/74 C
▲ 11/15 C
● 12/25 D
◇ 1/20/75 D
○ 3/29 E
● 4/17 D
□ 5/03 D
Letter-coding of flow conditions is explained in Table 5.

FIGURE 14 - Concentration of sodium in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8.

INTERPRETATIONS:

1. The sodium content of the wastewater treatment plant influent and effluent is significantly higher than that of most municipal plants. Part of the high concentration could be derived from sodium hydroxide and sodium carbonate commonly used for rinsing in metal-plating operations. (Environmental Protection Administration, 1973b) as well as from milk waste (Milk Industry Foundation, 1967, p. 499; the sodium content of milk is 0.28 g per pint.).
2. The sodium content of the effluent-bearing springs is usually slightly higher than that of most other springs, the shallow domestic wells, and Green River, but it is usually much lower than that of the springs in the Three-Springs Groundwater Basin. The reason for the high sodium values in this basin is the probable slight contamination by brines from oil and gas fields, as discussed in Interpretation no. 2 of Fig. 9.
3. The sodium content of the Three-Springs and Hidden River groundwater basins tends to increase during base flow, probably because of less dilution of effluent by rainfall. This is suggested by the generally small range of sodium values at Grady Spring (Site 7), Garvin Spring (Site 39), Beaver Spring (Site 42) and Lawler Blue Hole (Site 44).
4. There is a slight increase in sodium at Site 30 (Hick Spring) during June. The increase is probably related to the local brine contribution to the discharge of this spring which is discussed in Interpretation no. 3 of Fig. 8.
5. The sodium and potassium deficit at the effluent-bearing springs strongly suggests that ion-exchange reactions probably occur between these metals and clays. These reactions have been discussed by Langmuir (1971) and reviewed by Collins (1974). The calculations of dilution ratios that demonstrate the probability of these reactions is shown in Table 10.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

Letter-coding of flow conditions is explained in Table 5.

FIGURE 15 - Concentration of chloride in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent. The Description is the same as that of Figs. 6 and 8.

INTERPRETATIONS:

1. The chloride content of the wastewater treatment plant influent and effluent is higher than normal for most municipal plants. Some of it could be derived from plating operations.
2. The Three-Springs Groundwater Basin is characterized by a chloride concentration, and usually a sodium concentration, hardness, and specific conductance, that is significantly higher than that of any other basin studied. As discussed in the Interpretation no. 2 of Fig. 9, these high values are probably due to slight contamination by brines that have been released by oil and gas exploration. The chloride content of springs in the Hidden River Groundwater Basin is similar to that of the Lawler Blue Hole Basin but greater than that of the Grady Spring and Garvin-Beaver groundwater basins, shallow domestic wells, and the Green River.
3. The very slight increase in chloride at Hick Spring (Site 30) during June is due to seepage of an oil well brine, as discussed in Interpretation no. 3 of Fig. 8.
4. The apparent loss of chloride in June between Site HRC-E (Hidden River Cave, East Branch) is a slight loss. Assuming the analyses are correct, the difference can be caused by one or more of the following;
   - A. The dilution of East Branch water that has been contaminated by flow through talus from the South Branch. Proof of the possibility of this contamination was established by a dye-test.
   - B. Dilution by less saline water.
   - C. Lag in the change in water quality that is related to base flow recession. The Hidden River Cave samples were collected one day before the spring samples. Dye tests in the Turnhole Spring Groundwater Basin (B, on Fig. 5) have demonstrated that mean flow velocities range from 1300 ft per hour to as low as 30 ft per hour for the total distance between the same two points 5 miles apart, depending upon how much water is moving through the aquifer. Accordingly, and allowing for the effects of dilution, the water at Site 38 (Blow Hole West) could be the water that had been at Hidden River Cave as much as one or two weeks previously.
   - D. Ion-exchange reactions with clays, as discussed below.
5. The decrease in chloride in February between the East Branch of Hidden River (Site HRC-E) and Natural Tunnel Spring(Site 38) is most easily explained in terms of dilution and flow recession. There had been 4.7 inches of rain spread over a 2-day period ending 2 days before the springs were sampled. The Hidden River Cave sample was collected 2 days after the spring samples.
6. The chloride deficit at the effluent-bearing springs strongly suggests that ion-exchange reactions between clays and Cl^-, Na^+ and K^+ probably occur. These reactions have been reviewed by Collins (1974). The dilution calculations that strongly suggest these reactions are occuring are given in Table 10.

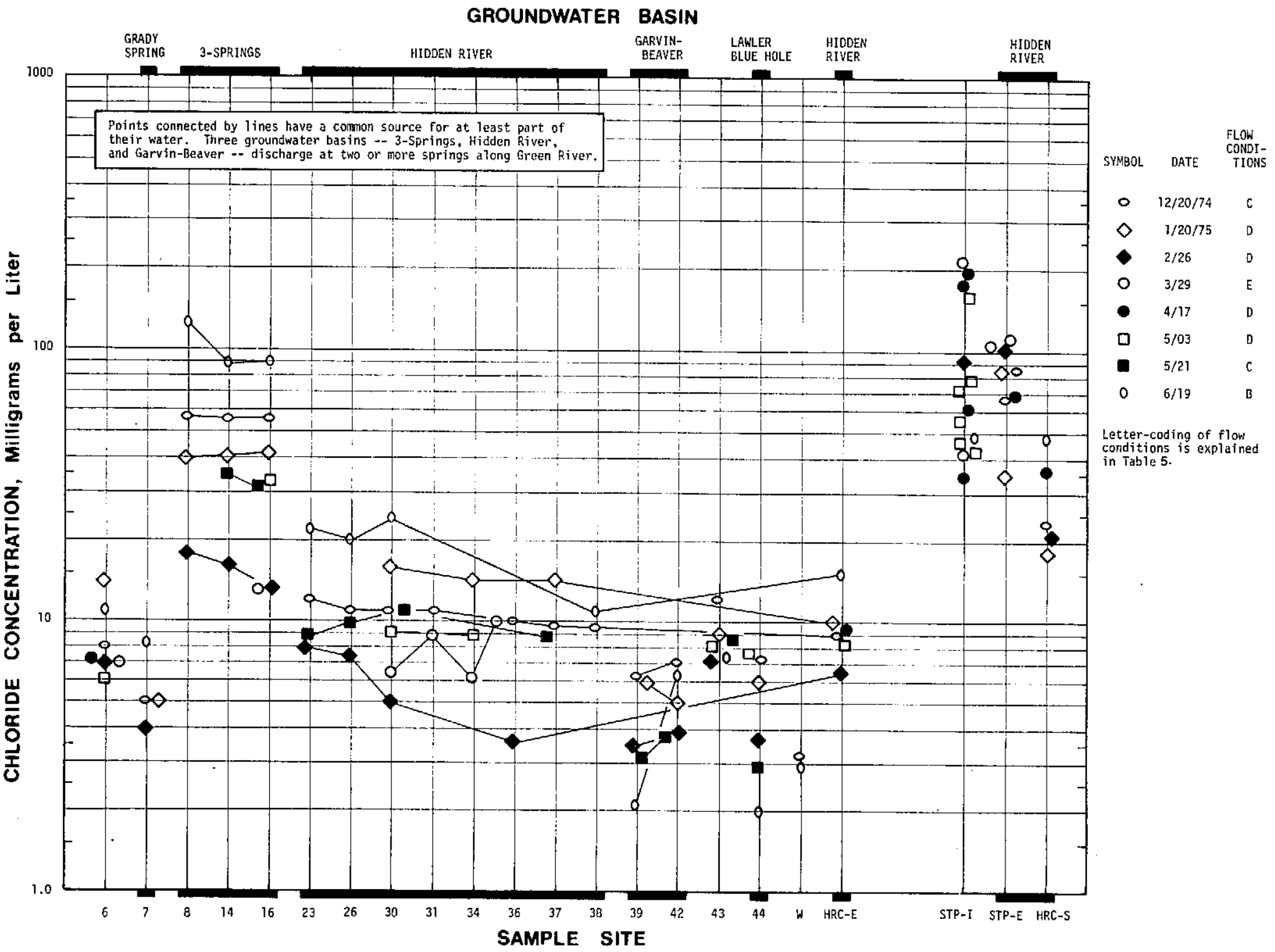
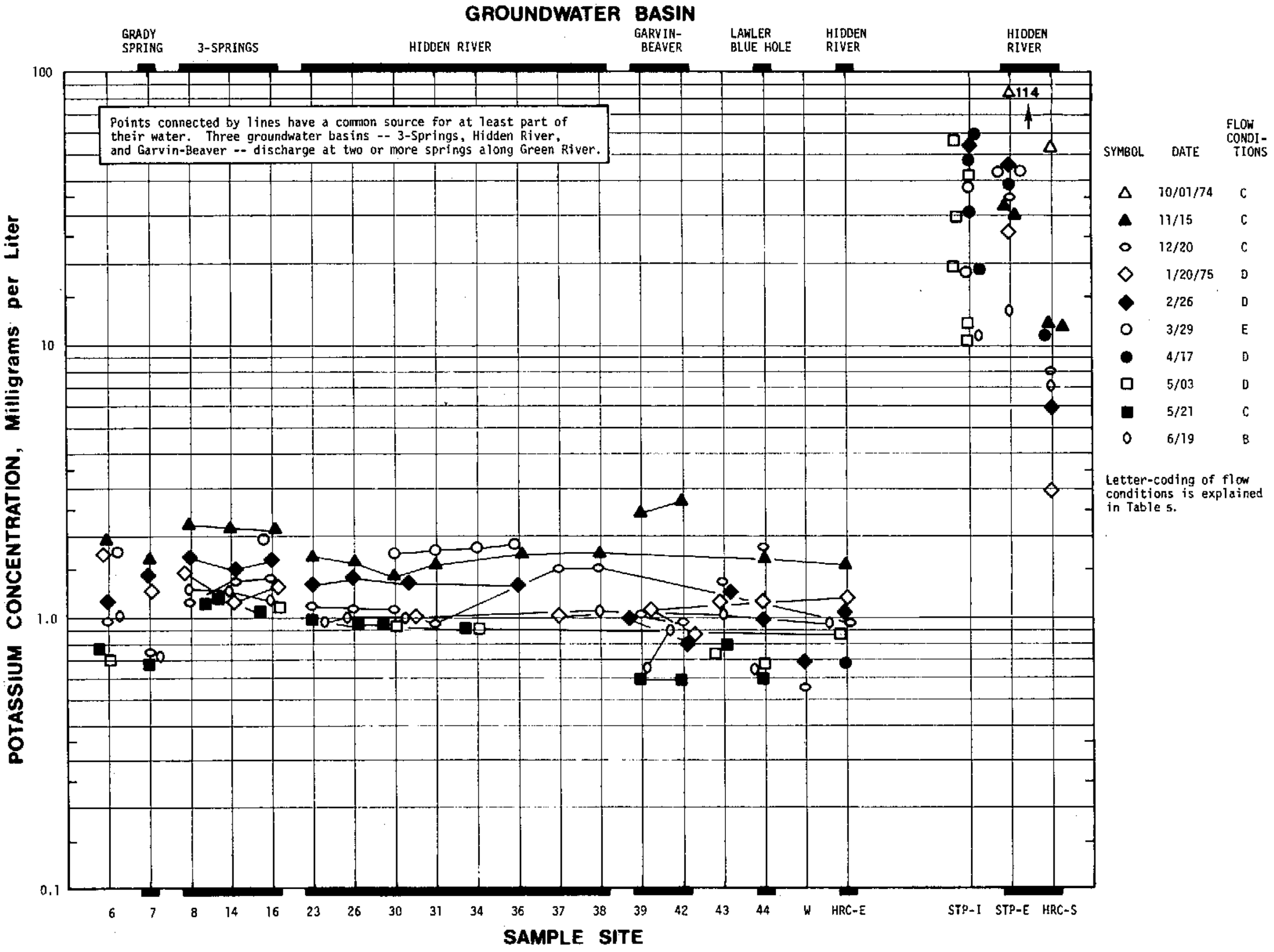

GROUNDWATER BASIN
GRADY SPRING
3-SPRINGS
HIDDEN RIVER
GARVIN-BEAVER
LAWLER BLUE HOLE
HIDDEN RIVER
HIDDEN RIVER
Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.
CHLORIDE CONCENTRATION, Milligrams per Liter
1000
100
10
1.0
6
7
8
14
16
23
26
30
31
34
36
37
38
39
42
43
44
W
HRC-E
STP-I
STP-E
HRC-S
SAMPLE SITE
SYMBOL
DATE
FLOW CONDI-TIONS
12/20/74 C
1/20/75 D
2/26 D
3/29 E
4/17 D
5/03 D
5/21 C
6/19 B
Letter-coding of flow conditions is explained in Table 5.

FIGURE 16 - Concentration of potassium in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Fig. 6 and 8.

INTERPRETATIONS:

1. The potassium levels in the influent and effluent of the wastewater treatment plant are higher than normal for a municipal plant. It could be derived both from metal-plating operations (Environmental Protection Administration, 1973b) and milk waste (Milk Industry Foundation, 1967, p. 499; the potassium content of milk is 0.7 g per pint.).
2. The differences in potassium levels at various sites is very slight, but persistant. The generally higher values in the Three-Springs Groundwater Basin are possibly related to slight contamination by brines associated with drilling for oil, gas, or even water, as discussed in Interpretation no. 2 of Fig. 9.
3. Potassium concentrations are not useful for discriminating between water of various groundwater basins. The relative smallness of the increase in potassium in the effluent-bearing springs that are fed by potassium-rich effluent suggests that they have a potassium deficit. This potassium (and sodium) deficit is indicative of ion-exchange reactions that probably occur between these metals and clays, as discussed by Langmuir (1971) and reviewed by Collins (1974). The calculation of the dilution ratios that demonstrate the probability of these reactions is shown in Table 10.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

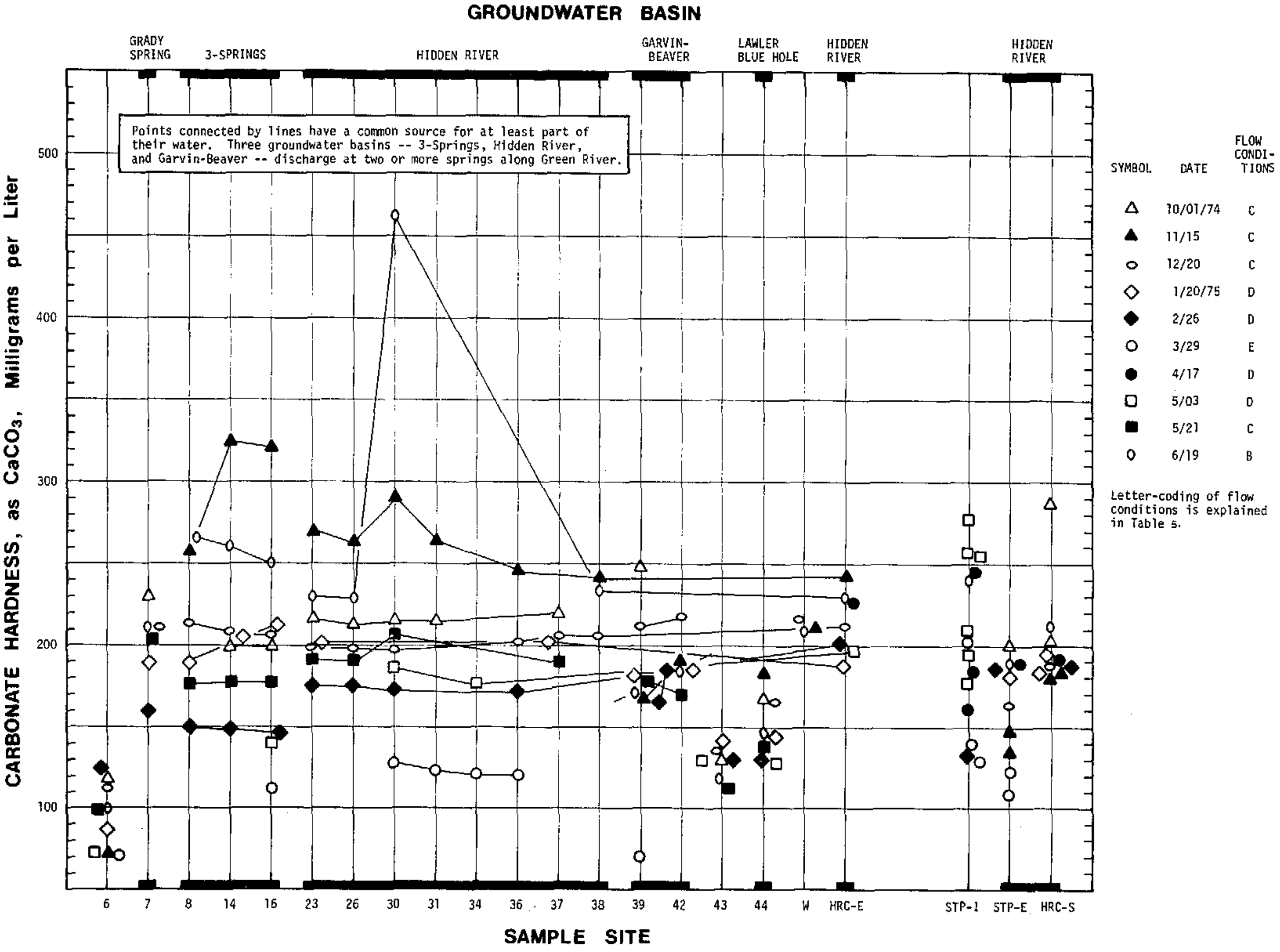
Letter-coding of flow conditions is explained in Table 5.

FIGURE 17 - Carbonate hardness in springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8.

INTERPRETATIONS:

1. Hardness of wells and springs other than Lawler Blue Hole is significantly higher than that of Green River -- a totally expected result concerning the river. The hardness of Lawler Blue Hole is significantly less than that of other springs, but the reason for the consistantly lower values is not yet known.
2. Hardness of the Three-Springs Groundwater Basin may be higher or lower than that of the Hidden River Basin. This may be related to the different amounts of dilution of Three-Springs water by brines that takes place at different stages. It could also be partly related to more rain falling on one basin than another.
3. The exceptionally high hardness at Hick Spring (Site 30) during June and the slight rise in November is related to the local contribution of an oil well brine to the flow of this spring. This anomaly is discussed in Interpretation no. 3 of Fig. 8. As mentioned in that discussion, an analysis of the brine was not made. (It should have been!) But study of the analysis of the spring and consideration of the subsequent analysis for sulphate (760 mg/l) indicates that it is primarily a calcium-magnesium sulphate water in which chloride is subordinate. For consistancy, the hardness of this sample is still reported as $CaCO_3$.
4. No evaluation has been made of how ion-exchange processes with clays increases the carbonate hardness.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

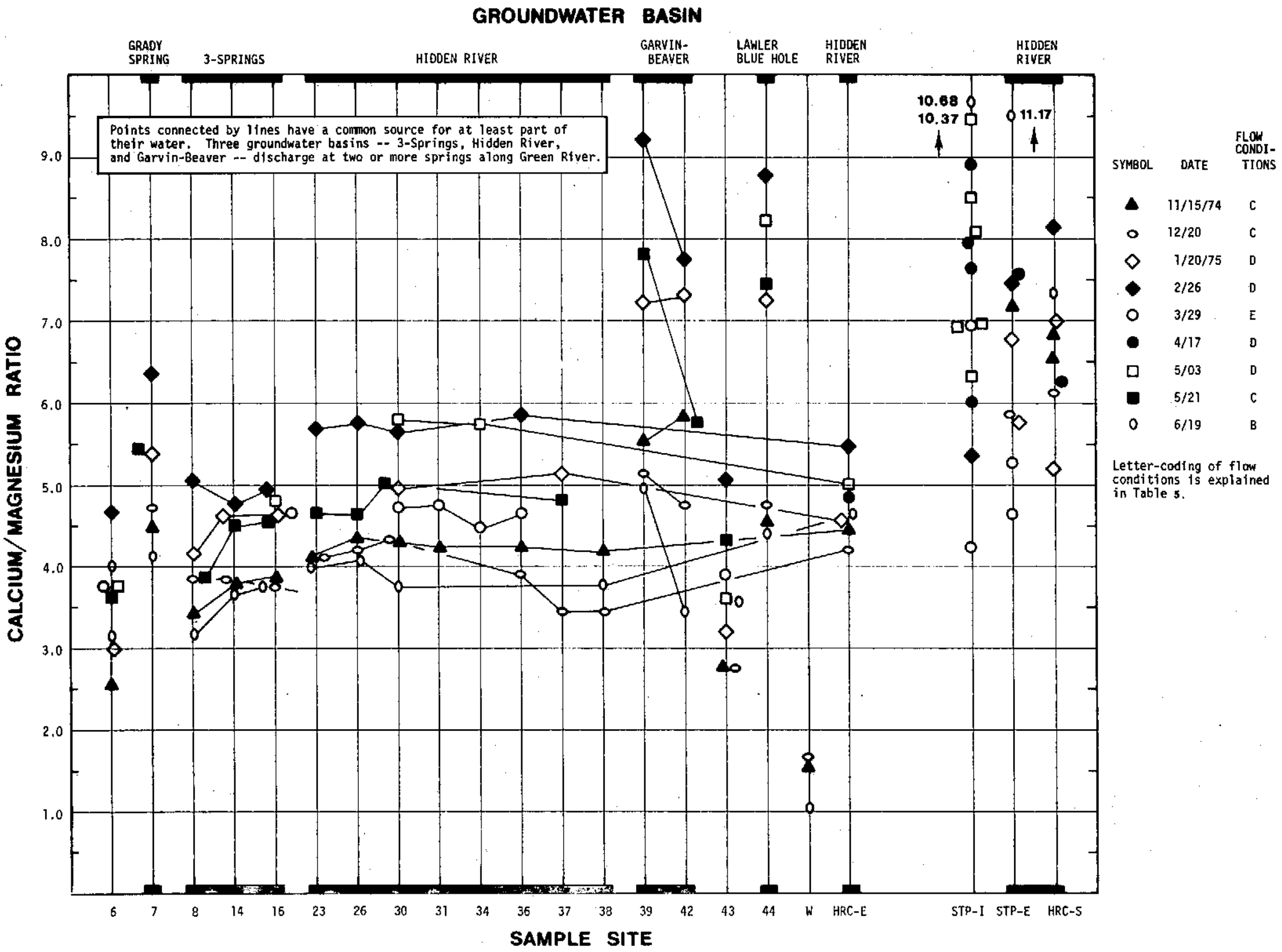
Letter-coding of flow conditions is explained in Table 5.

FIGURE 18 - Calcium/magnesium ratio of springs, cave streams and wastewater treatment plant effluent in the Hidden River Groundwater Basin, springs in four adjacent groundwater basins, shallow wells, Green River, and wastewater treatment plant influent.

DESCRIPTION: Same as that of Figs. 6 and 8. The molar calcium/magnesium ratio is a measure of the extent to which a water may have approached equilibrium with dolomite. It also is an indirect measure of the amount of dolomite present in a recharge area.

INTERPRETIONS:

1. Ca/Mg ratios are directly proportional to discharge. In two of the groundwater basins, Garvin-Beaver and Lawler Blue Hole, the ratio increases much more than in others. The most likely explanation for this behavior is the relative lack of dolomite in these two smaller basins and the probable shorter residence time of recharge within them.
2. The Ca/Mg ratio of the well waters is near unity, partly because of the relatively long residence time of these low-velocity waters. This distinctive low ratio, coupled with the relatively low concentrations of heavy metals, indicates that the wells neither intercept passages conveying water from Hidden River Cave nor are recharged by such water. It is conceivable, however, that the wells intercept low-order feeders for the cave passages that function as wastewater conduits between Horse Cave and the Green River. If there are such feeders it is possible that they could be back-flooded by the trunk drainage after heavy rains. But such waters would be highly diluted and unlikely to have a significant effect upon the quality of the well water.



Points connected by lines have a common source for at least part of their water. Three groundwater basins -- 3-Springs, Hidden River, and Garvin-Beaver -- discharge at two or more springs along Green River.

Letter-coding of flow conditions is explained in Table 5.

TABLE 8 - Bacterial quality and nitrate concentration at selected sites.

MEANS OF FIVE WEEKLY ANALYSES, MAY-JULY 1974 (after Holmes, 1974					
Site No.	GROUNDWATER BASIN and Site Name	Total Coliforms	Fecal Coliforms	Fecal Streptococcus	Nitrate (NO_3)
		Colonies per 100 ml			mg/l
6	Green R., near Grady Spring	310	100	120	3.2
	THREE SPRINGS				
14	Blue Hole	320	270	300	13.9
16	Dixon Spring	300	230	270	13.1
	HIDDEN RIVER				
23	Gorin Mill Sp.	340	130	160	12.8
30	Hick Spring	290	120	170	12.7
	GARVIN-BEAVER				
39	Garvin Spring*	1380 (370)	410 (220)	4870 (190)	6.4
43	Green River, above Lawler	250	125	110	4.8
	LAWLER BLUE HOLE				
44	Lawler Blue Hole	390	190	350	4.2

* The anomalously high mean bacterial counts for Garvin Spring are the result of one sample with very high counts. The figures in parentheses give the mean for Garvin if this one sample is not used for calculating the mean.

INTERPRETATIONS: Although the total coliform count of the effluent-bearing springs in the Hidden River Groundwater Basin is about the same as in the adjacent basins, the fecal coliform count may be less than in the adjacent basins and about the same as the Green River. The fecal streptococcus count may be less than that of adjacent basins and greater than that of the Green River. The data may not be statistically significant but it certainly suggests that the bacterial quality of the effluent-bearing springs is not greatly different from that of springs in adjacent basins or the Green River. We interpret the different nitrate concentrations of the springs to be partly determined by the percentage of each recharge area that is fertilized for crops.

TABLE 9 - Answers to the question, "Do samples exceed maximum limits for heavy metals?" for public water supplies and habitats for fish, a partial summary of Table 6.

Metal	Maximum Limits* (mg/l)	Do Samples Exceed Maximum Limits for Heavy Metals?					
		Site					
		Horse Cave Wastewater Treatment Plant, Effluent			Hidden River Cave South Branch		
		Mean	All Samples	Some Samples	Mean	All Samples	Some Samples
Chromium	Public Water Supplies (0.05)	Yes	Yes	Yes	Yes	Yes	Yes
	Fatal to Some Fish (5.0)	No	No	No	No	No	Yes
Nickel	Public Water Supplies ---	---	---	---	---	---	---
	Fatal to Some Fish (5.0)	Yes	No	Yes	No	No	Yes
Copper	Public Water Supplies (1.0)	Yes	No	Yes	No	No	Yes
	Fatal to Some Fish (0.02)	Yes	Yes	Yes	Yes	Yes	Yes
Zinc	Public Water Supplies (5.0)	No	No	No	No	No	No
	Fatal to Some Fish (0.3)	Yes	Yes	Yes	No	No	No

* Maximum limits for public water supplies are set by State and Federal Standards (Kentucky Department of Natural Resources and Environmental Protection (1973) and Environmental Protection Administration (1973a). Current Federal standards, however, do not specify a maximum contaminant level for copper and zinc in public water supplies (Environmental Protection Administration, 1975). The concentrations fatal to some fish are taken from a compilation by Cheremisinoff et al. (1976). They are the lowest levels that have been shown to be lethal. The lethal concentration varies with type of fish, pH, temperature, etc. The Environmental Protection Administration (1973) recommends that the following concentrations not be exceeded in order to protect mixed aquatic life: chromium - 0.05 mg/l, nickel - 0.1 mg/l, copper - 0.03 mg/l, zinc - 0.1 mg/l. All samples at both sites always exceeded these limits.

TABLE 10 - Calculation of true dilution ratios between wastewater treatment plant effluent and anomalous metal levels in effluent springs which can not be attributed to regional background.

Sample Site & Ratios Element mg/l	Mean of Effluent-Bearing Springs (ES)	Regional Background (Mean of values for Grady, Garvin-Beaver, and Lawler Blue Hole Basins) (B)	Anomaly Higher than Regional Background (ES-B)	Mean of Wastewater Treatment Plant Effluent* (STP-E)	Mean of Hidden River Cave, South Branch (HRC-S)	True Dilution Ratios $\left(\frac{STP-E}{ES-B}\right)$
Chromium	.005	.001	.004	3.48	2.73	870
Nickel	.018	.004	.014	9.22	4.13	660
Copper	.005	.002	.003	2.28	.58	760
Zinc	.009	.004	.005	.68 (1.78)*	.84	130 (360)*
Chloride	11.6	5.6	6.0	81.8	26.2	14
Sodium	5.8	2.0	3.8	165	54.6	43
Potassium	1.3	1.0	.3	41	13.2	140

* Mean dilution ratio of STP-E/HRC-S exclusive of zinc is 2.7. (Values are shown in column 4 of Table 7.) Since only zinc occurs in diluted effluent in higher values than in undiluted effluent, an improbability that is explained by statistics of sampling, the HRC-S value was multipled by 2.7 to get an estimated effluent zinc concentration of 1.78 mg/l. The mean of values in the 3-Springs Groundwater Basin were not used because such values have been interpreted to have been affected by brine from oil and gas exploration.

DESCRIPTION: Dilution ratios for heavy metals range from 870 to an estimated 360. But for chloride and alkalai metals it ranges from 140 to 14.

INTERPRETATION: It seems very likely that ion-exchange reactions are taking place between clays and Cl^-, Na^+, and K^+. Many samples would have to be analysed in order to demonstrate the rate and magnitude of these processes.

are 2.2 and 1.9 times greater than that of the mean of four adjacent groundwater basins. These mean difference concentrations are consistant and are useful for geochemically discriminating between the waters of different groundwater basins but the concentrations in the effluent-bearing springs pose no probable threat to public health or animal life.

3. It should be stressed that the heavy metal concentrations present in the waters of Hidden River Cave, summarized in Tables 6 and 9, are considerably higher than current state and federal standards for public water supplies. We are not qualified to say whether the metal concentrations present are toxic, dangerous, or a hazard to public health. But the once-abundant stream fauna is no longer present. The metals plus the high Biological Oxygen Demand and Chemical Oxygen Demand have destroyed the habitat of the blindfish in the accessible part of the cave. The extent to which this septic environment extends downstream is a matter of speculation.

   It is also to be stressed that metal concentrations that are not toxic to people or adult fish may be toxic or teratogenic to fish embryos. For example, Birge and Just (1974, p. 26-27) state,

> "the commonly accepted public health standard of 5 ppb for mercury in water is essentially an LD_{50} value for trout embryos, as better than 50% either die prior to hatching or exhibit gross anatomical defects when treated at this concentration."

They also cite work which shows that zinc concentrations as low as 0.01 ppm are lethal or toxic to trout eggs and alevins (fry) and 0.04 ppm is lethal for young rainbow trout. Very little is known about the toxicity and teratogenicity of heavy metals to the embryos of invertebrates, fish, and other vertebrates. Acute toxicity tests are usually run with adult specimens that may be resistant to concentrations 100 to 1000 times greater than those that are toxic or teratogenic to eggs or embryos of the same species. Even less is known about the synergistic manner in which two or more metals that are non-toxic at "X" concentration are very toxic when both are in the same solution at "X" concentration (Dan Stoneburner, National Park Service, verbal communication, 1975).

4. Column 4 of Table 7 indicates that the average dilution of effluent between the wastewater treatment plant and Hidden River Cave is 2.7.
5. Column 5 of Table 7 compares the composition of the South and East Branches of Hidden River Cave. Chromium, nickel, and copper levels average 940, 590, and 140 times higher in the South Branch.
6. Column 6 of Table 7 gives some apparent dilution factors for various elements at effluent-bearing springs relative to their concentration in treatment plant effluent, but a more accurate determination of dilution can be obtained by allowing for the background that would probably be present if no metal-rich effluent was being discharged into the cave system. These calculations are given in Table 10. Heavy metals are diluted by a factor of 360 to 870. (Mean = 660.) Chloride, sodium, and potassium are diluted by a factor of 14 - 140. (Mean = 70.) The low dilution of these latter three elements is interpreted to be a result of ion-exchange reactions with clays.
7. The remaining columns of Table 7 compare the concentration of heavy metals and other chemical properties of the effluent springs with those of four adjacent groundwater basins, shallow domestic water wells, and the Green River.
8. A study of columns 3 and 11 of Table 7 suggests that the effluent

springs average 1.9 times the chromium, nickel, and copper content of the East Branch of Hidden River Cave. They average 4.0 times the content of the Grady Spring, Garvin-Beaver, and Lawler Blue Hole Groundwater Basins. Therefore the East Branch averages 2.2 times as much chromium, nickel and copper as these three groundwater basins. And a very significant portion of the heavy metals in the effluent springs must come from the supposedly uncontaminated waters of the East Branch that do not drain a source area for such metals! This necessary hypothesis was discarded when a dye test by project personnel proved that, at low discharge rates, water from the South Branch seeps into talus, flows beneath it, and contaminates the flow of the East Branch at the most upstream point in which it can be sampled. Contamination might also take place during high discharge, but by a hypothetical passage sub-parallel to the South Branch.

9. Waters of the Three-Springs Groundwater Basin are easily discriminated from those of other basins by their characteristically higher sodium, chloride, carbonate hardness, and specific conductance. These relatively high levels are believed to be caused by brines released by oil and gas exploration, or even drilling for water wells.
10. The bacterial quality of the effluent-bearing springs is not significantly different from that of other springs and the Green River. The total coliform count of all three types of water averaged about 320 colonies per 100 ml, slightly less for fecal coliforms and fecal streptococcus. The fecal coliform and fecal streptococcus counts were lower, about 40% to 50% of the total coliform count, and slightly higher than those of the Green River.
11. According to Branstetter (1974) the mean monthly effluent discharge

of the Horse Cave wastewater treatment plant is approximately 12 million gallons, but 10 million gallons may be a more realistic figure. Using this latter discharge and the mean values for effluent cited in Table 10, the monthly discharge into the subsurface would be:

Chromium	290 lbs
Nickel	770 lbs
Copper	190 lbs
Zinc	150 lbs

An independent test of the accuracy of the chemical analyses can be obtained by checking the mass balance of Green River on days in which samples were taken both upstream and downstream of the effluent-bearing springs. This test is summarized in Table 11 and it suggests that there are no significant errors. Spring discharge was not measured or estimated (nor was it possible to do so) on all days sampling was done, so the actual dilutions can not be determined. But let us assume the following possible worst case that might occur during extremely low base flow for Green River and all springs:

Discharge of Green River, at Munfordville (This is less than half the lowest flow in 1975, the driest of the past 10 years. The lowest flow in 50 years is 39 cfs, in 1921.)	100 cfs
Discharge at Gorin Mill Spring (This value has been measured during very low flow conditions)	25 cfs
Concentration of chromium in Green River (The maximum recorded by this study)	0.0020 mg/l
Concentration of chromium at Gorin Mill Spring (The maximum allowable in public water supplies, 3.3 times greater than the maximum recorded at an effluent-bearing spring)	.0500 mg/l

The new concentration of the Green River (100 cfs x .0020 mg/l plus 25 cfs x 0.0500 mg/l) would be 0.0116 mg/l, an increase of 0.0096 mg/l, a quantity certainly detectable, but not an increase to a level that

TABLE 11 - Comparison of nine matched analyses of Green River water upstream and downstream from where springs discharge diluted heavy metal-laden effluent.

SITE LOCATION CHEMICAL PROPERTY*		GREEN RIVER			Is the Difference Significant?
		Above Grady Spring (Site 7)	Above Lawler Blue Hole (Site 44)	Difference	
Chromium	milligrams/liter	.0005	.0009	+ .0004	No
Nickel		.0041	.0041	0	No
Copper		.0022	.0021	- .0001	No
Zinc		.0058	.0053	- .0005	No
Sodium		3.87	4.20	+ .33	Probably
Potassium		1.06	1.08	+ .02	No
Carbonate Hardness		103	114	+ 11	Yes
Ca/Mg Ratio		3.77	3.78	+ .01	No
Specific Conductance µmhos/cm		247	268	+ 21	Yes

* Heavy metal analyses are usually not significantly accurate at concentrations of less than 0.001 but the 4th figure is used for calculations.

INTERPRETATION: During periods of moderately low flow to moderate flood, heavy metals from Hidden River Cave which are discharged at effluent-bearing springs along the river do not have any detectable effect on the heavy metal composition of the Green River. Spring discharge is diluted by an estimated factor of 40 to 200 or more. The balance between heavy metal input and output suggests that the samples (and analyses) are not significantly affected by statistical noise.

could be considered a threat to public health in cities downstream that use the river as their source of drinking water. Many similar calculations could be made.

Figure 19 shows the flow paths of groundwater in the Horse Cave area. It is redrawn from Fig. 7 and the site numbers of the wells and springs are shown on the latter figure. Except where mapped in caves, the flow paths are shown schematically as nearly straight lines. Water from the confluent streams in Hidden River Cave, the East Branch and South Branch, is discharged through a distributray system that includes 39 springs at 14 locations along a 5-mile reach of the river -- every spring but one* between Gorin Mill and Blow Hole West. Water in these springs has heavy metals in concentration that are as high as 30 times greater than other springs upstream and downstream, 20 times greater than Green River, and 60 times greater than in shallow wells in the area between Horse Cave and the river.

Metal-rich wastewater treatment plant effluent which also has a high Biological Oxygen Demand, Chemical Oxygen Demand and Suspended Solids content flows to Hidden River Cave where it is mixed with a river that flows from the southeast. During low base flow of the springs and Green River, the much-diluted effluent is discharged at 6 locations: Gorin Mill Spring, the three sites half a mile southwest of it, Hick Spring, and Blow Hole West. The total discharge in Hidden River Cave under such conditions is 7 cfs, that of Gorin Mill is 28 cfs, and that of all the other springs is estimated to total .5 to 1 cfs. In extreme flood, however at least 39 springs at 14 locations flow an estimated total of

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*Site 24, Trough Spring, discussed in Interpretation no. 5 of Fig. 8.

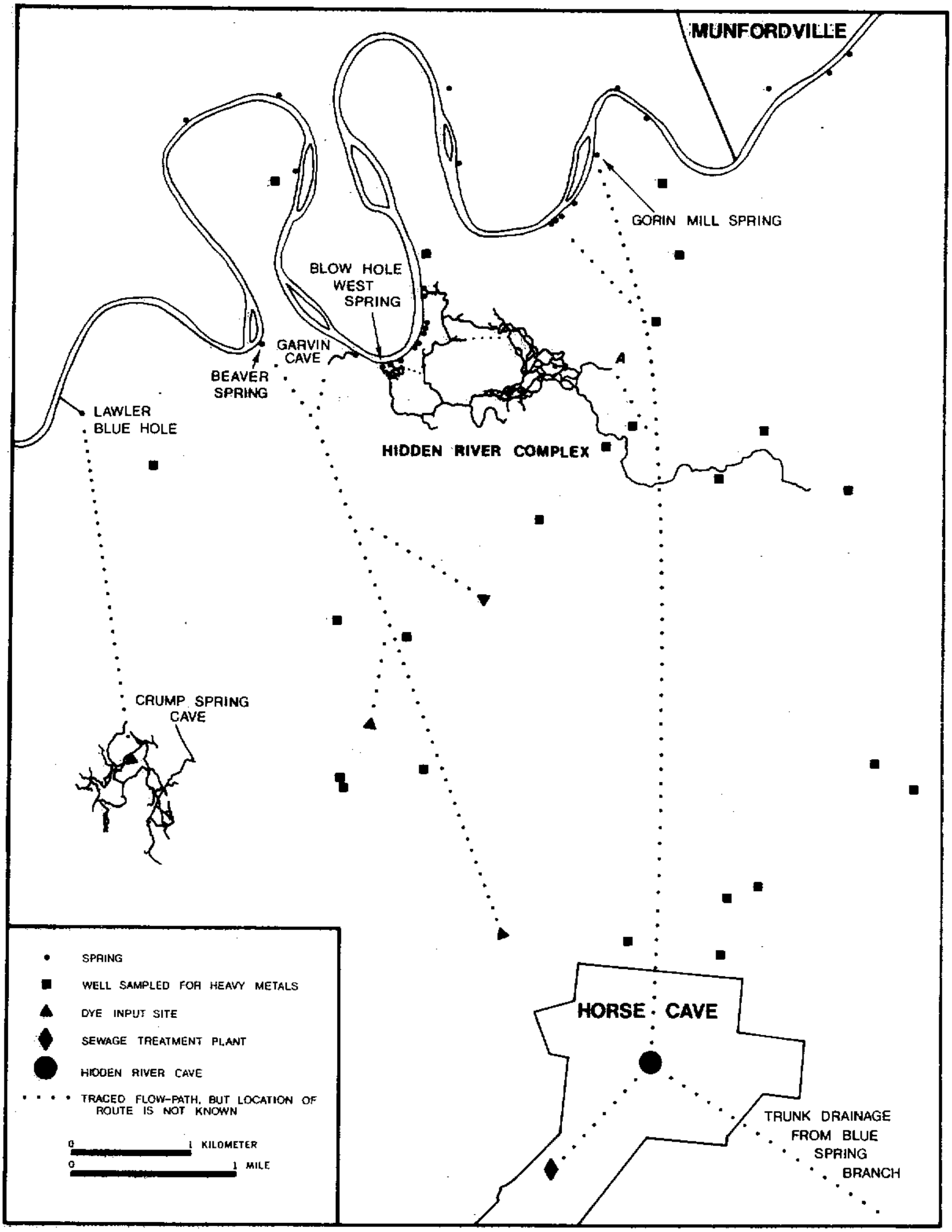

FIGURE 19 - Flow paths of groundwater in the Horse Cave area. Site names are identified in Table 2. The map of Crump Spring Cave is reproduced through the courtesy of Joseph Saunders, University of Kentucky. The map of Garvin Cave is reproduced through the courtesy of Jack Hess, Desert Research Institute, Nevada.

1000 to 1500 cfs. This is a very speculative figure; at such stages the springs are impossible to gage.

The Hidden River Complex, a major cave system

Fig. 20 shows the mapped portions of the Hidden River Complex, a 14.6 mile (23.5 km) cave system that was discovered in June 1975 by digging inspired by interpretation of the chemistry of the effluent-bearing springs to mean they are part of the widest known distributary system in America (Quinlan et al., 1975). It is the third largest cave in Kentucky, and is second only to Mammoth Cave (190 miles; 306 km) in Central Kentucky.

The flow paths of water in the mapped portions of the cave are briefly summarized in the legend for Fig. 20. The break-out dome at A is a large feature formed by the collapse and stoping the roof of a subjacent cave passage. Today it is a lake 100 ft wide and 56 ft deep, with a hemispherical ceiling 60 ft high. The ancient conduit below, shown by a dye test by project personnel to be blocked and not in line with flow to Gorin Mill Spring, is presumably related to a level occupied by the Green River during the Pleistocene before its valley was filled with about 50 ft of alluvium. The partially mapped cave shown is a floodwater maze (Palmer, 1975) that is probably an extreme modification of a cave older than the one from which the water rises at A.

A detailed discussion of the geology and hydrology of this cave, and that of other caves mapped because they are relevant to an understanding of the regional hydrology, will be included in the Phase II report.

The Hidden River Complex is accessible during only a few months of

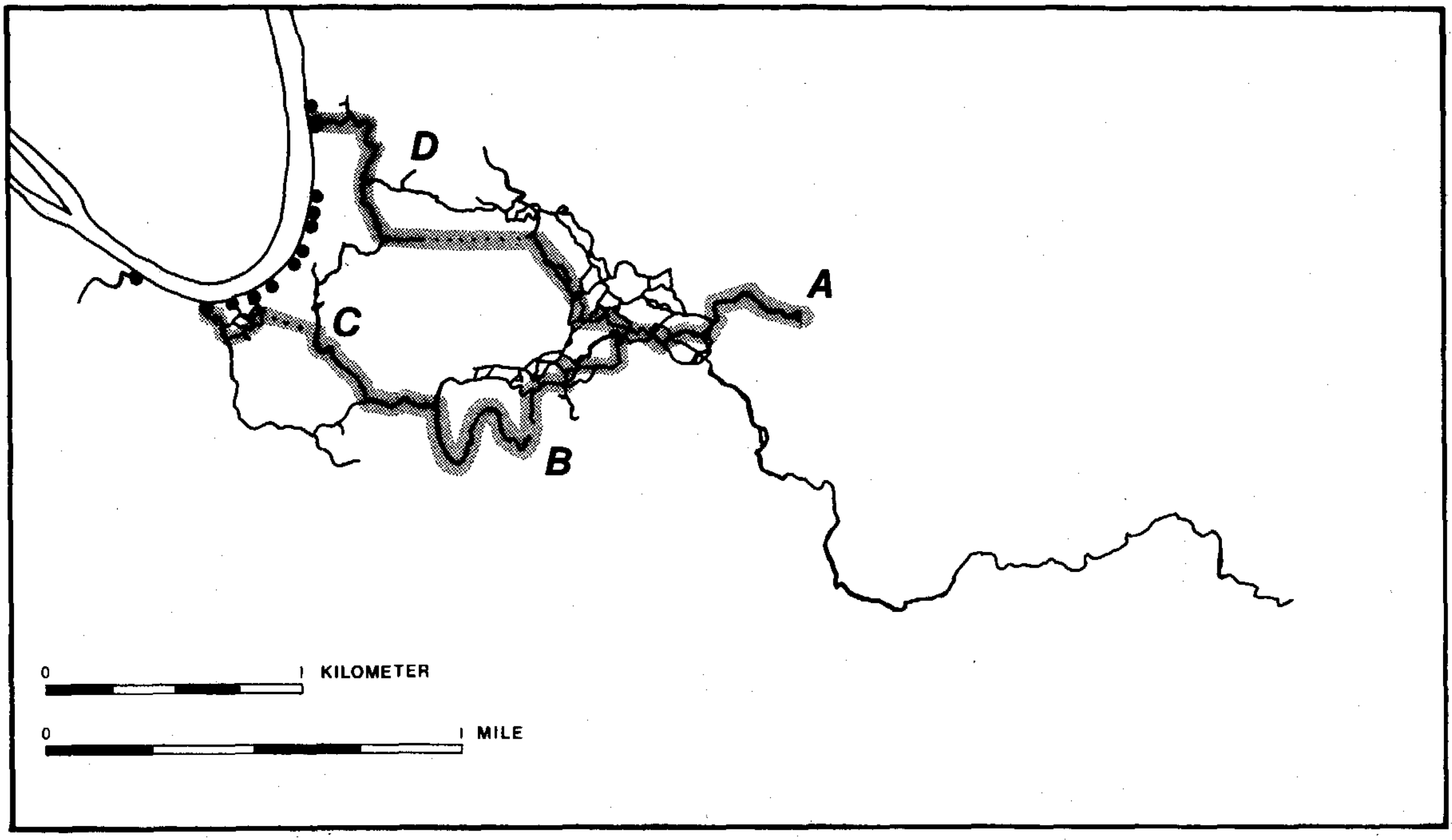

FIGURE 20 - Map of the Hidden River Complex, showing flow paths and springs. Each dot represents one or more springs. Water enters the horizontal cave at A by rising 56 ft up a break-out dome and, at low stages, takes the paths shown by the stippling. The route from B to C is a river 40 ft wide, 8 ft deep, and 1.5 miles long. Point D, at the head of a small tributary, is where brine from a nearby oil well enters the cave. Its effect on water quality of Hick Spring is shown in Figs. 8, 9, 14, 15, & 17. If the stage of Green River rises slightly, water from A takes a slightly different route through the maze. During high flood the water from A flows to 33 springs at 10 locations along the river. The entire cave is water-filled.

the year, when Green River is at low stages. A 1 ft rise in the Green River or a sudden thunderstorm can seal the cave shut for a day or two until the flow recedes. The cave was mapped by the skilled, dedicated people cited in the acknowledgements and the senior author. Wet suits were worn for protection from the cold water.

In July 1976 it was discovered that the Hidden River Complex and many other caves in the Sinkhole Plain had anomalous concentrations of radon gas. These concentrations are higher than those found in Mammoth Cave and other caves within Mammoth Cave National Park. The source and nature of these anomalies is being studied by the senior author.

Distributary flow in karst aquifers

After the distributary system of the Hidden River Groundwater Basin was discovered, dye tests by Quinlan and the staff of the Uplands Research Lab (National Park Service) showed that distributary flow is characteristic of the Garvin-Beaver, Three-Springs, Markum Mill (Fig. 5, Basin M), Graham Springs (Fig. 5, Basin A) and Double Sinks (Fig. 5, Basin C) groundwater basins. Joseph Saunders and associates discovered that Scott Spring (Site 5), a perennial spring, is a distributary for the Grady Spring Groundwater Basin. But Scott Spring functions as such only during moderate to high stages when water flows through a high-level "cut-around".

River Styx and Echo River (Sites 52 and 53), two springs upstream from the Mammoth Cave ferry, comprise a distributary of Mammoth Cave in which the Styx distributary is a high-level passage. When Green River is at a moderate stage and both it and springs are in a recessional phase, river water flows into Mammoth Cave at Styx and comes out 3000 ft downstream at Echo River. Quinlan has observed similar behavior in Pike Spring East and Pike Spring West (Sites 50 and 51). He also interprets two high-level passages adjacent to the Rotunda in Mammoth Cave, Houchins Narrows (and its continuation as Dixon Cave) and Audubon Avenue, to be distributaries of a Tertiary age river that flowed through Main Cave (the main passage in the historic part of the cave, near the main entrance). Lawler Blue Hole has a small distributary complex. Quinlan and National Park Service personnel and project personnel have demonstrated that distributary flow routes are characteristic of every large groundwater basin but one, Turnhole Spring, shown on Fig. 5. The other groundwater basin shown that lacks such flow is Mill Spring (Basin L).

Distributary flow systems have been recognized by dye tests to the numerous springs that feed the Ljubljanica River, near Ljubljana, Yugoslavia (Gospodarič and Habič, 1976). The conduit system that feeds them is inaccessible and can not be mapped.

Zötl (1974) summarized and interpreted the results of numerous dye tests (many made by him) in Austria, Yugoslavia, Greece, and Germany. Most of these tests were run in alpine and other high-relief areas in which the rocks have been intensely faulted and fractured. Many fascinating dye-dispersal patterns (such as flow paths that cross but do not mix) are illustrated and discussed. Some dispersal patterns can be interpreted to represent flow in a distributary complex, but much of the flow is believed to be in fissures. Most of the flow systems are inaccessible to man and there are no maps of the plumbing systems that feed the springs.

Perhaps the area most intensively studied by dye-testing is the

Mendip Hills, an area of southeastern England in which the stratigraphy and structure is similar to that of the Appalachians (Drew, 1975). Many of the caves there have been mapped. Indeed, more than 80% have been discovered by digging, sometimes over a period of years. Most of the caves are less than a mile long. But here too the hypothesized cave systems behind the numerous springs are generally inaccessible.

Three of the numerous reasons why the discovery and mapping of the Hidden River Complex is significant are the:

1. understanding it gives of the water quality of the effluent-bearing springs.
2. demonstration it gives of how pollutants from a point source in a limestone terrain can be widely dispersed
3. understanding it gives of how water moves in the ground and how caves can form.

It is the first distributary complex to be recognized as such and mapped. Grady Cave, an important 10-mile cave that feeds Grady Spring (Site 7) has subsequently been identified by Joseph Saunders as having a distributary system but during moderate and low flow all water goes only to a single spring.

Flow in limestones can be classified into two types -- diffuse and conduit (White, 1969). These are end-members of a continuum. In diffuse-flow aquifers water movement is through small interconnected joints and bedding planes. A water table is present; springs are small and numerous; circulation is deep; velocities are very low. In conduit-flow aquifers water movement is through well-integrated conduits. Springs are few, but their discharge is large. Flow may be very rapid.

Flow in the upper part of the principal aquifer in Central Kentucky, is disposed of by dumping it into a sinkhole about 1000 ft away. The sinkhole is grass-lined and lacks an accessible opening into the subsurface. Several years ago some of the sludge was used by local farmers as fertilizer.

According to Robert Ware (Sanitary Engineering Associate, Kentucky Division of Water Quality, Frankfort, verbal communication to D.R. Rowe, 1976) an August 1976 sample of digested sludge from the treatment plant has the following analysis (dry basis):

Chromium	15,440 mg/l
Nickel	13,607 mg/l
Copper	6,380 mg/l
Zinc	6,345 mg/l
Iron	5,393 mg/l
Lead	233 mg/l
Manganese	99 mg/l
Cadmium	6 mg/l

Sludge with such a high heavy metal content should not be put into a sinkhole. Since the sinkhole is not ponded it must be assumed that rainfall drains through its bottom. Such runoff can carry heavy metals into the subsurface and could potentially contaminate wells nearby. It is also possible that the soil that partially plugs the sinkhole bottom could collapse, thus putting a massive amount of toxic metals into the groundwater. We believe that the sludge from this plant should be properly treated before disposal. But until such proper treatment facilities are built and influent controls are established the sludge should be given alternative approved treatment. The sludge now produced should not be put into any sinkhole or spread on the ground.

GRAHAM SPRINGS GROUNDWATER BASIN

The sources of water to Graham Springs, just across the river from Bowling Green (Fig. 5, Basin A, and Fig. 21) have also been studied.

the one in which the active caves are forming, is by way of conduits. Flow in most wells, however, is diffuse. As discussed by Quinlan et al. (1975) it is theoretically possible for diffuse flow to be in one direction and conduit flow, because of subsurface piracy or other reasons, to be in a different direction. Accordingly, it is conceivable that although nearly all effluent from the Horse Cave wastewater treatment plant is discharged by conduit-flow at the effluent-bearing springs, as discussed, some could be moving west by diffuse-flow towards Mammoth Cave National Park. Such diffuse flow could contaminate wells in the intervening area and pose a threat to the subsurface fauna and flora of Mammoth Cave National Park. The probability of such diffuse-flow is very remote but if it occurs, it would be years before immediate remedial action could alleviate the problem. Wells in the intervening area should be monitored for heavy metals.

Sludge disposal

The sludge that is collected during the treatment of wastewater consists of organic and inorganic matter. After anaerobic digestion and drying it must be disposed of, usually in a sanitary landfill or by ocean dumping. Depending upon the nature of a sludge and the extent to which it has been digested, some can be used as a soil conditioner. Except for a deficiency of potassium, phosphates, and nitrates, such sludges are comparable with farmyard manure.

Sludge from the Horse Cave wastewater treatment plant is rich in organic matter because its metal content is toxic to the bacteria that would otherwise digest it.* About 1600 cubic ft per year of this sludge

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*Metals also kill the bacteria in the trickle filter which would otherwise digest the organic matter in the wastewater. This killing accounts for the high Biological Oxygen Demand of the effluent.

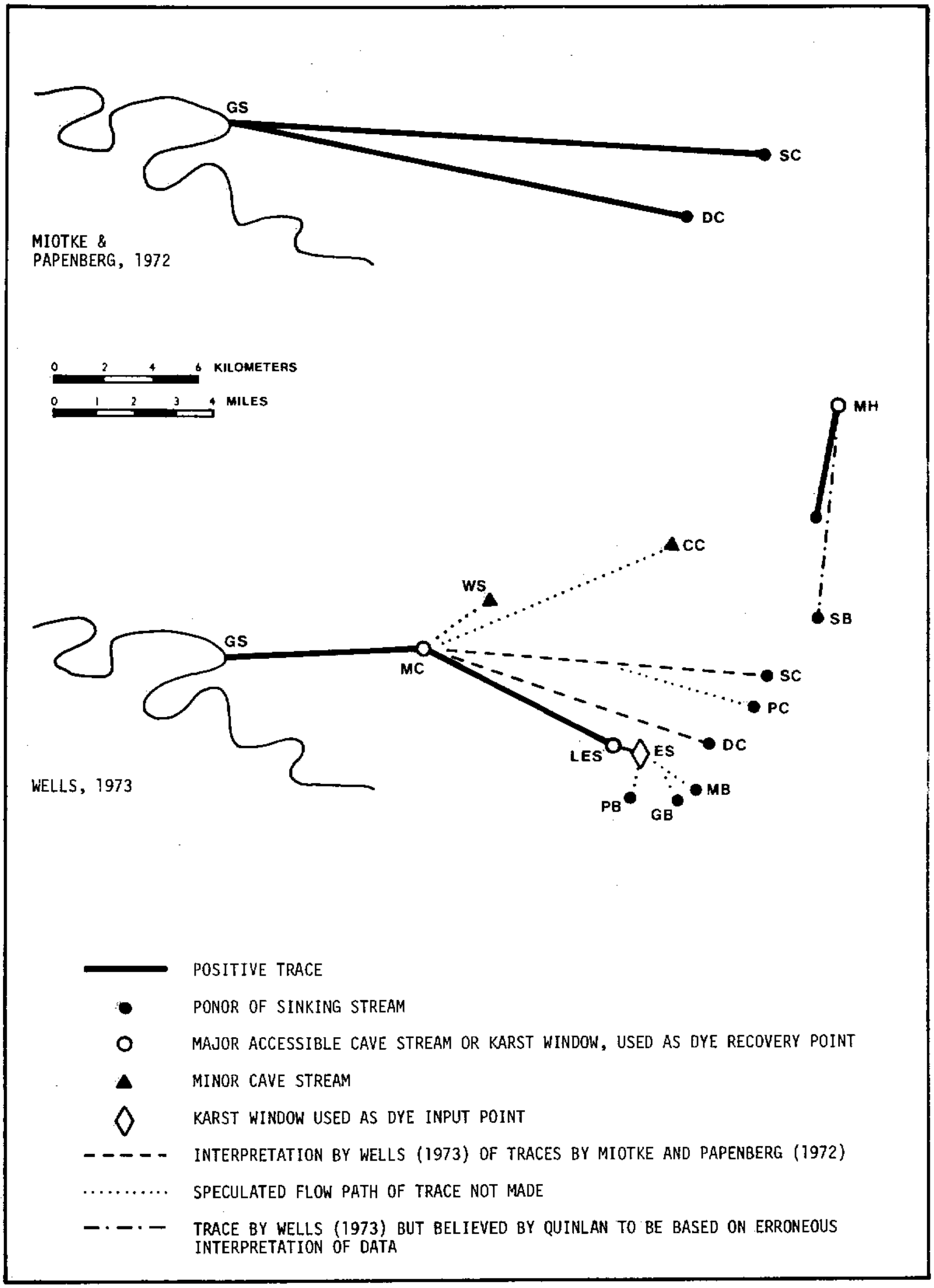

FIGURE 21 - Pre-November 1975 dye traces in the Graham Springs Groundwater Basin. The name of the various sites identified by letters is given in Table 12. Water was traced from the ponor (sinking point) of 5 streams but one of the flowpaths, from SB, was wrongly identified.

TABLE 12 - Names of sites within and adjacent to the Graham Springs Groundwater Basin

Main Trunk

GS	Graham Springs
GPC	Grant-Palmore Cave
MC	Mill Cave

Long Hollow Trunk

LHC	Long Hollow Cave
JS	Jackson Spring
MS	Meador Spring
LES	Little Elk Spring
MB	Meek Branch
PB	Petty Branch
ES	Elk Spring
BS	Bohannon Branch
GB	Grinstead Branch
MB	Madison Branch
RR	Robertson Run
CS	Cook Spring

Wolf Sink Trunk

WS	Wolf Sink (Cave)
CHC	Chicken Hollow Cave
MC	Mitchell Cave
CC	Crump Cave
MS	Madison Spring
CB	Cayton Branch
SS	Sledge Sinks
SG	Smiths Grove (town)
SB	Sinking Branch
SC	Sinking Creek
PC	Pondsville Creek
DC	Doty Creek

TURNHOLE SPRING GROUNDWATER BASIN

MH	Mill Hole
MS	Madison Spring
LSC	Little Sinking Creek

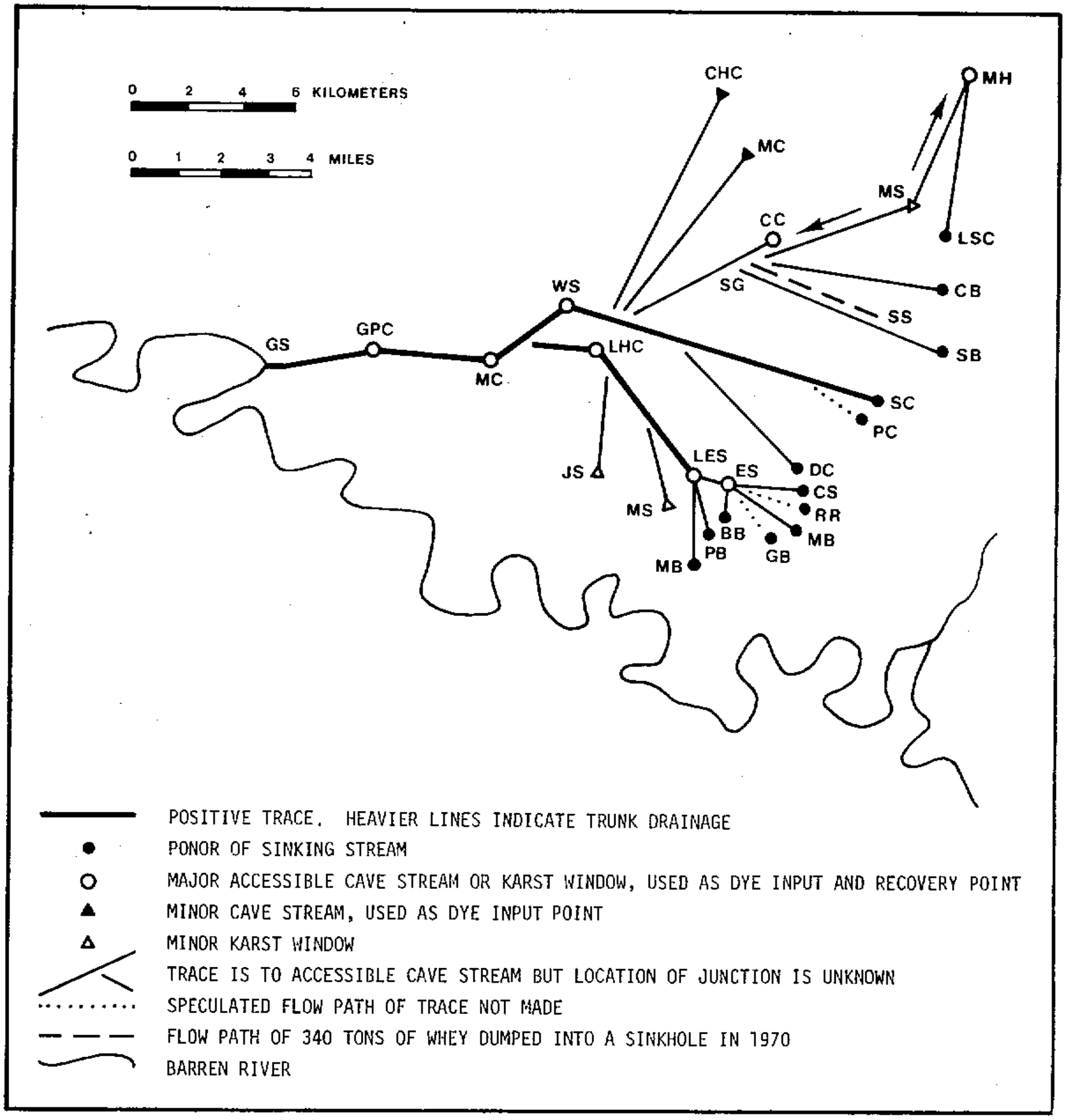

FIGURE 22 - Flow paths in the Graham Springs Groundwater Basin. The name of the various sites identified by letters is given in Table 12. Water has been traced from the ponor (sinking point) of ten sinking streams, three karst windows (sinkhole in which a stream emerges from one side, flows across the bottom, and sinks on the other side), and six caves to Graham Springs (GS), via one to three caves. This map schematically shows a dendritic subsurface drainage system in which two trunk streams, shown by heavy lines, converge to form a main trunk stream flowing to Graham Springs. Passage widths of these trunk streams are as much as 40 to 50 ft and water levels in them may rise as much as 100 ft in response to very heavy rains. During base flow conditions water from Madison Spring (MS) contributes flow to two groundwater basins, Graham Springs and Turnhole Spring. The extent to which these two groundwater basins partially overlap is not yet known, but as discussed by Quinlan (1976), their common boundary has been proven to shift during floods.

This is the largest spring in the Central Kentucky Karst. Flows of as much as 230 cfs have been measured by the U.S. Geological Survey (Miotke and Papenberg, 1972) but higher discharges occur. Graham Springs is a distributary complex of four alluviated rise pits, at least one of which is 50 ft deep.

Early dye tracing work is summarized in Fig. 21. One can see from it and from Fig. 22 that interpretation of dye tracing results is greatly aided by -- indeed, profoundly influenced by -- the availability of caves that intercept the regional drainage conduits. All of the caves shown have been mapped.

Although other dendritic subsurface drainage systems undoubtedly exist, the one shown is the first one in the world to be documented at so large a regional scale. The size of the trunk passages is described in the explanation of Fig. 22. Mapping and study of them has also given new insight into the mechanics of sinkhole development.

The dashed line on Fig. 22 shows the flowpath of the 340 tons of whey mentioned in the introduction as having been innocently dumped into a sinkhole in 1970. It contaminated the municipal well at Smiths Grove.

Use and application of maps showing flow paths and groundwater basin boundaries

Aside from the fact that the subsurface drainage patterns depicted by Figs. 5 and 22 are phenomenologically very interesting, these maps are rather useful. They can be used to predict:

1. Where sewage industrial effluent or other substances diliberately or accidently discharged into the ground will go.
2. Where pollutants in a domestic or municipal well probably came from --

thus making it possible to discover the probable source of such discharges sooner and stop them.

The most recent version of these maps could be usefully studied by individuals or agencies planning urban or industrial development.

The following is a specific application of these maps. Park City (1970 population: 576) does not have a sewage treatment plant. All domestic sewage is treated by septic tank or discharged directly into the ground, without treatment. Dye tests by Quinlan and Uplands Research Lab personnel have shown that surface water that drains into sinkholes at Park City flows to Echo River (Site 53), through Mammoth Cave.

Park City, Cave City, Horse Cave, and Munfordville have recently signed an agreement with an engineering consultant to plan for regional sewage disposal. This planning, to be done in compliance with section 201 of the Water Pollution Control Act of 1972 (Public Law 92-500), will evaluate the advantages and disadvantages of various types of regional sewage treatment. It will analyse costs, benefits, treatment plant designs, and environmental effects of various decisions to be made. For example, if a regional plant is to be built, what cities should it serve? All four or some? Where should it be located? We do not propose to recommend where it should be, but if the wastewater does not receive proper treatment the plant definitely should not be in the Park City area.

By use of Figs. 5 and 22 one can predict the probable consequences of subsurface disposal of effluent from a proposed regional wastewater treatment plant at various sites. It is to be stressed, however, that the groundwater basin boundaries drawn are tentative, work is still in progress, and the senior author should be consulted about the most recent work. Also, it would be wise to run tests from specific sites under consideration.

Work in progress

The following work is in progress and all or most of it will be discussed in the Phase II report:

1. Interpretation of analyses of spring, cave, and well waters in other areas of the Sinkhole Plain and Chester Cuesta, and an attempt to delineate areas of highest water quality.
2. Compilation and drafting of maps and limited continuation of mapping.
3. Dye tracing and continued delineation of groundwater basins.
4. Mapping of the piezometric surface and delineation of two or more aquifers beneath the Sinkhole Plain.
5. Compilation of a map showing the regional structure.
6. Continuation of spring surveys
7. Continued analysis of waters, but on a more limited scale.
8. Synthesis of the above in order to summarize structural, stratigraphic, and geomorphic controls on groundwater movement and quality.

CHAPTER IV

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

1. Heavy metal-laden effluent, with high concentrations of chromium, nickel, copper and zinc that greatly exceed maximums allowed by current standards, is discharged at the Horse Cave wastewater treatment plant. It flows to the entrance of Hidden River Cave where it is mixed with water from a much larger stream. From the cave the effluent-rich water travels at least 4.5 miles north to Green River where, depending upon flow conditions, it is discharged at as many as 39 springs at 14 locations over a 5-mile reach of the river. Some of these springs flow only after heavy rains, when they and the river are at flood stages. The heavy metal content of this effluent at Hidden River Cave still greatly exceeds maximums allowed by current standards but, by the time it reaches Green River, it is diluted to concentrations below the maximum allowed by current standards for public water supplies. The effluent-bearing spring waters have heavy metal concentrations that are as high as 30 times greater than other springs upstream or downstream, 20 times greater than the Green River, and 60 times greater than shallow domestic wells between the cave and the river. Mean ratios between concentrations at effluent-bearing springs and other springs, the river, and wells however, based on spring samples collected chiefly during conditions of moderate to flood flow, average 3.8, 4.4 and 4.5, respectively. The concentration of heavy metals in effluent-bearing springs is greatest during low flow because there is less water available for dilution. None of the operating wells between Horse Cave and Green River intercept the effluent-bearing water -- as proven by their relative lack of heavy

metals and their calcium/magnesium ratios, and as suggested by their lack of coliform bacteria. There is a slight theoretical possibility that a small amount of effluent moves by diffuse-flow toward Mammoth Cave National Park but this is not considered probable.

2. Interpretation of the anomalous heavy metal content and presence of optical brighteners uniquely in the 39 effluent-bearing springs, and consideration of the unusual uniformity of their specific conductance, led to the hypothesis that they were fed by a distributary complex unlike any known. Excavation of a spring led to the discovery of the hypothesized cave, 14.6 miles of which has been surveyed. Study of the cave map has made it possible to understand the hydrology and water quality of the springs and has given an insight into the geomorphic history of the area.
3. Thirteen groundwater basins have been recognized and their boundaries have been partially delineated. At least two of these basins partially overlap. Distributary flow systems are a property of ten of the thirteen groundwater basins. These flow patterns, hitherto unrecognized anywhere in North America, are extremely important because they enable pollutants from a point source to be dispersed over a broad area. Such flow patterns could occur in karst areas elsewhere in Kentucky and in other states.
4. Maps showing the boundaries of groundwater basins are exceedingly relevant to problems of sewage disposal, water supply, and industrial development. Knowledge of the flow direction of water in a basin enables prediction of where toxic (or other) pollutants will go or where they might originate. Such knowledge can guide wise location of new industrial facilities. It is to be stressed that some of the

boundaries of the groundwater basins are not yet known; others are only tentatively located.

5. Groundwater velocities in the upper part of the main aquifer range from 30 ft per hour to 1300 ft per hour -- depending upon the duration and intensity of rains. Most deeper water moves at an undertermined rate that is several orders of magnitude slower.
6. Sludge from the Horse Cave wastewater treatment plant has as much as 15,400 mg/l chromium, 13,600 mg/l nickel, 6,400 mg/l copper, 6,300 mg/l zinc, and other metals. The sludge is dumped into a surface depression that lacks an accessible outlet but it still could contaminate water supplies. The sludge should be properly treated but, until such facilities are available, it should be given alternative approved treatment. All sinkholes or other surface depression in a karst area should be regarded as recharge points for the conduit-flow and diffuse-flow of the aquifer. Surface depressions should never be used as disposal sites for any type of waste.
7. It is possible to geochemically discriminate between the waters of several of the groundwater basins studied. For example, the Hidden River Groundwater Basin is characterized by anomalous heavy metal and optical brightener concentrations and by generally uniform specific conductances. The Three-Springs Groundwater Basin is characterized by relatively high chloride, sodium calcium, and specific conductance. These anomalous properties are interpreted to be a result of slight contamination by brines released by drilling operations.
8. Ion-exchange reactions between clays and sodium, potassium, and chloride have been shown to probably occur in the conduit system conveying effluent-laden waters from Horse Cave to the Green River.

9. Water wells that might be drilled in the area between Horse Cave and Green River could intercept the conduit system that carries effluent to Green River. Not only would such water be unsuitable for use but, if the well were not properly cased, the aquifer could be contaminated; other wells, now safe, could also be contaminated.
10. The map of flow paths in the Graham Springs Groundwater Basin (Fig. 22) is a useful planning document. In this basin and in the Turnhole Spring Groundwater Basin (Quinlan, 1976) it can be shown that the plumbing system of the principal aquifer is very much analagous to the form of a major surface river. Low-order tributaries join intermediate-order tributaries that join high-order trunk streams as much as 40 ft wide that flow to a distributary complex or a large spring. Water levels in these trunk streams may rise and fall as much as 100 ft in response to heavy rains.
11. If the whey dumped into a sinkhole east of Smiths Grove had been dumped a few miles to the north and east, it could have flowed into Mammoth Cave National Park -- and potentially destroyed much or all of the unique fauna of a part of the park.
12. The facts and interpretations based on dye tracing results, flow velocities, and research on the geometry of caves are essential to the development of future computer simulations of groundwater movement in limestone -- if such simulations are in any way to model the real world.
13. Several large springs, Lawler Blue Hole, Gorin Mill, and Graham Springs, and Disappointment Lake (within the Hidden River Complex, at Point A, on Figs. 19 and 20) are potential sources of public water supply but, assuming water rights can be acquired, and neglecting

the costs of necessary treatment for sediment during high flow and perhaps for chemical quality, it would be expedient to:

1. Run pumping tests during low flow conditions -- in order to determine the sustained yield of the springs
2. Define the drainage basin boundaries as accurately as possible, by dye tests
3. Pass and enforce zoning ordinances that would assure protection of the water supply from toxic wastes.

14. It is possible that part of several of the major cave systems that underlie the Sinkhole Plain could be developed as public or industrial water supplies. In a sense, these caves could be considered as natural aquaducts. In a sense also, the caves could be considered as natural sewers. Corporate and regional planning decisions can be influenced by these alternatives.

15. We recognize that not all of this preliminary report is directly relevant to the interests of public officials within the study area. Accordingly, after completion of the Phase II report, we propose to make a large scale summary map of the groundwater basins. This map and the style of its text would be for general distribution.

BIBLIOGRAPHY

Allen, R.L.M., 1971. Colour Chemistry. London. Nelson. 422 p.

Barren River Area Development District, 1976. Barren River Area Development District 1976 Data Book 112 p.

Birge, W.J. & J.J. Just, 1974. Sensitivity of vertebrate embryos to heavy metals as a criterion of water quality: Phase I. University of Kentucky, Water Resources Research Institute. Research Report No. 71. 33 p.

Branstetter, J.A., 1974. Groundwater pollution as related to sewage disposal and water supply in a limestone terrane, Horse Cave, Kentucky. Independent Research Report, U. of Ky., 45 p. (Copy held by the Munfordville Public Library).

Cheremisinoff, P.N., A.J. Perna, & J. Ciancia, 1976. Treating metal finishing wastes: Industrial Wastes, v. 22, no. 6, p. 31-34.

Collins, A.G., 1974. Geochemistry of liquids, gases, and rocks from the Smackover Formation: U.S. Bureau of Mines, Report of Investigations 7897, 84 p.

Crabtree, H., 1970. Water tracing with optical brightening agents: Univ. Leeds Speleological Assoc., Review. no. 7, p. 26-28.

Drew, D.P., 1976. The Limestone Hydrology of the Mendip Hills, *in* Smith, D.I. & D.P. Drew, *eds.* Limestones and Caves of the Mendip Hills. David & Charles, Newton Abbot, p. 171-213.

Environmental Protection Administration, 1973a, Water Quality Criteria, 1972. EPA Report R 3.73.033.

Environmental Protection Agency, 1973b. In-process pollution abatement: upgrading metal-finishing facilities to reduce pollution: EPA Technology Transfer Seminar Publication, Report 625/3-73-002. v. 1, 69 p.

Environmental Protection Agency, 1975. Interim Primary Drinking Water Standards. Federal Register, v. 40, no. 51, p. 11989-11998.

Glover, R.L., 1972. Optical brighteners -- a new water tracing reagent. Cave Research Group of Great Britain, Trans. v. 14, no. 2, p. 84-88.

Gospodarič, R. & P. Habič, 1976. Underground Water Tracing: Investigations in Slovenia 1972-1975. Institute for Karst Research, SAZU, Ljubljana. 312 p.

Hensley-Schmidt, Inc. 1973. Comprehensive Water and Sewer Plan, Barren River Area Development District. 277 p.

Hess, W., Jr. & W.B. White, 1974. Hydrograph Analysis of Carbonate Aquifers, Pennsylvania State University, Institute for Research on Land and Water Resources, Research Publication No. 83. 63 p.

Holmes, M.A., 1974. Water quality of springs and underground streams in the Central Kentucky Karst. National Science Foundation SOS Project GY 11479, Completion Report. 151 p.

Izaak Walton League of America, 1973. A citizen's guide to clean water. Izaak Walton League of America, Washington, D.C. 94 p.

Kentucky Department of Natural Resources and Environmental Protection, 1973. Public and Semi-Public Water Supplies. Frankfort.

Lambert, T.W., 1976. Water in a limestone terrane in the Bowling Green Area, Warren County, Kentucky. Ky. Geological Survey, Series X, Report of Investigations 17. 43 p.

Langmuir, D., 1971. The geochemistry of some carbonate groundwaters in central Pennsylvania: Geochemica et Cosmochimica Acta, v. 35, p. 1023-1045.

Little, L.W. & M.A. Chillingworth, 1974. Acute toxicity of 10 selected basic dyes to the fathead minow, Pimephales promelas, in Dyes and the Environment. American Dye Manufacturers Institute, Inc., New York. v. 2, ch. 4, 23 p.

Matera, A., 1975. Sewer overloaded: Ken-Dec, Inc. & Hart County Creameries complex cited: Hart County Herald, July 17, 1975.

Milk Industry Foundation, 1967. Manual for Milk Plant Operators, 3rd ed. Milk Industry Foundation, Washington, D.C.

Miotke, F-D., 1976. Die Höhlen im Mammoth Cave-Gebiet (Kentucky). Würzburg, Böhler Verlag. 133 p.

Miotke, F-D., 1975. Der Karst im zentralen Kentucky bei Mammoth Cave: Geographische Gesellschaft zu Hannover, Jahrbuch für 1973. 360 p.

Miotke, F-D. & H. Papenberg, 1972. Geomorphology and hydrology of the Sinkhole Plain and Glasgow Upland, Central Kentucky Karst: Preliminary Report. Caves and Karst, v. 14, p. 25-32.

Palmer, A.N., 1975. The origin of maze caves: National Speleological Society, Bulletin. v. 37, p. 57-76.

Palmer, M.V. & A.N. Palmer, 1975. Landform development of the Mitchel Plain of southern Indiana: origin of a partially karsted plain. Zeitscrift für Geomorphologie. n.s. v. 19 p. 1-39.

Payton, L.S., 1932. A sanitary report on the water supply and sewage disposal systems in the city of Horse Cave, Kentucky. MS(?) Thesis, University of Kentucky, Lexington. 50 p.

Quinlan, J.F., 1977. New fluorescent direct dye suitable for tracing groundwater and detection with cotton: International Symposium of Underground Water Tracing, 3rd (Ljubljana-Bled, Yugoslavia; Sept. 1976), Proceedings (in press)

Quinlan, J.F., 1976. Hydrology of the Turnhole Spring Drainage Basin and vicinity, Kentucky: Guidebook. International Symposium on Hydrologic Problems in Karst Regions, Western Kentucky University, Bowling Green, Ky. 21 p.

Quinlan, J.F., 1970. Central Kentucky Karst. Réunion Internationale Karstologie in Languedoc-Provence, 1968, Actes: Meditarenée, Etudes et Travaux, v. 7, p. 235-253.

Quinlan, J.F., M.R. McCann, W.M. Andrews, & J.A. Branstetter, 1975. Heavy metals and optical brighteners as groundwater tracers in the Central Kentucky Karst: Implications concerning regional hydrology (abs): International Association of Hydrogeologists, Karst Hydrology Congress, Abstracts, p. 82. Pub. by Alabama Geological Survey.

Quinlan, J.F. & D.R. Rowe, 1977. Review of the physical hydrology of the Central Kentucky Karst: International Symposium on Hydrologic Problems in Karst Regions (Western Kentucky University, Bowling Green, Ky., April 1976), Proceedings. (in press)

Smart, P.L., 1976. The use of optical brighteners for water tracing: British Cave Research Association, Trans. v. 3, no. 2, p. 62-76.

Smart, P.L., 1972. A laboratory evaluation of the use of activated carbon for the detection of the tracer dye Rhodamine WT. MS Thesis, U. of Alberta. 118 p.

Smart, P.L. & I.M.S. Laidlaw, 1976. An evaluation of some fluorescent dyes for water tracing: Water Resources Research. (in press)

Turner Associates, G.K., 1971. Fluorometry studies of pollution and movement of fluids: Fluorimetry Reviews, May 1971. G.K. Turner Associates, Palo Alto, Calif. 12 p.

U.S. Army Engineer District, Louisville, 1975. Continued Operation and Maintenance, Green and Barren Rivers, Kentucky -- Final Environmental Impact Statement. 525 p.

U.S.D.A. River Basin Planning Staff, 1975. Report For Green River Basin, Kentucky-Tennessee. U.S. Dept. of Agriculture Field Advisory Committee, Lexington, Ky. 189 p.

U.S. Public Health Service, 1962. Drinking Water Standards. Public Health Service Publication no. 956, 61 p.

Wells, S., 1973. Geomorphology of the Sinkhole Plain in the Pennyroyal Plateau of the Central Kentucky Karst. MS Thesis, University of Cincinnati. 108 p.

Weston, Roy F., Inc. 1976. The River Basin Water Quality Management Plan for Kentucky, v. 3, Green River Basin. Prepared as Section 303 Report for the State of Kentucky. 320 p.

White, W.B., 1969. Conceptual models for carbonate aquifers: Ground Water v. 7, p. 15-21.

White, W.B., R.W. Watson, E.R. Pohl, & R. Brucker, 1970. The Central Kentucky Karst. Geographical Review. v. 60, p. 88-115.

Zötl, J.G., 1974. Karsthydrogeologie. Springer Verlag, Vienna. 291 p.