WATER AVAILABILITY AND VULNERABILITY OF GROUND WATER TO CONTAMINATION IN NORTHWESTERN HARDIN COUNTY, KENTUCKY

By D.S. Mull, Robert J. Faust, and Gary R. Martin

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CONVERSION FACTORS

For readers who prefer International System (SI) units rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.305	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
foot per second (ft/s)	0.305	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Ground water is the source of water for about 27,000 people served by the Hardin County Water District Number 1 in northwestern Hardin County in north-central Kentucky. Water is obtained from four wells in the alluvial aquifer bordering the Ohio River near West Point, Kentucky, and from Pirtle Spring, a large karst spring near Howe Valley. Some wells in the alluvium are producing water that contains elevated levels of chloride, and Pirtle Spring cannot satisfy current water demand during prolonged dry periods. Supplemental sources of high-yield, good quality water are needed.

The alluvial aquifer near West Point is the most favorable site for high-yield wells. However, present conditions indicate that the concentration of chloride in water from the well field is likely to increase. This will limit the quantity of usable water available from wells in the aquifer.

The principal bedrock aquifer in the study area consists of limestone and dolomite of the St. Louis and Ste. Genevieve Limestones of Mississippian age. Well yields are controlled by the nature of solution-enlarged fractures penetrated by wells. High-yield bedrock wells were not inventoried in the study area; however, individual wells are known to yield about 500 gallons per minute from the same aquifers in the Elizabethtown area, about 8 miles east of the study area. Areas most favorable for high-yield wells are in the southwestern part of the study area near Pirtle Spring and were identified on the basis of geology, water-level contours, and fracture-trace lineaments identified on aerial photographs.

Potential surface water-supply sources are the Ohio, Rough, and Salt Rivers. Use of the Ohio River is limited because of State restrictions on the placement of public water-supply intakes within 5 miles downstream of sewage treatment plant outfalls. The potential for the Rough River as a water-supply source is limited because of its relatively small watershed in the study area. Its 7-day, 10-year low flow is about 2.9 million gallons per day. Abundant water is available from the Salt River above its confluence with the Ohio River at West Point.

Pirtle and Head of Rough Springs are the largest springs in the study area. The drainage basins for both springs are typical karst terranes with abundant sinkholes and karst windows which funnel surface runoff into the ground-water system. Results of the tracer tests and quality of water data indicate that the ground-water basins draining to these springs are not connected and that runoff from farmlands as far as 6 miles to the east drains to Pirtle Spring. Ground-water velocity ranged from about 5 to 15 feet per minute during low-flow conditions. Widely fluctuating values of specific conductance and turbidity in water from the springs indicate that ground-water

flow is primarily through solution-enlarged, pipe-like openings. This results in fairly rapid flow which can transport potential contaminants to the wells or springs. Thus, both springs are vulnerable to contamination from surface sources.

INTRODUCTION

The Hardin County Water District Number 1 (HCWD #1) provides water to about 27,000 people in northwestern Hardin County, Kentucky. Future growth and development in the area served by the HCWD #1 is dependent in part on a reliable source of good quality water. The HCWD #1 obtains water from four wells in the Ohio River alluvial aquifer downstream from West Point and from two wells that tap a conduit draining to Pirtle Spring. Two wells in the alluvial aquifer are having contamination problems from chlorides, oil and grease, and radionuclides, and the wells at Pirtle Spring decline in yield during prolonged dry periods. Thus, additional sources of water are needed to enable the HCWD #1 to provide dependable supplies to their consumers and to provide for expected growth and development. The U.S. Geological Survey and the Water District began a study to evaluate additional sources of water that could be used to augment current supplies and to assess the vulnerability of existing water supplies to contamination.

Purpose and Scope

The purpose of this report is to present information on potential ground- and surface-water sources in northwestern Hardin County and to assess the vulnerability of ground-water sources to contamination. The information consists of a discussion on the water-bearing characteristics of the aquifers, flow of major springs and streams, field and laboratory analyses for selected water-quality characteristics, results of dye traces, and potential water-quality problems in the alluvial and karst aquifers in the study area. The area of study is about 113 mi^2 (square miles) in northwestern Hardin County in north-central Kentucky (fig. 1).

Description of Study Area

Physiography

The study area lies within the Interior Low Plateaus physiographic province (Fenneman, 1938) and contains a diversity of topographic features. Except for the northern and western edges of the study area, the major topographic feature is a sinkhole plain named the Pennyroyal (Sauer, 1927, p. 21). The sinkhole plain in the study area is bordered by Muldraugh's Hill to the north and the Dripping Springs escarpment to the west. The Pennyroyal is a gently rolling broad upland (dissected in places) that slopes to the southwest, is underlain by soluble limestone, and is characterized by karst

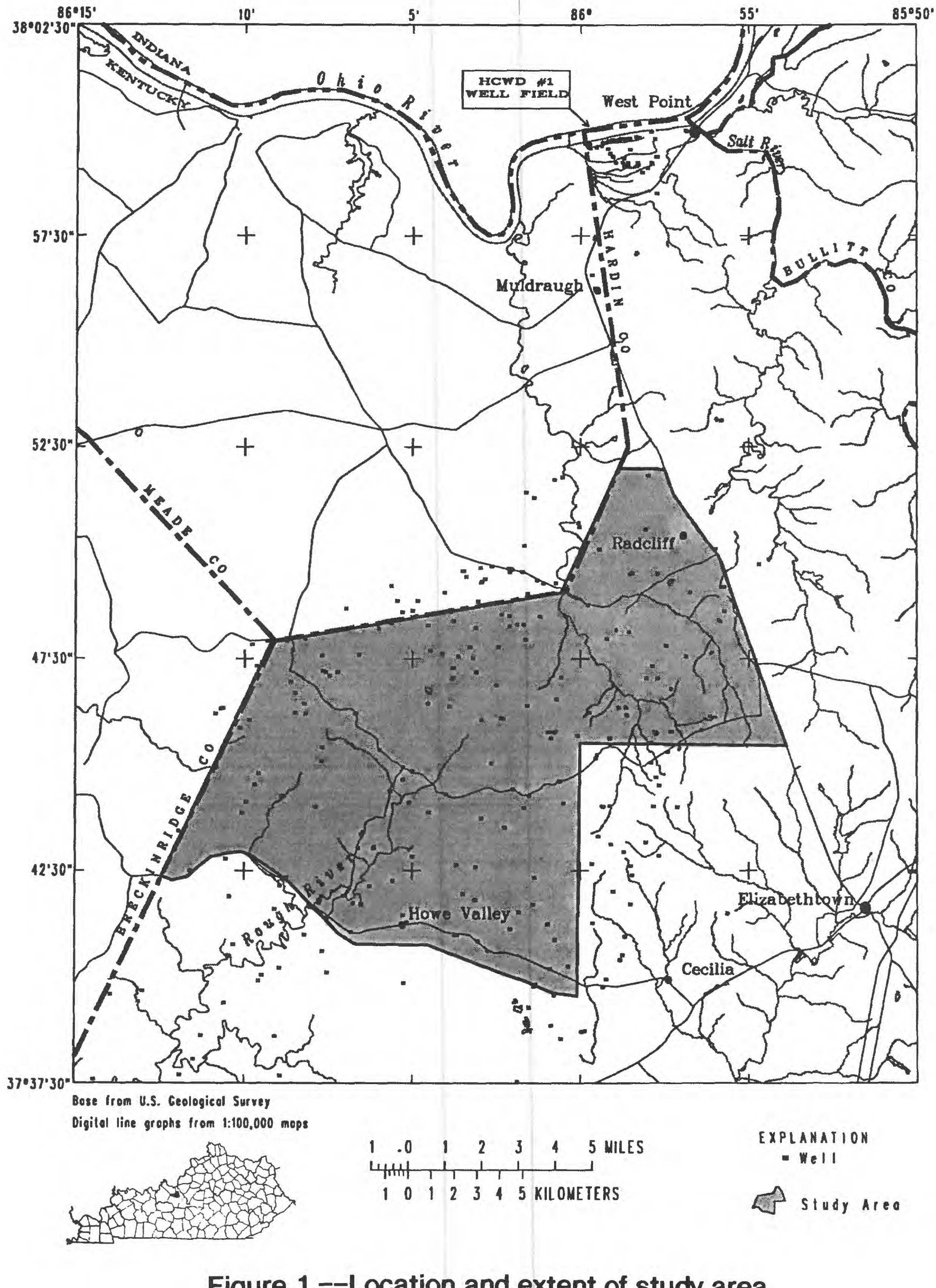


Figure 1.--Location and extent of study area.

features such as sinkholes, springs, and subsurface drainage. There are many high level caves, but most are of limited lateral extent. One of the longest explored passages is reported to be about 3,100 feet in length and is part of the subsurface conduits which link the karst window at Stiles Spring to the resurgence at Pirtle Spring (George and McCarty, 1983).

Altitudes on the sinkhole plain generally range from 800 to less than 700 feet at the base of the Dripping Springs Escarpment. The lowest altitude, Rough River near Vertrees, is about 610 feet above sea level; the highest, Blueball Hill, is about 1,017 feet. The relief in most of the sinkhole plain is less than 150 feet. The lowest altitude is actually at the Ohio River near the HCWD #1 supply wells in the alluvial aquifer, but this area is outside the service area of the Water District. The smaller streams usually flow in shallow channels less than 5 feet deep in regolith or alluvium. The northern part of the area is drained to the Ohio River by Otter Creek and its tributaries.

The Dripping Springs Escarpment marks the boundary between the sinkhole plain and a higher upland along the western and southwestern part of the study area. This upland is fairly rugged and is dissected by stream drainage which is incised about 200 feet. Resistant beds of sandstone and shale form broad, flat-topped ridges which rise about 200 feet above the level of the sinkhole plain and lie in areas between narrow stream valleys. Valley walls are steep and cliffs are present. Sinkhole development is generally limited to beds of limestone which have been exposed due to faulting or in valley bottoms where the overlying resistant units have been removed by erosion.

The study area also includes about 5.7 mi^2 of a cut-off meander of the Ohio River, about 2.6 miles west-southwest from West Point, Kentucky, and about 9 miles northeast of Radcliff. Four wells, drilled in the alluvial aquifer in this valley, supply water for the water-treatment plant at Muldraugh, about 7 miles north of Radcliff. This area is gently rolling and altitudes range from about 440 feet near the base of the valley wall on the south side of the area to less than 400 feet at the Ohio River on the north side.

Precipitation

Rainfall is the principal source of water in the study area. Based on precipitation records from 1950 to 1988 at Cecilia and at St. John Bethlehem Academy, Elizabethtown, the average annual precipitation in the study area is approximately 48 inches. However, precipitation is not evenly distributed throughout the year (fig. 2). For example, in 1982 the wettest month was January; October was the driest month, and February, June, and November were the next driest. Precipitation also can vary considerably within fairly short distances. For example, the variation in monthly precipitation between Cecilia and Elizabethtown, a straight line distance of approximately 5-1/2 miles, was as much as 4.10 inches in July 1982 (fig. 2).

Long-term precipitation trends are useful for evaluating water availability. The cyclic nature of precipitation is shown by the cumulative departure curve in figure 3. The curve shows how much the cumulative

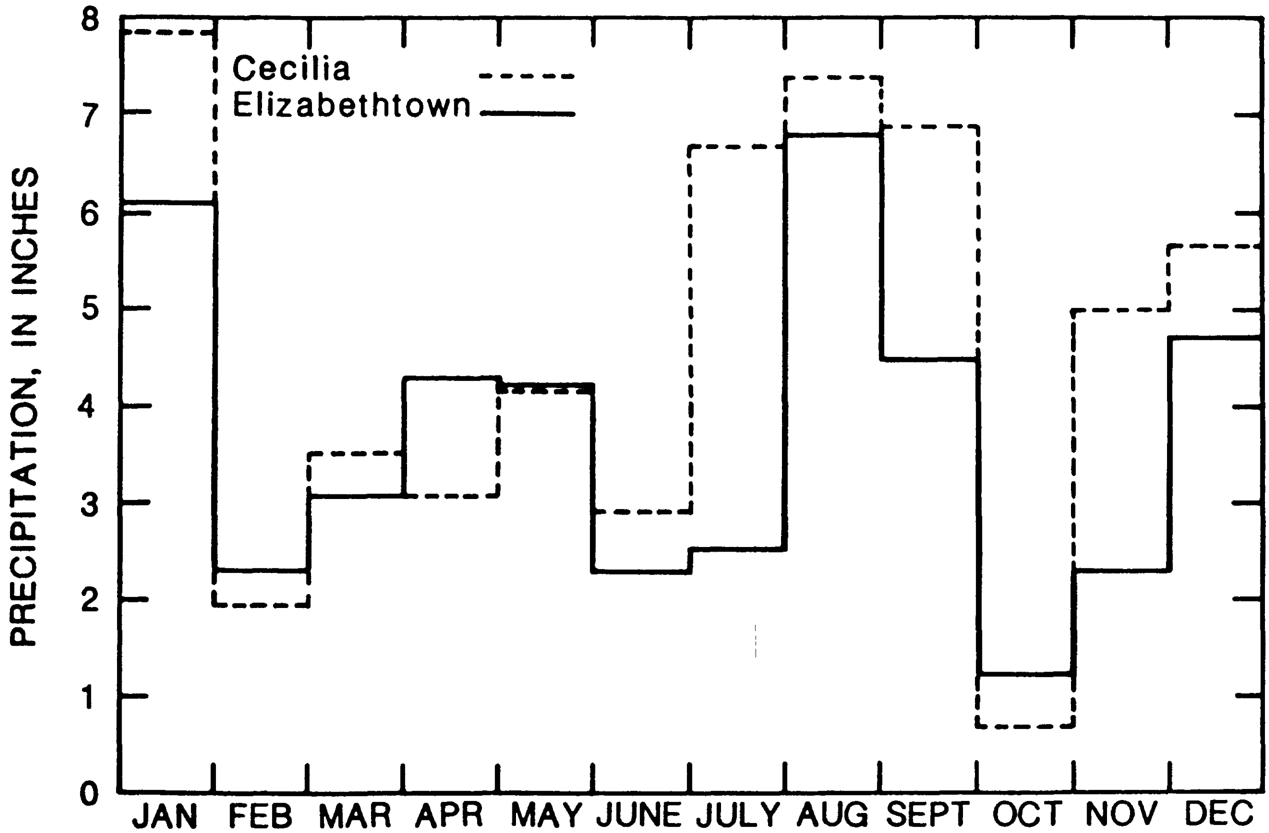


Figure 2.--Comparison of monthly precipitation at Cecilia and Elizabethtown, 1982.

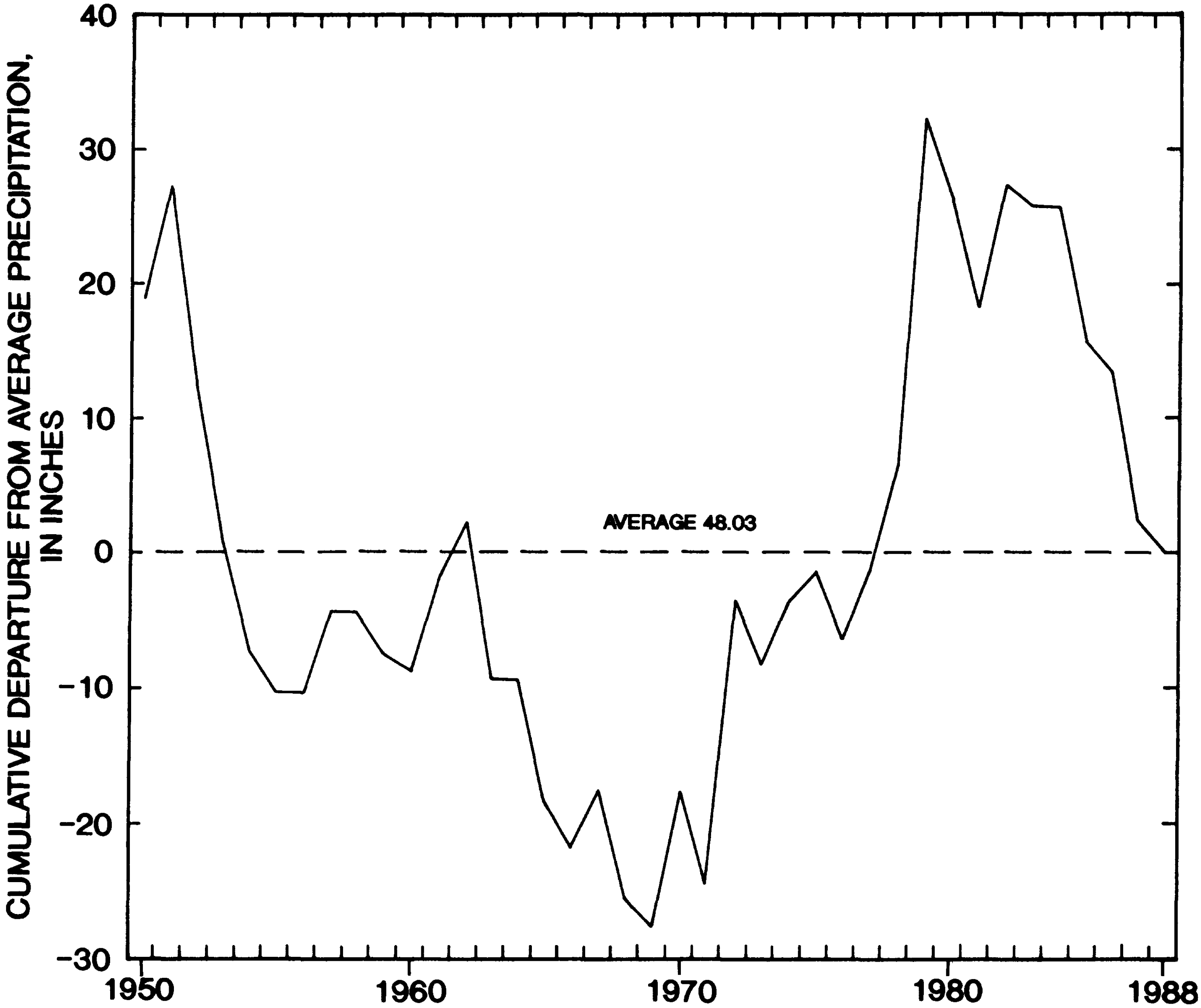


Figure 3.--Cumulative departure from average precipitation at Elizabethtown, 1950-88.

precipitation for the period 1950-88 varied above or below the average annual precipitation. Furthermore, the curve shows that the periods between 1953-69 and 1980-88 were periods of generally deficit precipitation. The maximum deficit was about 27.5 inches in 1969. The deficit decreased rapidly beginning in 1970, and by 1979 there was a cumulative surplus of approximately 32 inches.

Previous Investigations

Several published reports discuss the geology and water resources of the study area. Most recently, Lyverse and Unthank (1988) prepared an assessment of ground-water contamination in the alluvial aquifer near West Point, the location of wells which are a major source of water for the HCWD #1. Brown and Lambert (1963a and 1963b) described the geology and water resources of the Mississippian Plateaus region of Kentucky which includes northwestern Hardin County. Plebuch and others (1985) described the geology, water quality, and the regional potentiometric surface in the Mississippian Plateaus region of Kentucky. The fresh-saline water interface in rocks underlying the study area is shown on a map of Kentucky at a scale of 1:500,000 by Hopkins (1966). The U.S. Geological Survey has published detailed geologic maps at the scale of 1:24,000 for the Big Spring (Peterson, 1964), Cecilia (Kepferle, 1963a), Constantine (Sable, 1964), Flaherty (Swadley, 1963), Fort Knox (Kepferle and Sable, 1977), Howe Valley (Kepferle, 1963b), and Vine Grove (Kepferle, 1967) 7-1/2 minute quadrangles. Reports that cover a part of the study area or ground-water resources in adjacent areas are those by Lambert (1979), Mull and Lyverse (1984), Mull and others (1988), and Mull and others (1989). Data on basin characteristics and low flow of streams are presented in reports by Melcher and Ruhl (1984) and Sullavan (1984).

Methods of Investigations

Following a review of existing hydrologic data, wells that were accessible for water-level measurements and springs were inventoried. Generally, the inventoried sites were selected so that the distance between sites did not exceed 1 mile. The inventoried wells are shown in figure 1. The approximate altitude at each site was determined from 7-1/2 minute topographic maps at a scale of 1:24,000. Water levels were measured during dry periods to lessen the effect of locally heavy rains. The altitude of water levels from selected wells and springs were used to draw the generalized potentiometric surface on plate 1.

A field reconnaissance of sinkholes and sinking streams was completed to locate potential dye-input points for dye-tracer tests to Pirtle and Head of Rough Springs. The selection of dye-input points was based on the susceptibility of the site to receive surface runoff directly from roadways or farmlands, and the apparent upgradient location of the sinkhole with respect to springs as shown by the water-level contour map (pl. 1). Both qualitative and semi-quantitative dye traces were completed to identify subsurface connections between selected sinkholes and the two major springs. These techniques are summarized in this report.

Miscellaneous discharge measurements were used to quantify the discharge from Pirtle and Head of Rough Springs under low-flow conditions. Discharge measurements at selected springs were used to define the downgradient increase in discharge, especially during dye traces.

Field measurements of temperature and specific conductance were made in all springs and selected wells. Turbidity was measured in water samples from Pirtle and Head of Rough Springs.

Acknowledgments

The authors are grateful to the many individuals who granted access and provided information on their wells and springs and to those land owners who granted access to their property for the purpose of inspecting springs, sinking streams, and sinkholes. Personnel at the HCWD #1 water-treatment plant at Pirtle Spring collected water samples during dye-tracer tests and performed turbidity tests. The assistance and cooperation of these individuals contributed significantly to the investigation.

WATER USE

Most of the water users in the study area are supplied by the HCWD #1. There are no withdrawals by self-supplied industrial users in the HCWD #1 service area. The Water District currently relies on ground water as its supply source. The ground water is treated by two separate plants; one plant at Muldraugh on the northern edge of the service area with a capacity to treat 2.16 Mgal/d (million gallons per day) of water supplied by the West Point well field, and a second plant at Pirtle Spring near the southern edge of the service area with a treatment capacity of 2.3 Mgal/d.

The West Point well field consists of four wells drilled in the Ohio River alluvium; whereas, at Pirtle Spring, two bedrock wells tap conduits draining to the spring. Until September 1986, water was withdrawn from a reservoir supplied by Sanders Spring near the northeastern boundary of the study area. This source was abandoned in August 1986 (William Smallwood, HCWD #1, oral commun., 1989).

The average daily withdrawals from each source, based on the water withdrawal permit file of the Division of Water, Kentucky Natural Resources and Environmental Protection Cabinet, are shown graphically in figure 4. Except for 1985 and 1987, the water demands of the HCWD #1 have increased steadily since 1984. Water needs of the Water District are estimated to be about 4.6 Mgal/d for the year 2000 (William Smallwood, HCWD #1, written commun., 1990).

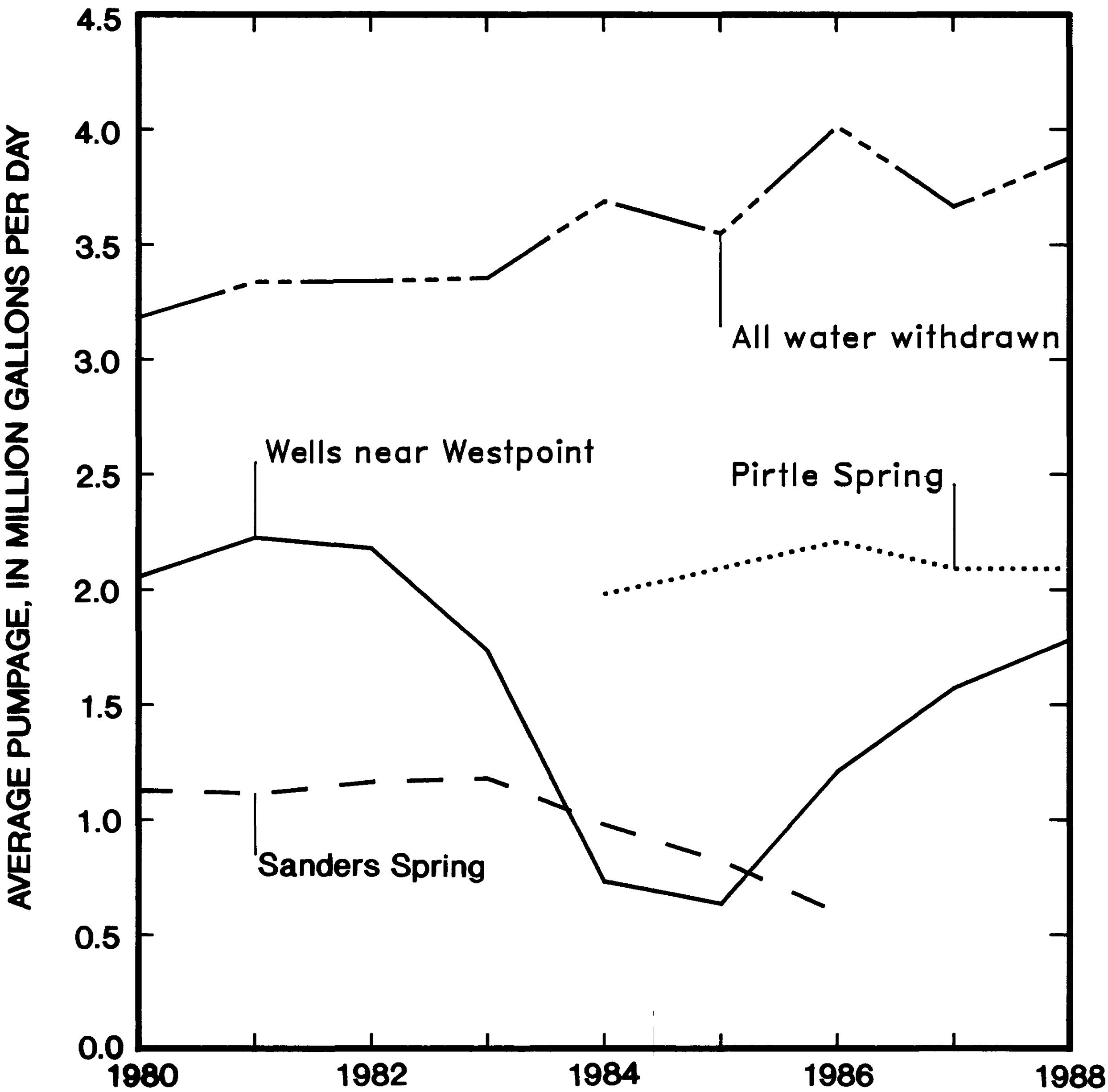


Figure 4.--Source and amount of water withdrawn by the Hardin County Water District Number 1 water system, 1980-88.

HYDROGEOLOGIC FRAMEWORK

Geology

The geologic units in west-central Kentucky are shown in figure 5. Many of these units are present in the study area but only the Ste. Genevieve and St. Louis Limestones are important water-bearing bedrock units. Thus, the following discussion focuses on these units. The geology is discussed in more detail in reports by McFarlan (1943), Brown and Lambert (1963a) and Lambert (1979). Detailed geologic maps at the scale of 1:24,000 are available for each topographic quadrangle of the study area and these are listed in Previous Investigations and in the Selected References.

The St. Louis Limestone ranges from about 200 to 310 feet in thickness in the study area and consists of limestone, chert, dolomite, and thin shale beds. It is the major bedrock unit near land surface in the study area and it is the principal ground-water aquifer. Interbedded limestone, gypsum, and anhydrite occur in the lower part of the formation in places (Kepferle and Peterson, 1964; McGrain and Helton, 1964; Moore, 1964; and George, 1982).

The Ste. Genevieve Limestone overlies the St. Louis Limestone and consists of light gray to almost white, partly oolitic, massive to thin-bedded limestone interbedded with medium-gray dolomitic limestone. Some beds have abundant chert. Locally it contains greenish-gray, fine-grained sandstone and siltstone beds up to 10 feet in thickness in the upper part of the unit. The formation weathers to a deep red or maroon clay containing abundant residual chert. The formation is about 80 feet in thickness in the study area where the entire unit is present. However in most of the study area erosion has removed part of the unit. The Ste. Genevieve Limestone is separated from the underlying St. Louis Limestone by the Lost River chert bed of Elrod (1899). The Lost River chert bed is about a 10-feet zone of limestone containing coarse fossil fragments and abundant chert. The unit is generally marked at the surface by rough-weathered blocks and slabs of chert.

In places, the Ste. Genevieve and St. Louis Limestones are overlain by unconsolidated regolith and slumped material. The regolith consists of clay and chert from weathered limestone and it rests on an irregular karst surface of the underlying karstified limestones. It is relatively thin but may be as much as 70 feet in thickness. The slumped material occurs as irregular lenses and ridges and consists of sand, clay, and boulders of limestone that may be as much as 120 feet in thickness. The material was derived from overlying rocks that slumped in caverns during an early cycle of karst erosion (Kepferle, 1967).

The near surface geologic units dip about 20 to 30 feet per mile to the southwest in the study area. Numerous faults occur in the western part of the study area. One prominent fault zone trends northeast to southwest just west of Pirtle Spring and Head of Rough Spring.

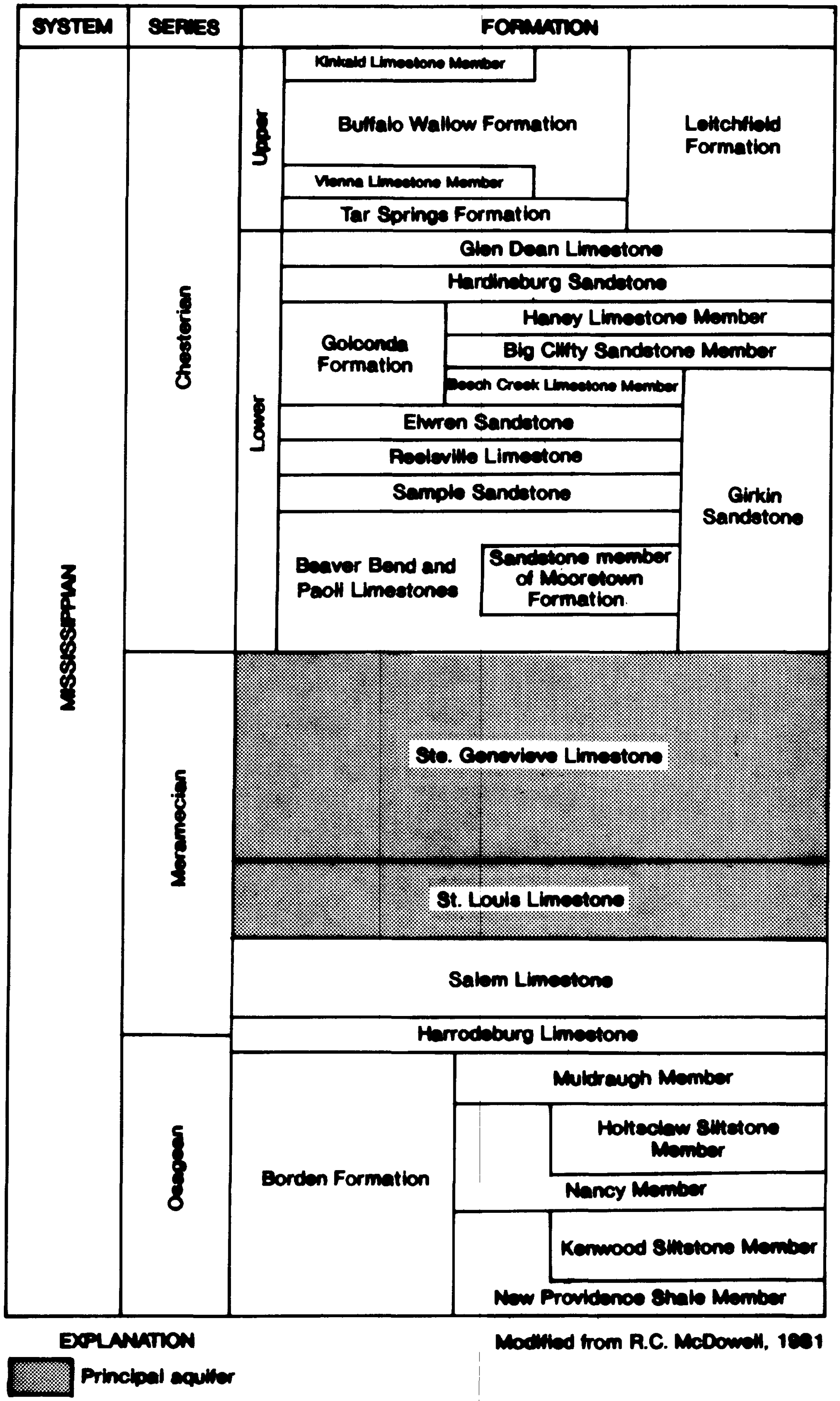


Figure 5.--Stratigraphic column for west-central Kentucky and formations which form the principal bedrock aquifer in Hardin County.

Karst Features

The term karst refers to distinctive features commonly developed in areas of carbonate rock such as limestone or dolomite. The development of karst features is controlled in part by the geology and structure. In addition to soluble bedrock, the principle requirement for karstification is the presence of openings along joints or bedding planes that permit the circulation of ground water sufficient to enlarge the openings through the solution and removal of bedrock.

Although some karst landforms such as sinkholes may develop in the zone of unconsolidated regolith overlying bedrock, it is the presence of solution-enlarged openings in bedrock that ultimately controls the development of such features. Most karst features are hydrologically significant because of their unique relation to the ground-water system; that is, they collect and discharge water into, store and transmit, or discharge water from the ground-water system. Karst features common in the study area includes sinkholes, karst windows, springs, and caves.

Sinkholes

As used in this report, the term sinkhole refers to an area of localized land surface subsidence, or collapse, due to karst processes which result in a closed depression. In general, there are two types of collapse that form sinkholes: (1) collapse of limestone cave roofs or regolith arches overlying openings in bedrock and (2) slumping of surface material into solution-enlarged openings in limestone bedrock. Sinkholes caused by the collapse of cave roofs can develop suddenly when the cave roof can no longer support itself above the underlying passage. Slumping of material into subsurface openings may occur gradually or develop suddenly.

The principal cause of sinkhole development in the study area is slumping of regolith, which is unconsolidated material overlying bedrock, into openings in the underlying bedrock. This migration usually results in the gradual formation of the typical funnel-shaped depression in the land surface. Although sinkholes generally develop gradually during this process, dramatic and sudden collapses have been reported in the study area. For example, several landowners north of State Highway 86 near Howe Valley reported sudden collapse of sinkholes, and the authors observed several collapsed sinkholes in pastures north of State Highway 1357, near Head of Rough Spring. These sinkholes have vertical sides and a sharp break of the soil rim which is characteristic of sudden collapse of the unconsolidated material over bedrock rather than development through gradual subsidence of the surface material.

Hundreds of sinkholes are present in the study area, but the distribution is irregular and the density varies considerably from place to place. Much of this variation is probably related to geology and structure, especially the outcrop pattern of the chert horizons in the lower Ste. Genevieve and upper St. Louis limestones. Because of the limitations of scale, sinkholes may be more abundant than shown by topographic contours on the 7-1/2 minute topographic maps.

Sinkholes are circular to irregular in outline and range in diameter from less than 10 to about 3,000 feet. A few are as deep as 80 feet below the surrounding area. In general, increasing sinkhole development is accompanied by complexity of form such as elongation of the depression or the coalescing of smaller sinks. For example a sinkhole, whose major axis is about 4 miles in length and trends in a northeasterly and southwesterly direction near the community of Howe Valley, intersects another sinkhole about 1.5 miles in length which trends almost due east.

There are numerous systems for the classification of sinkholes based on characteristics as varied as their formation process, size and orientation, and relation to surface runoff and the water table. The classification system suggested for the study area is based on the relative ability of the sinkhole to transmit water to the subsurface which emphasizes the interrelation between sinkholes and the ground-water system. This system was used by Mull, Smoot, and Liebermann (1988) to identify those sinkholes with the greatest potential for contaminating the ground water in the Elizabethtown area, Kentucky, which is similar to the study area. The sinkhole classification criteria are based on the material in which the sinkhole is developed and the presence or absence of swallets (drain holes). These criteria describe four types of sinkholes:

(1) Sinkholes developed in unconsolidated material overlying bedrock with no bedrock exposed in the depression, but with well developed, open swallets that drain into bedrock;

(2) Sinkholes that have bedrock exposed in the depression and a well developed swallet that empties into bedrock;

(3) Sinkholes or depressions in which the bottom is covered or plugged with sediment and in which bedrock is not exposed; and

(4) Sinkholes in which bedrock is exposed but the bottom is covered or plugged with sediment.

Sinkholes of types 1 and 2 generally have the greatest potential for transporting polluted ground water because the open drain is usually connected to subsurface openings that lead directly to the ground-water system. Although sinkhole types 3 and 4 may be hydraulically connected to the ground-water system, the potential for transporting polluted water is generally less than from sinkholes with open drains because the percolation of water through sediments may provide some enhancement of quality before the water reaches the aquifer.

The nature of the swallet and the hydraulic characteristics of the underlying aquifer will, in part, control the rate and quantity of water draining from the sinkhole. Ponding or sinkhole flooding can occur in types 1 and 2 sinkholes if runoff exceeds the drainage capacity of the swallet or if the subsurface system of conduits which receive sinkhole drainage is blocked with debris or is filled with runoff. Occasional sinkhole flooding in the area about 2.5 miles north of Franklin Crossroads is apparently caused by filling and overflowing of the subsurface system of conduits by runoff from precipitation outside the immediate area.

Because virtually all surface runoff that is collected by sinkholes is eventually funneled directly into the ground-water system, drainage through sinkholes can seriously affect water supplies developed from carbonate aquifers. The potential effect of drainage through sinkholes can be especially severe when such drainage transports various pollutants which may originate in agricultural chemicals, urban runoff, improper disposal of hazardous materials, or accidental dumping of toxic substances while in transit. Thus, identification of those sinkholes or sinkhole areas that recharge a particular karst water-supply spring or well is needed to develop adequate protection procedures. Procedures can be preventive, such as land-use restrictions around selected sinkholes, or reactive, such as the determination of water travel times and other aquifer flow characteristics, developed from dye tracing, needed to respond to specific contamination events such as toxic spills.

Karst Windows

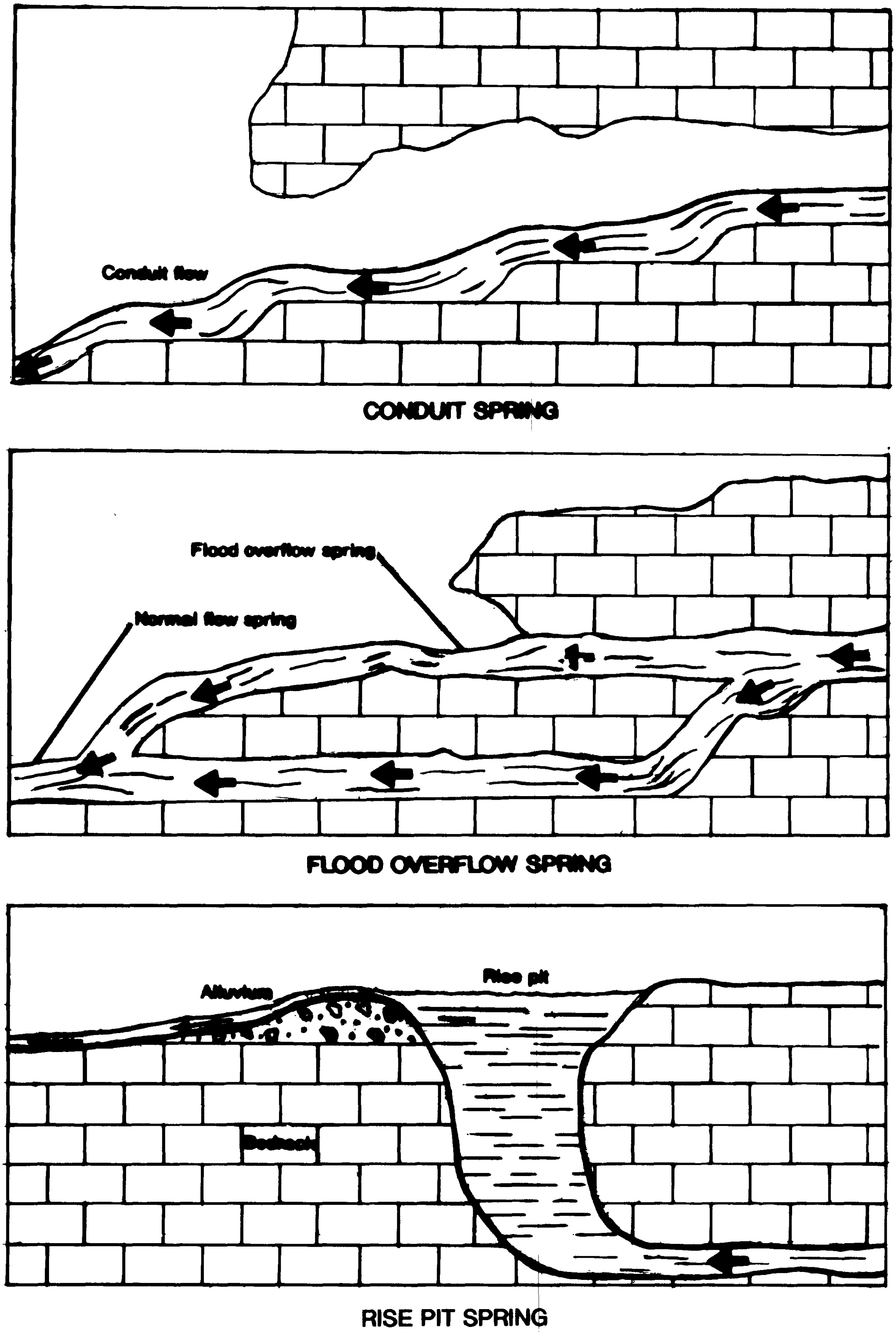
A karst window is a landform that has features of both a spring and sinkhole. It is a depression with a stream that issues as a spring from one end of the sinkhole and flows across the floor of the depression to sink into the subsurface, generally through an open swallet or cave at the lower end of the depression. Karst windows are hydraulically significant because the exposed streams provide a direct path to the subsurface for any contaminant deposited in the water-catchment area of the sinkhole.

The karst windows in the study area range from less than 10 to as much as 80 feet below the surrounding area. The floor of the depressions range in size from less than 50 to 1,200 feet in diameter. Roaring Springs, which is one of the most striking karst windows in the study area, contains about 5 acres which is often cultivated for corn and other crops.

The fact that streams flowing across the bottom of karst windows are especially vulnerable to contamination from runoff has special significance in the case of the karst windows at Stiles, Roaring, and Head of Rough Springs because water in these streams has been traced to Pirtle Spring, part of the water supply for the HCWD #1. Also, the stream in the karst window at Jent Spring was traced to Head of Rough Spring which is a potential supplemental water source.

Karst Springs

A karst spring occurs where the land surface intersects the water table or water-bearing conduits as a natural point of discharge from the ground-water reservoir. Discharge from a karst spring may issue from openings ranging in size from less than an inch to many feet in diameter. Water may either flow out under gravity or rise under pressure to form small seeps or large rise pools. Several types of karst springs common to the study area are shown in figure 6.



(modified from J.N. Jennings, 1985, figure 15, page 47)

Figure 6.--Principal types of karst springs.

Karst springs in the study area range from wet-weather seeps that flow only during or after a period of rainfall to relatively large springs that discharge from cave-like conduits in limestone and are generally perennial. Wet-weather springs range from seeps to relatively large openings that act as overflow springs when lower passages are filled during periods of heavy rainfall. Such overflow springs were observed in the valley wall about 30 feet above the normal level of rise pool in Stiles Spring. Flows from wet-weather seeps (springs) were not measured during this investigation because these springs are generally too small for consideration as a water-source for public use.

The largest springs in the study area, Head of Rough and Pirtle Springs, are the resurgence points for a large underground system of branching openings that collect water over an extensive area, funnel the water to the main conduits leading to the spring, and thence to the surface at the mouth of the spring. Drainage from sinkholes is a major source of recharge from the surface catchment areas that drain to the pipe-like trunk or master conduit system draining to the springs. Because these springs are the principal discharge points for a large part of a ground-water basin, the quality of water from the springs tends to reflect surface activities throughout the basin. This fact is of special concern because many small-scale land-use activities in the water-catchment area of a spring might produce potential contaminants which have the capability for rapid entry into the ground-water system.

The large springs in the study area are developed in the lower Ste. Genevieve limestone near its contact with the underlying St. Louis limestone. Both units contain massive beds of limestone with well-developed solution openings along fractures and bedding planes which form the conduits or pipes for ground-water movement.

Head of Rough Spring

The Head of Rough Spring is a conduit spring which flows from crevices at the base of a low cliff formed by collapsed bedrock. During high flow, water also issues from the mouth of a cave, which is about 10 feet above the low-flow resurgence. The mouth of the cave is about 660 feet above sea level. Water in the cave conduits has a free surface with the atmosphere. The cave mouth is accessible and the passage leading to the cave mouth has been explored for a distance of about 3,000 feet (Angelo I. George, private consultant, oral commun., 1988).

Discharge from the spring flows about 1 mile to its confluence with Mays Run to form the headwater of Rough River. The channel is incised about 8 feet below the surrounding land surface and at places is developed on limestone bedrock. Flow from Head of Rough Spring was continuous during the drought of 1988.

Pirtle Spring

Pirtle Spring is an alluviated blue hole, rise-pit type spring that drains to the head waters of Rough River. Rise-pit springs are frequently called a blue hole spring because of the blue color of the water in the central part of the pit. However, the blue color is frequently masked at Pirtle Spring because of the abundance of sediment. Sediment is reportedly more noticeable at Pirtle Spring since October 14, 1988 (William Smallwood, HCWD #1, oral commun., 1989). He reports that the water level in the pit dropped about 14 feet and there was a noticeable increase in sediment. Apparently there was a collapse or wash out of a sediment plug in the conduits which now drain a greater quantity of sediment to the spring.

Pirtle Spring discharges by way of a rise pool that is about 20 feet in diameter and issues at the base of a limestone ledge. The rise pool is about 635 feet above sea level. The rise pool is rimmed on the downgradient side with sand and small pebbles transported and deposited by the discharging water. The rise pool is about 35 feet deep and is apparently the mouth of a major conduit. During high flow, water issues from the conduit with sufficient force to cause a boiling effect as high as 8 inches above the water surface. The conduit is tapped by two wells, 65 feet deep, that supply part of the water used for public supply by the Water District. The wells are about 640 feet above sea level.

Discharge from Pirtle Spring flows about 0.5 mile to its confluence with Rough River in a channel that is incised about 8 feet below the surrounding land surface. At places, the channel is developed on limestone bedrock. Although the rise pool did not go dry, the channel draining from the rise pool was dry for several days during the drought of 1988. This indicates that the discharge from the spring likely cannot meet the water-supply needs during prolonged drought conditions.

Sanders Spring

Sanders Spring flows from the partially blocked mouth of a conduit at the base of a limestone cliff near the base of the St. Louis Limestone. The mouth of the spring is about 620 feet above sea level. Until August 1986, Sanders Spring supplied part of the water used by the Water District. At present (1989) water from the spring is unused. On August 29, 1989, discharge was estimated to be 700 gal/min (gallon per minute) and the specific conductance was 600 μS/cm (microsiemens per centimeters at 25°C), which is relatively high. This indicates that at the time of this measurement, most of the water draining from the spring was from the ground-water reservoir rather than recent inflow from the surface.

Boutwell Springs

Boutwell Springs consists of a group of four springs about 4.8 miles south-southwest of Pirtle Spring. Although outside the immediate study area, these springs are important for developing an understanding of the ground-water flow pattern in the study area. Drainage from an abandoned waste disposal site about 2.0 miles south of Pirtle Spring was traced to Boutwell Spring 2 (pl. 1) during a low-flow dye trace in the fall of 1988 and also during a high-flow trace in February 1989. These dye traces were conducted by the responsible parties for the site as part of the remedial investigation process. Dye from these traces was not recovered from Pirtle Spring.

Boutwell Springs includes one conduit spring (spring 1), two blue-hole springs (springs 2 and 3), and one karst window (spring 4). Discharge was not measured at these springs because they are inadequate as a supplemental source of water. However, each spring was monitored for the presence of dye during all dye traces in the study area because the springs are potential resurgences for ground-water basins which might drain from the study area, especially under high-flow conditions.

OCCURRENCE AND MOVEMENT OF GROUND WATER

Ground water is present in the study area in unconsolidated sediments and in bedrock that make up a complex interrelated aquifer system. Depending on the location and extent of unconsolidated sediments, such as gravel, sand, and silt, these sediments can store and transmit water to underlying bedrock or receive water from the bedrock. If sufficiently large in areal extent and located at relatively high elevations such as upland or high terrace deposits, unconsolidated sediments can be a significant source of recharge to the underlying bedrock. Sediments at lower altitudes, such as in river valleys, are recharged by water draining from the surrounding bedrock and may be a major source of water.

Ground water in the alluvial deposits along major streams, including the Ohio River, occurs in intergranular (primary) openings and in conduits or pipe-like (secondary) openings. Although there is a tendency to assume that all water in unconsolidated material occurs in primary openings, Mull, Smoot, and Liebermann (1988, p. 8) report numerous voids and the presence of pipe-like conduits in unconsolidated material overlying bedrock in the Elizabethtown area, Kentucky. Also, Quinlan and Aley (1987) discuss the movement of ground water in macropores (root channels, cracks or fissures, animal burrows, and textural transitions) that is commonly several orders of magnitude more rapid than in the adjacent unconsolidated sediment.

Typically, water moves through intergranular openings in unconsolidated material at only a few feet per year. Because of this, water-quality generally improves as water moves through the soil horizon as a result of filtration and other physical, chemical, and biological processes. However, the presence of various pipe-like openings in the unconsolidated sediments indicates the possibility for rapid ground-water movement with relatively little opportunity for water-quality improvement. Thus, potential ground-water contaminants placed on the surface can enter the ground-water flow system fairly quickly with little or no change in water quality despite the fact that the thickness of the unconsolidated surficial material may be 50 feet or more.

The predominant water-bearing bedrock in the study area is limestone. It is the solution and erosion of the limestone that causes the karst terrane characteristic of most of the study area. The limestone is relatively impervious except where fractures (secondary openings) have been enlarged by circulating ground water. The circulating water dissolves calcium carbonate and enlarges openings to allow rapid movement of water. The enlarged openings may be vertical or horizontal and range in size from less than an inch to cave-size, such as the openings that form the mouths of caves in the area.

There are generally two types of flow in karst aquifers; diffuse (slow, laminar flow) and conduit (rapid, turbulent flow). Diffuse flow occurs in primary openings in unconsolidated sediments and bedrock and can be a major component of ground-water recharge, especially where extensive deposits of unconsolidated sediments overlie bedrock. Diffuse flow occurs primarily near the boundary of ground-water basins where conduits have not been enlarged sufficiently for conduit flow and in the uppermost zone of bedrock near its contact with the overlying residuum.

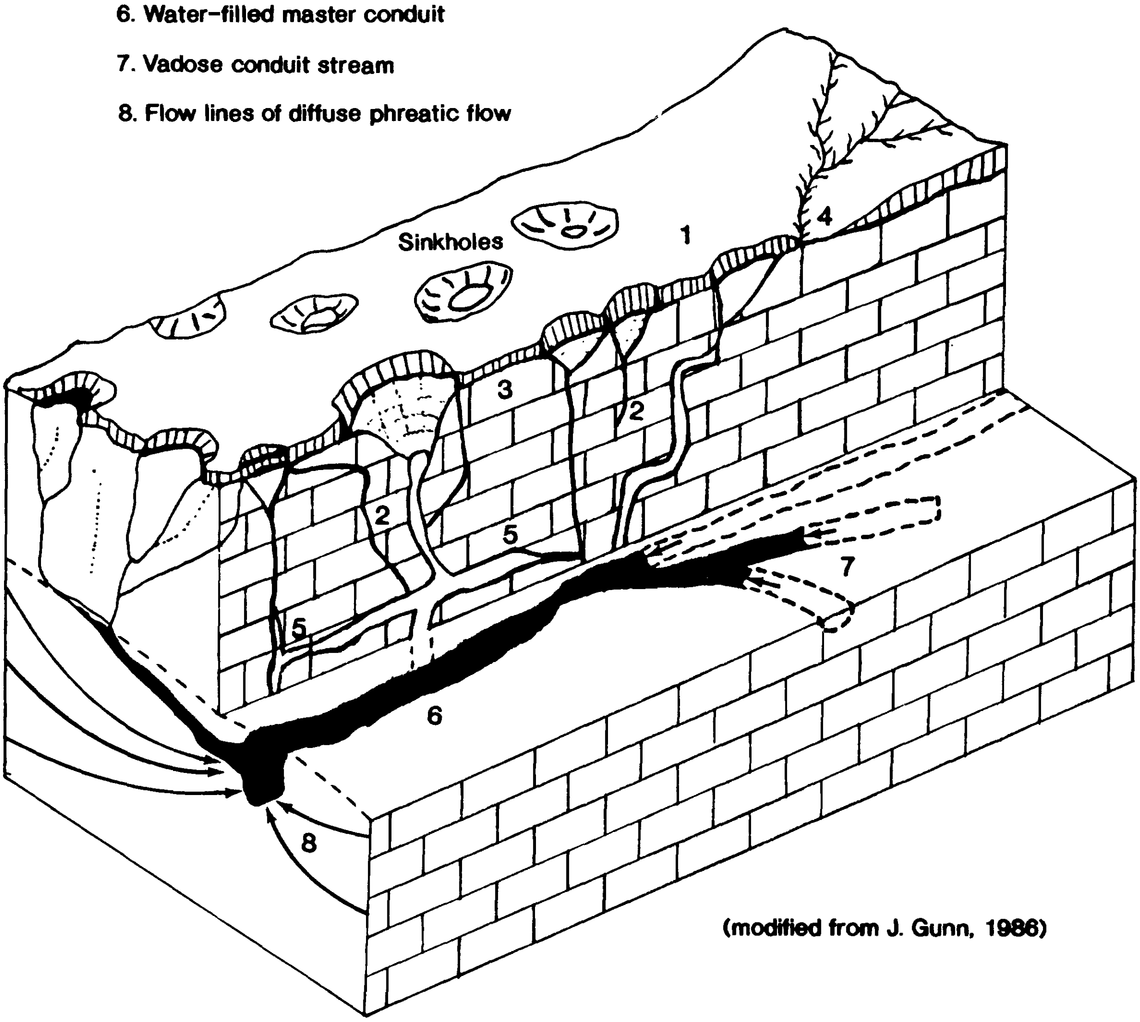
Conduit flow occurs in secondary openings that range in size from a few millimeters to several feet. Water enters conduits at discrete points such as sinkholes or sinking streams or by slow drainage from overlying strata. The hydrologic significance of conduit flow is the rapid introduction and transmission of water through the aquifer. Thus, potential ground-water contaminants placed on the land surface or disposed through sinkholes into the subsurface have the potential for rapid transport and impairment of ground-water quality downgradient. The relation between diffuse and conduit flow and other components of the hydrologic cycle in karst terrane are shown by the generalized block diagram in figure 7.

In mature karst terrane such as that in most of the study area, solution-enlarged conduits commonly exhibit either a dendritic or a trellis-like pattern, develop along horizontal and vertical openings, and form trunk conduits or channels that concentrate direct recharge from sinkholes and sinking streams and typically discharge from the ground-water system at large springs. Virtually every sinkhole acts as a point of entry for surface runoff to subsurface conduits. Flow in major conduits is typically turbulent, has highly variable turbidity and temperature, and has relatively direct response to precipitation. These are characteristics of most of the springs inventoried in western Hardin County and also in the Elizabethtown area (Mull, Smoot, and Liebermann, 1988, p. 23).

Ground water moves in response to hydraulic gradients and is generally from the uplands to stream valleys. Movement is primarily through solution-enlarged joints and bedding planes. The configuration of the potentiometric surface is shown by contours on plate 1. The contours show the average summer condition and are based on water-level measurements in individual wells. The contours are generalized because some water levels were taken from historical data and were measured in wells with a wide range in depth. Thus, some water

EXPLANATION

1. Diffuse flow through soil, residuum, or unconsolidated surficial material
2. Flow through enlarged vertical conduits
3. Diffuse flow in primary openings in bedrock
4. Surface streams draining into sinkholes
5. Horizontal and vertical flow to master conduit
6. Water-filled master conduit
7. Vadose conduit stream
8. Flow lines of diffuse phreatic flow



(modified from J. Gunn, 1986)

Figure 7.--Components of ground-water flow in a mature karst aquifer.

levels were not used in drawing the map, and contours were drawn that were consistent with most data points and with the regional potentiometric surface published by Plebuch and others (1985).

The general direction of ground-water flow can be estimated by drawing flow lines perpendicular to the potentiometric contours. The contours on plate 1 show that ground water moves generally from northwest to southwest in the study area. This corresponds to the land-surface gradient and also to the dip of bedrock which is about 20 to 30 feet per mile to the southwest. The direction of ground-water flow at a specific site may differ, however, because water will follow available secondary openings whose orientation may not be normal to contour lines at that site.

WATER AVAILABILITY

Ground Water

Ground water is available from wells in the alluvial aquifer along the Ohio River, from wells in limestone aquifers, and from springs. All of the above sources are currently being used, and each has certain characteristics and limitations.

Wells in the Alluvial Aquifer

The HCWD #1 maintains a well field in the alluvial aquifer along the Ohio River downstream of West Point, Kentucky. The Fort Knox military reservation and West Point also maintain well fields in the same alluvial aquifer. In recent years, some wells have been abandoned by these users because of increasing chloride concentrations. The chloride problem may be related to unplugged and improperly plugged abandoned oil and gas test wells near the well fields (Lyverse and Unthank, 1988). Any increased pumpage in the existing well fields would widen and deepen the cones of depression and could increase the migration of brines toward the pumped wells. Thus, the quantity of usable water available from this source may be limited to a rate that would minimize drawdowns and halt or slow migration of brines. Because of the chloride problem, ground-water availability is limited in this area of the alluvial aquifer.

Wells in the Limestone Aquifers

Most of the study area is underlain by carbonate rocks with a well-developed aquifer system. The St. Louis and Ste. Genevieve Limestones are the principal units at or near surface, and they are the principal water-bearing bedrock units (fig. 5). As with most karst aquifers, well yields are extremely variable and depend to a large extent on the size and number of water-bearing openings penetrated during drilling. Little information is available in the study area to estimate the yields of wells. However, individual wells, drilled in the same limestones a few miles east at Elizabethtown, are known to yield as much as 500 gal/min (Mull and Lyverse, 1984).

Development of ground-water supplies in karst aquifers generally requires test drilling to locate high-yield wells. Areas for test drilling can be selected on the basis of favorable topographic, geologic, and hydrologic conditions to increase the chance of obtaining high-yield wells. Interpretation of the results of this investigation indicates that the most favorable conditions in the study area are northwest of Howe Valley in the vicinity of Pirtle Spring. This area is in the valley of Rough River in a low topographic area. The limestones in the Rough River basin dip gently toward the southwest just slightly more than the slope of the land surface. Ground-water movement is focused toward the Pirtle Spring vicinity from higher topographic areas to the north, northeast, and east on the basis of the potentiometric contours shown on plate 1. This is substantiated by ground-water discharge points of Roaring Spring, Stiles Spring, Head of Rough Spring, and Pirtle Spring. This movement also is substantiated by selected dye traces which are discussed in another section of this report.

The conditions mentioned above are similar to those in the Elizabethtown area where several high-yield wells have been developed. Wells that penetrate some of the larger, conduit-type openings in the Pirtle Spring area can produce up to several hundred gallons of water per minute. However, the installation of test wells will be needed to more fully understand the ground-water system in the Pirtle Spring area.

A fault zone parallels the stream valleys of Rough River and Mays Run (Kepferle, 1963b), but its effect on ground-water movement is unknown. Test drilling and aquifer tests may indicate whether the fault zone is an area of higher or lower ground-water yields. The Lost River chert bed of Elrod (1899), a chert layer in the lower part of the Ste. Genevieve Limestone, crops out northeast of Pirtle Spring (Kepferle, 1963b). This chert bed is relatively impermeable in places, and its effect on ground-water circulation in the Pirtle Spring vicinity is unknown. It could retard ground-water movement and karst development in the underlying St. Louis Limestone, especially southwest of Pirtle Spring where it dips farther beneath land surface. Knowledge of the effects of the fault zone and Lost River chert bed on ground-water movement is needed to evaluate the ground-water supply potential in the Pirtle Spring vicinity and to select sites for potential production wells.

Depth of Wells

Individual wells were inventoried to provide a data base for the assessment of the various factors such as well depth that effect well yields in the study area. A cumulative curve based on 288 well depths show that most wells in the study area are completed at relatively shallow depths (fig. 8). Well depths ranged from about 30 to 250 feet below land surface. About 80 percent of the wells are 180 feet deep or less.

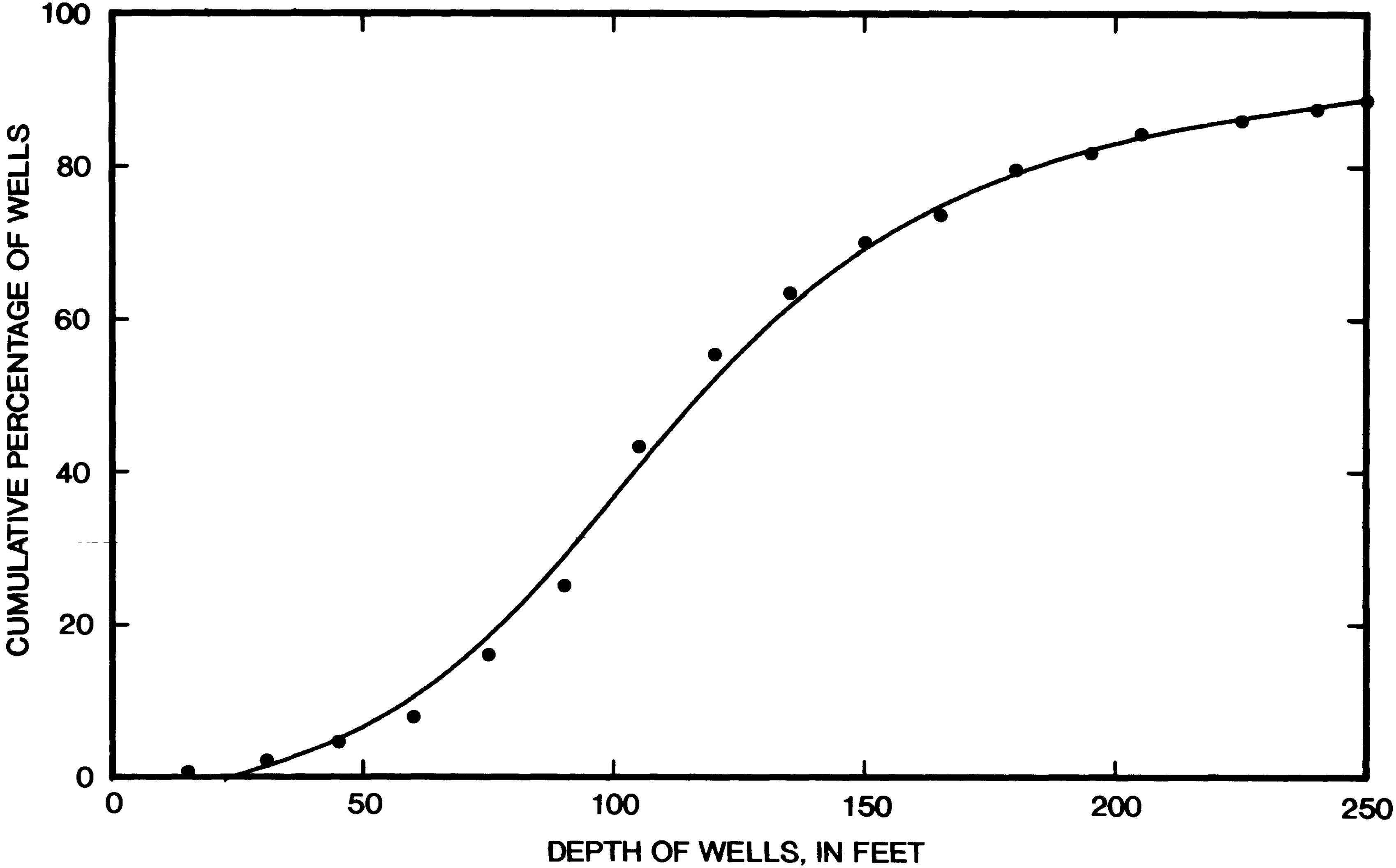


Figure 8.--Cumulative distribution by depth of 288 drilled wells. Curve indicates percent of wells having depth equal to or less than indicated amount.

Two factors may account for the shallow depths. First, most inventoried wells were drilled for the purpose of providing a domestic supply which is usually about 3 to 5 gal/min. Once it is determined that the well can yield 3 to 5 gal/min, drilling is stopped, generally without testing the full thickness of the water-bearing rocks and the underlying potential aquifers. Second, deeper wells are likely to penetrate zones containing poor quality water. Lambert (1979) indicates that wells completed in or below the basal part of the St. Louis Limestone may yield highly saline or sulfurous water in the Elizabethtown area. Because the study area is underlain by the same rock units, similar conditions are likely to occur in the study area.

Water Levels

Water levels from 288 wells were used to prepare the cumulative curve in figure 9. The curve indicates that water levels are relatively shallow in the study area. Water levels ranged from 14 to 135 feet below land surface and were 60 feet or less below land surface in 50 percent of the wells and 90 feet or less in 80 percent of the wells. In general, water levels are deeper in the western and southwestern part of the study area which reflects the increasing depth of the aquifers below land surface. Water levels do not remain constant but fluctuate in response to variations in pumping and natural ground-water discharge and recharge.

Springs

Springs in the study area include wet-weather seeps that flow only during or shortly after periods of rainfall, small springs located at high altitudes where catchment and recharge areas are limited, and large springs that issue river-like from cave openings or rise pools and are perennial. Wet-weather seeps or high-level springs were not measured during this investigation because these springs rarely furnish sufficient water for domestic supply purposes.

The quantity of water discharged from a karst spring is directly related to the nature and size of the catchment area draining to the spring and the quantity and extent of recent precipitation. The largest springs in the study area, Pirtle and Head of Rough, are the natural discharge points for large catchment areas which funnel water to the major conduits of the springs and thence to the surface. Dye traces have shown that the area draining to Pirtle Spring extends more than 5 miles east of the spring and about 1.6 miles northeast of Head of Rough Spring. In both instances, the catchment areas are likely larger because the dye was injected into water that surfaced in a karst window. Obviously, the water in the karst window at the time of dye injection represents drainage from the upgradient parts of the catchment areas that are beyond the karst windows.

Although no gaging stations are maintained on springs in the study area, miscellaneous springflow measurements have been made over the years and during this investigation. Because the utility of springflow is largely dependent on

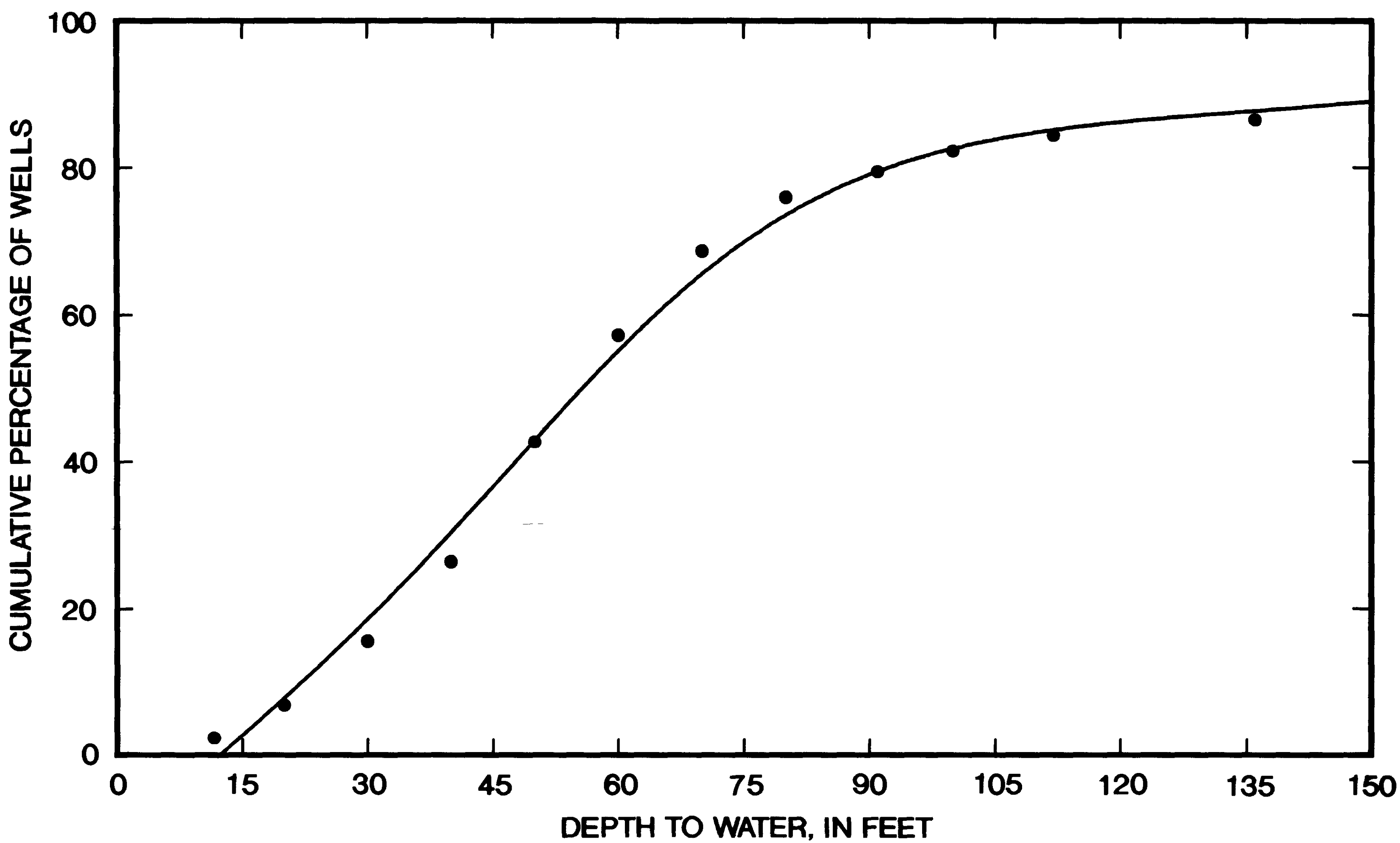


Figure 9.--Cumulative distribution of 288 water-level measurements. Curve indicates percent of water levels having depth below land surface equal to or less than indicated amount.

the magnitude and occurrence of discharge during low-flow conditions, spring flow measurements generally were made only during dry periods. The discharge measurements from six springs are listed in table 1 and the spring locations are shown on plate 1.

Pirtle Spring is the only spring presently used as part of the water supply by the HCWD #1. On October 9, 1989, the base flow at Pirtle Spring was 2.04 ft^3/s (cubic foot per second) and at Head of Rough Spring was 3.56 ft^3/s. However, the channel below Pirtle Spring was not dry as was observed during the drought period of 1988. This indicates that the base flow from Pirtle Spring was greater in 1989, or that the withdrawal rates were less than during the drought period of 1988 when all water from the spring was being taken by the Water District. Although recent pumpage from Pirtle Spring has not exceeded its base flow, the projected water demand of the HCWD #1 from Pirtle Spring is 4.2 ft^3/s. This indicates that although Pirtle Spring has met part of the water needs of the HCWD #1, extended dry periods in conjunction with increased demand are likely to exceed this part of the Water District's water supply.

Areas with Greatest Potential for High-Yield Wells and Springs

High-yields are potentially available from wells drilled in the alluvial aquifer downstream of West Point and in bedrock aquifers near Pirtle Spring. However, increasing concentrations of chloride in the alluvial aquifer has caused the abandonment of several wells and the drilling of replacement wells closer to the Ohio River (Lyverse and Unthank, 1988). Present conditions indicate that chloride levels are likely to continue increasing and will limit the quantity of usable water available from alluvial wells drilled in the part of the aquifer available to the HCWD #1. Locating wells sufficiently close to the Ohio River to induce infiltration from the river may slow or halt the migration of chlorides toward the pumped wells.

Various geologic, hydrologic, and topographic factors, such as well depth, nature of openings penetrated by the well, presence of thick-bedded limestones, and location in a structural low, affect the yield of wells tapping bedrock aquifers. A major factor affecting well yield in the study area is the size and number of water-filled openings penetrated by the well. Most high-yield wells obtain water from horizontal openings that usually develop along bedding planes and have been enlarged by circulating ground water. Caliper logs of high-yield wells in the Elizabethtown area show as many as six zones of horizontal openings, some as much as 5 feet in height and less than 100 feet below land surface (Mull and Lyverse, 1984).

Based on the depths of wells in the study area (fig. 8), the circulation of ground water is concentrated within 250 feet of the land surface where solution-enlarged openings are best developed. These openings are generally best developed in relatively thick beds of limestone in the Ste. Genevieve and St. Louis Limestones that occur in the central and western parts of the study area. Thus, the potential for high-yield bedrock wells in the study area is greatest where wells penetrate the maximum thickness of these rocks, for example in the area northeast of Pirtle Spring and in the faulted areas west and northwest of the spring.

Table 1.--Miscellaneous spring discharge measurements

[μS/cm, microsiemens per centimeter at 25°C; C, conduit; R, rise pit; K, karst window; --, no data]

Name (latitude, longitude)	Type of opening	Date	Discharge, in cubic feet per second	Specific conductance, in μS/cm
Graus Spring	K	July 20, 1977	1.11	435
3742250860105		June 30, 1989	.45	--
Franklin Crossroads				
Spring	K	July 7, 1977	.81	--
3740050860104		July 26, 1989	1.28	380
Head of Rough	C	Aug. 26, 1980	5.40	405
Spring		July 24, 1989	8.88	320
3743070860454		Aug. 14, 1989	7.00	460
		Oct. 9, 1989	3.56	680
Pirtle Spring	R	Dec. 13, 1955	8.08	350
3741460860631		Aug. 26, 1980	7.35	330
		May 11, 1989	32.20	340
		May 17, 1989	30.30	400
		July 24, 1989	17.96	405
		July 28, 1989	14.70	450
		Aug. 14, 1989	8.81	420
		Oct. 9, 1989	2.04	--
Roaring Spring	K	Dec. 13, 1955	1.70	--
3740000860414		July 26, 1989	4.30	370
		July 28, 1989	4.36	--
		Oct. 9, 1989	.43	470
Stiles Spring	K	Dec. 13, 1952	3.80	--
3740380860604		May 11, 1989	19.53	305
		May 17, 1989	17.78	330
		July 24, 1989	8.85	370
		July 28, 1989	7.48	380
		Oct. 9, 1989	2.15	420

Ground water moves from areas where water levels are high to areas where levels are low. The major natural discharge points from the ground-water system are springs in the low-lying areas. Ground-water flow is concentrated in discharge areas, and these areas have the best potential for high-yield wells. Analysis of the potentiometric contours (pl. 1) indicates that the direction of ground-water flow in the study area is toward the southwest to natural discharge points such as Head of Rough and Pirtle Springs. In addition, the structural contours on the Howe Valley geologic quadrangle map (Kepferle, 1963a) indicate that the bedrock dips toward the southwest. Thus, the potential for high-yield bedrock wells is relatively high in this area.

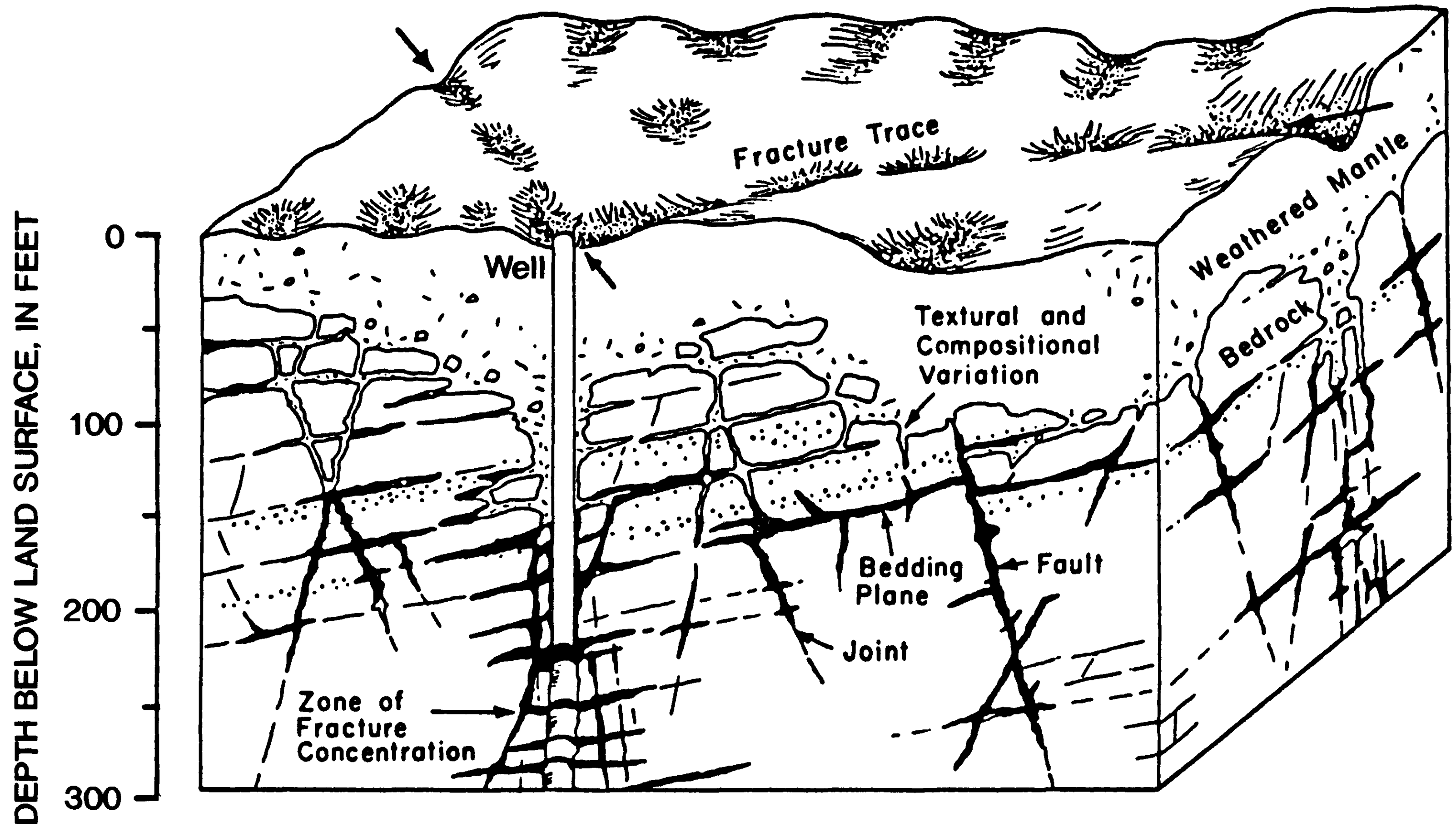
Selected Techniques for Locating High-Yield Wells

High yields are not always a certainty when wells are drilled into thick limestone aquifers because of the irregular occurrence of water-filled openings. One method that can improve the chances of a well penetrating water-filled openings is to locate the well on a fracture trace or lineament. A fracture trace is a natural linear feature, less than 1 mile long, that is believed to be the surface manifestation of almost vertical zones of fracture concentration that delineate zones of increased weathering, solution, and permeability where ground-water flow is concentrated (fig. 10). Lineaments are similar to fracture traces except that they exceed 1 mile in length. According to methods discussed by Lattman and Parizek (1964), fracture traces appear as color tonal differences on aerial photographs. Fracture traces also are indicated by alignment of various surface features such as surface sags and sinkholes or depressions, gaps in ridges, aligned springs, seeps, perched surface ponds, and straight stream and valley segments. According to this method of selecting well sites, the optimum site is at the intersection of two or more fracture traces or along a major lineament.

High-yield bedrock wells in the Elizabethtown area were located by fracture analysis (George, 1982). The sustained yield from individual wells is in excess of 500 gal/min. During this investigation, potential test-well sites were selected on the basis of fracture-trace analysis of low altitude black and white aerial photographs.

Ground water moves from areas with high water levels to areas with low water levels. These low areas are shown by the potentiometric contours on plate 1. In addition, a trough on the surface of the potentiometric surface can be interpreted as an area of concentrated ground-water flow. For example, Quinlan and Ewers (1989, p. 96) report that all major cave streams in the Mammoth Cave area are coincident with troughs on the potentiometric surface. Thus, the most favorable areas for developing high-yield wells in the study area are likely to occur along the axes of troughs in low areas of the potentiometric surface (pl. 1).

Although knowledge of geology and detailed well records can indicate the potential yield from wells in specific areas, ultimately, well yield must be proved by test drilling and properly conducted aquifer tests. Although several sites were identified as favorable for high-yield wells in the study area, test wells were not drilled at these sites because of access



(modified from L.H. Lattman and R.R. Parizek, 1964, figure 5, page 87).

Figure 10.--Fracture traces and other geologic factors that influence cavity development in carbonate rocks.

restrictions. However, one test well was completed on property owned by the HCWD #1, about 1,000 feet northeast of Pirtle Spring. The site was selected on the basis of fracture trace analysis and the proximity of the site to a water-treatment plant at Pirtle Spring.

The test well was drilled with a small air-rotary rig, using drilling fluid except when circulation was lost because of crevices in bedrock. Drilling began on October 4 and was completed on October 24, 1989. The test well was 8 inches in diameter and 198 feet in depth. Altitude at the test site is about 670 feet above sea level. According to the geologic map (Kepferle, 1963a), the test-well site was about 40 feet above the Lost River chert bed in the lower part of the Ste. Genevieve Limestone. The well penetrated numerous crevices but did not penetrate typical subsurface fracture-trace conditions such as zones of loose and broken bedrock, gravel-filled crevices, or relatively deep regolith-bedrock interface. At this site, the regolith overlying bedrock was less than 1 foot in thickness.

A log of the crevices penetrated by the well is shown in figure 11. The size of individual crevices was estimated on the basis of the increased rate of descent or drop of the drill stem. Individual crevices were estimated to range from 2 to 8 inches and were fewer below 140 feet. Several crevices or zones of crevices, were sufficiently large to accept drilling fluids and, thus, prevent the return of those fluids to the surface. These zones are shown as lost circulation in figure 11.

To restore and maintain circulation, the sealing material (bentonite) was added to the drilling fluid when the well reached depths of about 40 and 121 feet. The greatest loss of drilling fluids occurred at a depth of approximately 121 feet below land surface. At this depth, the well was taking drilling fluids at the rate of approximately 300 gal/min. An auxiliary air compressor was added to continue drilling below 121 feet. However, circulation of drilling fluids was not restored until the well reached a depth of 128 feet.

Drilling ceased at a depth of 198 feet below land surface, primarily because of the decrease in the number of crevices. Also, Hopkins (1966) indicates that the fresh-saline water interface occurs about 200 feet below land surface near the test site. Prior to test pumping, the well was surged with a cleaning tool which directed compressed air into crevices and against the well bore to remove cuttings and drilling mud. After about 8 hours, the drillers reported that water from the well was almost clear. However, it was impossible to determine whether or not the crevice-sealing materials were removed or if they remained in place and might be plugging water-bearing crevices.

After surging, 6-inch diameter, PVC casing was installed to a depth of 45 feet below land surface. The well bore was open below 45 feet. To determine the yield of the well, a 20-horse power submersible pump was installed. Drawdown was measured with airline and pressure gage. Water discharged through a 6-inch diameter flexible hose to a section of steel pipe equipped with a 4-inch circular orifice weir and piezometer tube for measuring discharge.

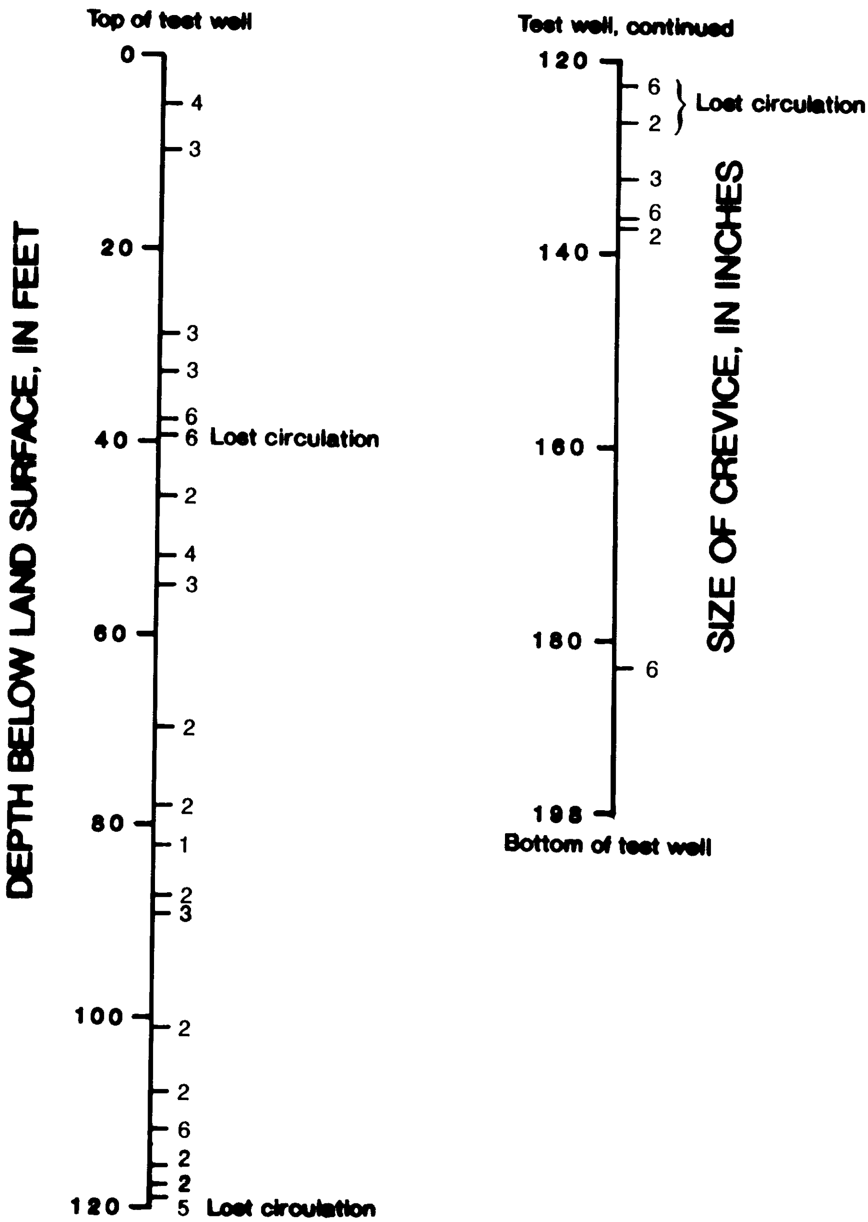


Figure 11.--Driller's log of crevices penetrated by test well.

The static water level in the well was 40 feet below land surface at the beginning of the pumping. After 8 hours of pumping, the drawdown in the well was lowered to 110 feet. During this period, the pumping rate was adjusted to about 80 gal/min to avoid lowering the water level to the pump intake and breaking suction. In general, the yield of the well is indicated when drawdown stabilizes to a particular pumping rate. Test pumping is usually continued for at least 24 hours to better estimate long-term reliability of a well. However, in this instance, well yield (about 80 gal/min) was considered too small for use as a supplemental supply, and pumping and further testing was discontinued.

Although inadequate for use as a supplemental water source, the test well did show the presence of abundant bedrock crevices. The crevices were probably not connected to a major conduit system at this particular site, and the yield was somewhat reduced. Wells penetrating crevices that are connected to major conduit systems can produce larger quantities of water in this geologic setting. Thus, the failure of one test well to produce water will not necessarily be construed as representing the ground-water potential in this area. Rather, it indicates that in many areas of limestone terrane, several test wells are needed to adequately test the water-bearing characteristics of the aquifer.

Surface Water

Potential surface-water supply sources in the study area include the Rough, Salt, and Ohio Rivers. The assessment of the availability and reliability of these sources for this study is based primarily on historic flow information. The quality of water from these sources was not considered in this assessment.

Rough River

Rough River drains a small area in the southwestern part of the study area. The U.S. Geological Survey operates a low-flow partial-record station at the State Highway 86 bridge over the Rough River near Vertrees, Kentucky. The drainage area to this station is 45.3 mi^2 (exclusive of areas contributing through karst interbasin transfers). On the basis of nine base flow measurements from 1975-79, Sullavan (1984) presented the 7-day, 2-year and 7-day, 10-year low flows at this site as 6.4 and 4.5 ft^3/s. This is equivalent to 4.1 and 2.9 Mgal/d. These estimates and measurements were made prior to more recent extreme low-flow periods, and also do not reflect current withdrawals of up to 2.3 Mgal/d from Pirtle Spring by the HCWD #1. These withdrawals are in the drainage area upstream of the low-flow site and are equivalent to 3.2 ft^3/s or 2.3 Mgal/d.

Further assessment is possible by comparing the low flow in Rough River tributaries, Head of Rough Spring, and Mays Run. Flow in Mays Run is maintained by flow from small springs which drain the upland areas northwest of Pirtle Spring. On August 14, 1989, measured flow from Head of Rough Spring was 7.00 ft^3/s but was only 0.71 ft^3/s in Mays Run. The measurement site on

Mays Run was about 200 yards above its confluence with the channel from Head of Rough Spring, north of the bridge on State Highway 1357. Although numerous low-flow measurements may be required to define low-flow characteristics where flow is greater, additional measurements were not warranted at this site. On the basis of these measurements and an evaluation of historic data from Rough River at Vertrees, the potential to develop a water supply from Rough River in this area is limited.

Salt River

The Salt River drainage basin covers 2,920 mi^2 above its confluence with the Ohio River near West Point, Kentucky. Flow data or low-flow estimates are not available for the Salt River at this site. Low-flow estimates by the U.S. Geological Survey are available at two upstream sites. The 7-day, 10-year low-flow value for Rolling Fork near Boston, Kentucky (1,299 mi^2 drainage area), is 2.3 ft^3/s and the value for the Salt River at Shepherdsville, Kentucky (1,197 mi^2 drainage area), is 0.22 ft^3/s based on data collected before completion of Taylorsville Lake.

To determine the bathymetric characteristics of the lower Salt River near West Point, Kentucky, both the U.S. Army Corps of Engineers Flood Profile (George Herbig, U.S. Army Corps of Engineers, Louisville District, written commun., 1988), which shows the approximate channel bottom profile, and field survey data were used. The field survey data indicated that just downstream of the U.S. Highway 31W bridge over the Salt River (0.15 miles upstream of the confluence with the Ohio River), the minimum channel bottom elevation is approximately 362.5 feet or about 2 feet above the elevation shown on the earlier Corps floodway channel bottom profile. This information and the fact that the normal minimum pool elevation of the Ohio River in this reach is 383 feet, indicates that the water-surface elevation of the lower Salt River is hydraulically controlled by the Ohio River. The zone of backwater influence can extend for more than 15 miles up the Salt River. The expected available depth of water at the U.S. Highway 31W bridge during low-flow periods is approximately 20 feet.

To assess the reliability of this supply, discharge and stage records of the Ohio River from the U.S. Geological Survey in this area were reviewed. The nearest upstream gaging station on the Ohio River is at Louisville at river mile 607.3. The period of record at this station extends from January 1928 to the present (1989). An auxiliary gage for this station, 19.8 miles downstream at Kosmosdale, Kentucky, is approximately 3 miles upstream of the confluence with the Salt River. The lowest mean daily discharge during 1988, a year of low-flow extremes, was 7,280 ft^3/s on July 8. The lowest mean hourly stage at Kosmosdale, Kentucky, recorded that day was approximately 382.5 feet or 0.5 feet below the normal minimum pool level.

For the period of record at Louisville, a daily mean flow of 6,600 ft^3/s was equaled or exceeded 99 percent of the time. The lowest discharge for the period of record occurred August 12, 1930, and was 2,100 ft^3/s. Since 1930, many impoundments and control structures have been added in upstream areas and can be expected to augment present day low flows. A discharge of 2,100 ft^3/s at Louisville with the current channel hydraulic rating would result in a river stage of approximately 381.5 feet or 1.5 feet below normal pool stage at Kosmosdale. It is apparent from this information that failure to maintain the minimum pool elevation of 383 feet would be rare. Thus, the quantity of water available from the Salt River near West Point is controlled by the stage of the Ohio River and the stage of the Ohio River is maintained near the normal pool stage even in times of low flow. Therefore, the Salt River at the U.S. Highway 31W bridge is a potential source of water.

Ohio River

From the previous discussion, it is obvious that the flow of the Ohio River is more than adequate as a source of supply. However, present State restrictions on placing water intakes for public supplies within 5 miles downstream of sewage outfalls precludes the use of the Ohio River as a public-water supply near the area where Hardin County borders the Ohio River, because of the sewage outfall at West Point.

VULNERABILITY OF GROUND WATER TO CONTAMINATION

Ground water in karst terrane can be extremely vulnerable to contamination. This vulnerability varies according to the nature of the contaminant, karst features, movement of ground water in karst terrane, the degree of contact of infiltrating water with the soil zone, and the opportunity for transport of pollutants into the aquifer system.

Water quality can be considered in terms of physical, chemical, and biological characteristics. Contaminants of concern are generally of a chemical or biological nature. The chemical contaminants which may be transported in a karst ground-water flow system can be classified as inorganic or organic, dissolved or suspended (particulate), or non-volatile, semi-volatile, or volatile. Contaminants may originate from various land uses, such as agricultural, mining, industrial, and urban and from a variety of stormwater, wastewater, and solid waste management practices, such as municipal or industrial stormwater and wastewater discharges, septic tank leachate, and landfill leachate. Crawford (1982) has identified many of these contaminants and contaminant sources in the Lost River drainage basin near Bowling Green, Kentucky. That basin is developed on mature karst terrane which is similar to that in the area of this investigation. Although the Lost River drainage basin is generally more urbanized than the area of this investigation, the vulnerability of ground water to contamination is similar.

Dissolved contaminants in conduit-flow aquifers can be readily transported under all types of flow conditions and may include many industrial organic compounds, pesticides, nutrients, and trace metals. Constituents associated with suspended material generally require more energy (generated by high velocities and turbulence) for transport. The amount of energy required for transport is related to the density, size, and shape of the suspended particles. Contaminants could include sediment with attached pesticides, nutrients, and trace metals. Contaminants associated with suspended material can be filtered out mechanically by the small pore openings in the diffuse-flow part of the aquifer. In contrast, in the large, well-developed solution openings in some karst aquifers, it is common for large-grain sediment and other particulate material with associated contaminants to be readily transported. These contaminants enter the aquifer from a sinking stream or sinkhole, move rapidly through the conduit system, and exit through a spring or well. High-energy subsurface systems sufficient to transport large amounts of sediment are a common feature of conduit flow in karst terrane.

Biological contaminants such as viruses, bacteria, and other microorganisms, as well as larger organisms, may be readily transported in a karst aquifer in much the same manner as chemical contaminants. They may or may not be associated with other suspended matter. The larger organisms and organism/suspended matter aggregates generally require large openings and high velocities for ground-water transport similar to those that typify ground-water movement in karst terranes.

Almost all water that infiltrates into a ground-water flow system in non-karst terranes must percolate through a soil zone. The soil zone can significantly enhance the quality of percolating water by filtration, various physical and chemical reactions (solution, precipitation, oxidation-reduction, ion exchange, adsorption-desorption, and acid-base reactions), microbiological transformation, and other physical, chemical, or biological processes. However, in karst terrane, soil zones may be thin and the infiltrating water may have little or no contact with the soil. This limits the opportunity for quality enhancement before water enters the ground-water flow system. In addition, Mull, Smoot, and Liebermann (1988, p. 8) report the presence of pipe-like openings and numerous conduits in the unconsolidated material overlying bedrock in the Elizabethtown area, Kentucky. Many of these conduits contained water, in some instances, as much as 40 feet above bedrock. Quinlan and Aley (1987) state that flow in macropores (root channels, cracks or fissures, animal burrows, and textural transitions) is generally several orders of magnitude more rapid than in the adjacent unconsolidated sediment. This indicates that, in places, there is a conduit system in the unconsolidated material that can collect and funnel water directly to conduits in the underlying bedrock. Thus, potential ground-water contaminants placed on the land surface can enter the ground-water flow system fairly quickly, although the thickness of the unconsolidated surficial material may be several tens of feet.

Although sinkholes with plugged drains may be hydraulically connected to the aquifer system, the potential for pollution is generally less than from those with open drains. Because water infiltrates through sediments in the bottom of the sinkhole, some water-quality enhancement can occur.

The development of solution-enlarged openings in soluble bedrock below the soil zone and other unconsolidated material is generally the first phase of sinkhole development. The growth and interconnection of these openings provide the subsurface drainage system for the slumping and transport of overlying unconsolidated material that results in sinkhole formation. It is this same network of subsurface openings that provides avenues for rapid movement of contaminants to ground water. Because water in karst aquifers moves mainly through open conduits, it typically moves much faster than in other aquifers and may be on the order of miles per day. Results of dye tracing during this investigation showed that even under conditions when ground-water velocities would be expected to be the lowest, potential water-borne contaminants could travel more than a mile in one day. Therefore, almost any contaminant entering the ground-water system in karst terrane, such as a contaminant being carried by surface runoff, has the potential for rapid transport and distribution within the subsurface flow system.

Results of dye tracing also indicated that several different sinkholes drain to a particular spring. Given the abundance of sinkholes and the nature of water movement in karst aquifers, most springs are at constant risk from contamination from accidental spills of toxic materials or improper use or disposal of agricultural chemicals. Both Head of Rough and Pirtle Springs are at risk of contamination from these and other sources.

Under usual conditions, the unconsolidated alluvial aquifer near West Point would be considered much less vulnerable to contamination than bedrock aquifers because the intergranular movement of water-borne contaminants is much slower than through the solution-enlarged fractures (conduits) of a karst aquifer. Although this assessment is generally true, especially for potential contaminants placed on the land surface, contamination by brines has already occurred at places within the well field at West Point. Lyverse and Unthank (1988) reported that chloride concentrations ranged from 6.5 to 6,600 mg/L (milligram per liter) in water from observation and water-supply wells tapping the alluvial aquifer. Comparison of the chloride concentrations in samples collected in July 1987 with those collected in October 1987 showed an increase from 250 to 530 mg/L in HCWD #1, well no. 1, and from 170 to 210 mg/L in HCWD #1, well no. 3. The wells were drilled in 1988 to replace two water-supply wells that were abandoned because of increasing concentrations of chloride. Lyverse and Unthank (1988) stated that the presence of the brines was related to improperly abandoned oil and gas exploration wells. The migration of the brines to successive water-supply wells was related to the gradients established by drawdown associated with the pumped wells.

Dye Tracing in the Study Area

The concepts and techniques for qualitative and quantitative dye tracing are discussed in the Appendix. The results of qualitative dye traces conducted during this study are summarized in table 2; injection and recovery sites are shown on plate 1. Although the traces are shown on plate 1 as straight lines between the dye injection and recovery points, the lines are not intended to indicate the exact path of ground-water movement. The traces are numbered sequentially and include traces from the springs in five karst windows and one swallet. For the dye injection at all karst windows, dye was added to flowing water 30 to 40 feet above the point where the water drained underground to provide some mixing before the dye drained underground.

Qualitative methods were used during all dye traces in the study area to confirm connections during different flow conditions. For those traces where the Water District personnel collected samples at Pirtle Spring, qualitative methods also were used to confirm passage of the dye cloud if the selected interval for collecting water samples or the sampling process missed the dye cloud entirely. Because large springs represent discharge points for a

Table 2.--Summary of dye-tracer tests

[NA, not available]

Trace no.	Injection: Date	Injection: Name of spring on Plate 1	Recovery site	Tracer and quantity injected	Apparent: Travel distance, in feet	Apparent: Travel time, in hours	Apparent: Ground-water velocity, in feet per minute
T-1	5-11-89	Stiles Spring	Pirtle Spring	Fluorescein 0.5 pound	7,100	8	15
T-2	5-25-89	Roaring Spring	Stiles Spring Pirtle Spring	Fluorescein 0.5 pound	16,700	20	14
T-3	6-23-89	Jent Spring	Head of Rough Spring	Tinopal (5BM-GX) 1.5 pounds	8,400	NA	NA
T-4	6-30-89	Graus Spring	Pirtle Spring	Fluorescein 4 pounds	26,400	45.5	9.7
T-5	7-13-89	Roaring Spring	Stiles Spring Pirtle Spring	Fluorescein 3 pounds	16,700	35.5	8
T-6	5-16-89	Sinking stream	Pirtle Spring	Rhodamine WT 400 mL	14,250	47.25	5
T-7	7-26-89	Franklin Crossroads Spring	Roaring Spring Stiles Spring	Fluorescein 2 pounds	31,700	87	6

ground-water basin, Pirtle and Head of Rough Springs were monitored for dye recovery during all dye traces. In addition, the Boutwell Springs were monitored. The fact that dye was recovered either from Pirtle Spring or Head of Rough Spring during every trace indicates that these springs are the major points of discharge from their respective ground-water basins, that is for the flow conditions of the dye traces performed during this investigation. It is possible that subsurface flood-flow or overflow routes are present and might provide interbasin connections during conditions beyond those observed during the time period of the traces.

Qualitative Dye Traces

Trace 1 originated from the karst window at Stiles Spring, about 7,100 feet southeast of Pirtle Spring. The karst window is about 300 feet in length and 100 feet wide with a stream flowing across the bottom of the sinkhole. The stream channel is about 60 feet below the adjacent land surface and its banks are alluviated with sand transported by the stream. Remnants of a breached dam is evidence of a mill that was powered by the stream. The stream rises as a blue-hole spring at the base of limestone cliff and drains into the cave mouth that is partially blocked with flood debris. About 3,000 feet of cave passage has been explored beyond the cave mouth (George and McCarty, 1983).

Fluorescein dye (0.5 pound) was added to water draining into the cave at 1100 hours on May 11, 1989. The leading edge of the dye cloud was detected at Pirtle Spring 8 hours later. Discharge measurement showed that stream flow was 19.5 ft^3/s. Based on the straight-line (map) distance of about 7,100 feet between the dye injection point at Stiles Spring and recovery point at Pirtle Spring, the ground-water velocity during this trace was about 15 ft/min (foot per minute). Dye from the injection at Pirtle Spring was not detected at any other monitored site during this trace.

Although cave exploration has indicated that the directional trend of the cave-size conduit draining Stiles Spring is toward Pirtle Spring, this dye trace was the first confirmation of this connection. The potential for contamination of Pirtle Spring from this site is relatively high because the karst window may receive surface runoff from pastures and cultivated fields. In addition, runoff from a barnyard may drain directly into the karst window.

Trace 2 and 5 originated in the Roaring Spring karst window about 9,700 feet east-southeast of Stiles Spring. Roaring Spring rises in the largest karst window in the study area. The valley bottom is about 80 feet below the surrounding upland and includes several acres that are under cultivation. The spring issues at the base of a limestone cliff through breakdown that is likely blocking a cave conduit. The spring-formed stream flows across the valley bottom to drain underground in swallets and a cave mouth that is almost blocked with trees and limbs. Trace 2 began at 1400 hours on May 25, 1989 when 0.5 pound of fluorescein dye was poured into water draining underground through the swallets upgradient from the cave mouth. Estimated streamflow was about 20 ft^3/s. Dye recovery from this trace was faintly positive on passive detectors at Stiles Spring but was positive in water samples from Pirtle

Spring at 1000 hours on May 26. The straight line distance connecting Roaring Spring to Pirtle Spring is about 16,700 feet. The apparent velocity of the ground water carrying dye was about 14 ft/min during this trace.

To verify the connection between Pirtle Spring and Roaring Spring by way of Stiles Spring, another trace (trace 5) was initiated from Roaring Spring at 1230 hours on July 13, 1989. Three pounds of fluorescein dye were added to water draining underground in Roaring Spring. Estimated streamflow in Roaring Spring was about 10 ft^3/s. Passive dye detectors were installed at all monitoring points. In addition to the installation of a passive detector at Pirtle Spring, water samples were collected from Pirtle Spring. Only the passive dye detectors from Stiles Spring and Pirtle Spring were strongly positive. The appearance of dye in Stiles Spring confirmed the connection between Roaring Spring and Pirtle Spring by way of Stiles Spring and that, for this flow condition, drainage from Roaring Spring does not reach Head of Rough Spring. Fluorometric analyses of water samples from Pirtle Spring showed the leading edge of the dye cloud arrived at the spring at 2400 hours on July 14. However, sampling was inadequate to completely define the dye-recovery curve for this trace. Based on the map distance between Roaring Spring, Stiles Spring, and Pirtle Spring, the ground-water velocity during this trace was about 7.8 ft/min.

Trace 3 originated from a sinking spring in the Jent karst window about 8,400 feet north-northeast of Head of Rough Spring. The sinkhole is about 30 feet deep and is elongated in an east-west direction. The stream issues from a cave mouth at the base of a limestone cliff, flows about 75 feet, and drains into a cave mouth on the south side of the depression. On June 23, 1989, 1.5 pounds of optical brightener (Tinopal 5BM-GX) were poured into the stream at 1430 hours. Passive dye detectors that were recovered on June 26 from water issuing from Head of Rough spring were strongly positive for optical brightener, but passive dye detectors recovered from water issuing from Pirtle Spring were negative. Monitoring for the dye continued at Pirtle Spring through June 29 but remained negative. This trace further indicates that the ground-water basins draining to Head of Rough and Pirtle Springs are not connected during the flow conditions of these dye traces.

Trace 4 was the longest trace during this investigation that connected one sinking stream to Pirtle Spring. Trace 4 began in the sinking stream of the Graus Spring karst window which is about 5 miles east-northeast of Pirtle Spring. Unlike the other karst windows used for dye injection during this investigation, the Graus Spring karst window is only a few feet below the surrounding land surface. The water rises in a blue hole, flows about 150 feet, and drains underground through several open swallets. On June 30, 1989, at 1030 hours, 4 pounds of fluorescein dye were poured into the stream draining underground at the rate of approximately 500 gal/min, and all dye was underground within minutes after the injection. A relatively large amount of dye was used for this injection because of expected dilution prior to its arrival at Pirtle Spring which was flowing at the rate of about 30 ft^3/s. It was expected that water from this injection point would flow south to the karst window near Franklin Crossroads and then to Roaring Spring, Stiles Spring, and finally to Pirtle Spring. However, results of this trace showed that drainage from the Graus Spring karst window does not go to the Franklin Crossroads and other springs but flows west to Pirtle Spring.

During trace 4, both water samples and passive dye detectors were intended to be used for dye detection at Pirtle Spring. However, because of equipment problems, water samples were not collected, but the passive detector recovered from Pirtle Spring on July 3 was strongly positive for fluorescein. Also, plant operators reported the faint green color of dye in water from Pirtle Spring at 0800 hours on July 2. Dye was not detected at any other monitoring point although fresh dye detectors were in place until July 13. This is significant because dye from a later injection in the Franklin Crossroads Spring (trace 7) flowed to Roaring Spring, Stiles Spring, and then to Pirtle Spring. An evaluation of these results will be discussed later.

On the basis of the straight-line distance and the first observation of dye in Pirtle Spring, the apparent ground-water velocity during this trace was about 9.7 ft/min. However, the actual ground-water velocity of the leading edge of the dye cloud was likely greater because low concentrations of dye, typical of the leading edge of the dye cloud, are invisible to the human eye.

Semi-quantitative Dye Traces

For this investigation, dye traces were classified as semi-quantitative if the frequency and number of dye samples generally were adequate to develop a dye-response curve. For more quantitative analysis of the dye-recovery curve, discharge measurements are required during the period of dye recovery. Dye concentration in water samples was measured with a filter fluorometer which was calibrated several times during each round of testing.

As mentioned previously, the development of information from dye traces is based primarily on the analysis of the dye-recovery curves, which are graphs showing the relation between the measured dye concentration in water samples and the elapsed time since injection. Such curves also are known as time-concentration, breakthrough, or dye-response curves. Plotted dye-recovery data typically give a positively skewed, bell-shaped curve that is steeper on the rising limb than on the falling limb.

Semi-quantitative traces (traces 6 and 7) were completed to Pirtle Spring. Trace 6 originated from a small sinking stream that flows into a swallet and drains approximately 0.5 mi^2 that is primarily agricultural land use. Trace 7 originated in the karst window near Franklin Crossroads Spring. Unlike most other karst windows in the study area, the depression around this karst window receives runoff from an area of approximately 1.5 mi^2 beyond the immediate vicinity of the karst window. Most of the area around this site is devoted to agricultural land use and is crossed by State Highway 86 and several county roads. Thus, for the sinking stream and the karst window, agricultural chemicals associated with farming can drain directly into the ground-water system and be transported to Pirtle Spring. In addition, any substance accidentally spilled or intentionally dumped along the highways in the drainage area of the karst window near Franklin Crossroads Spring can drain directly into the ground-water system.

Trace 6 originated on May 16, 1989, at 1245 hours when 400 milliliters of rhodamine WT dye was injected into a swallet about 14,250 feet east of Pirtle Spring. Water was flowing into the swallet at the rate of about 5 gal/min. The injection swallet is near the eastern end of a narrow, elongated sinkhole about 0.5 mile in length and is one of several sinkpoints for water draining from a small farm pond, several wet-weather seeps, and surface runoff. The swallets generally are aligned in a southwesterly direction following the trend of the axis of the sinkhole. The channel leading to the swallets is about 2 feet below the surrounding land surface. When runoff exceeds the acceptance ability of a particular swallet, water drains to the next downgradient swallet until during heavy or prolonged rainfall all swallets are flooded. However, all water collected in the sinkhole eventually drains underground through the series of swallets because there is no overland drain from this depression.

Passage of the dye cloud was monitored hourly in water samples from Pirtle Spring and by passive dye detectors at all other monitoring points. Dye was only recovered at Pirtle Spring. During this trace, discharge from Pirtle Spring was about 30 ft^3/s (May 17). Inspection of the dye-recovery curve for this trace (fig. 12) shows that the leading edge of the dye cloud arrived at Pirtle Spring at 1200 hours on May 18 and the peak dye concentration arrived nine hours later. Based on the straight-line distance between the swallet and Pirtle Spring, the apparent velocity of water carrying the leading edge of the dye cloud was about 5 ft/min. The apparent velocity of the leading edge of the dye cloud is described here to emphasize the velocity of ground water in a karst aquifer. The fact that dye from this injection was not recovered at any other monitored site further indicates that a ground-water divide separates the basins of Pirtle and Head of Rough Springs, at least under the flow conditions of this trace.

Trace 7 originated at the spring in the karst window near Franklin Crossroads Spring, about 5.3 miles southeast of Pirtle Spring. Water issues from a cave mouth at the base of a limestone cliff and flows about 200 feet toward the southwest into a cave opening that is partially blocked with debris and breakdown. The stream is about 25 feet below the surrounding land surface. During periods of intense or prolonged precipitation, the limited capacity of subsurface conduits or the presence of debris partially blocking the cave mouth causes flood waters to overflow the channel into adjacent fields and has, at times, blocked State Highway 86. However, all surface runoff that accumulates in the depression draining to the sinkpoint in the karst window eventually drains underground because there are no surface overflow routes from the site.

Trace 7 was begun at 1300 hours on July 26, 1989, when 2 pounds of fluorescein dye were injected into water draining underground in the karst window at the rate of about 500 gal/min. Passive dye detectors were installed at all monitoring points and water samples were collected hourly from Pirtle Spring until the leading edge of the dye cloud arrived. Then the sampling interval was reduced to 15 and 30 minutes for the remainder of the test.

Based on the results of analyses of the passive dye detectors and results of previous dye traces, it seems likely that water from the Franklin Crossroads karst window flows to Roaring Spring and Stiles Spring and then to Pirtle Spring. The dye was first detected visually in water from Roaring

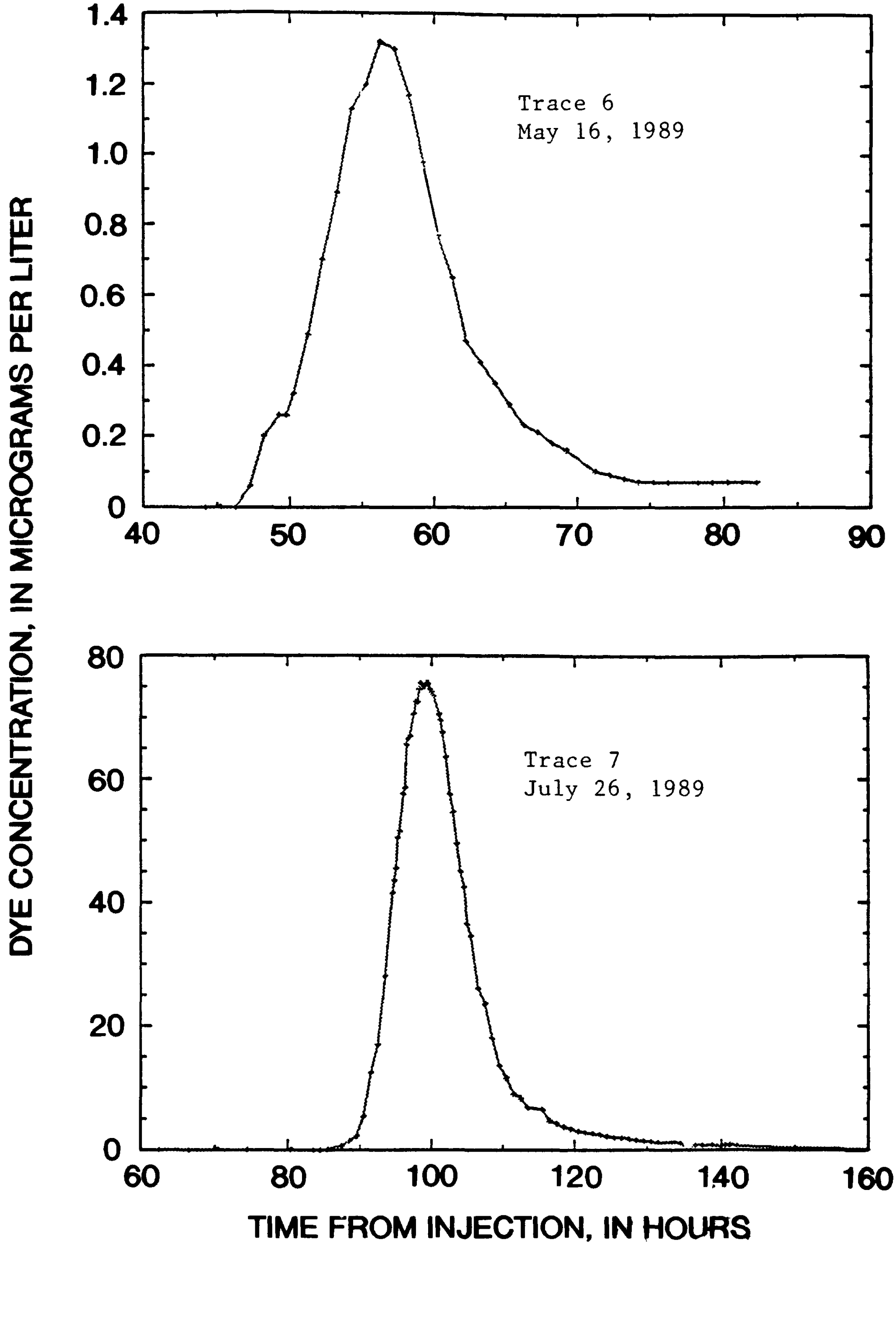


Figure 12.--Dye-recovery curves at Pirtle Spring for traces begun May 16 and July 26, 1989.

Spring at 1100 hours on July 28. Dye from this injection was not detected at Head of Rough Spring or at the Boutwell Springs although monitoring continued at both sites for two weeks following the appearance of dye at Pirtle Spring.

Inspection of the dye-recovery curve for this trace (fig. 12) shows that the leading edge of the dye cloud arrived at Pirtle Spring at 400 hours on July 30 and the peak dye concentration arrived 12 hours later. The straight line connection between the Franklin Crossroads karst window to Pirtle Spring by way of Roaring and Stiles springs is about 31,700 feet (table 2). The apparent time of travel between the Franklin Crossroads karst window and Pirtle Spring was 87 hours. Based on the elapsed time between injection and the arrival of the leading edge of the dye cloud, the apparent ground-water velocity during this tracer test was about 6 ft/min. However, as is true for all the dye traces in this study, the actual ground-water velocity was likely greater because the actual travel distance is likely longer than a straight line connecting the dye injection and recovery points.

Interpretation of Dye-Recovery Curves

Because repeated dye traces between the same dye-injection and recovery points during different flow conditions were not within the scope of this investigation, quantitative information and predictive estimates derived from such dye traces are not available. However, more information is available from inspection of the semi-quantitative dye-recovery curves than is available from the results of qualitative dye traces.

The dye-recovery curves at Pirtle Spring indicate that the dye-transport characteristics vary in the same manner as for dye traces in other karst terrane near the Elizabethtown area (Mull, Smoot, and Liebermann, 1988). These dye-transport characteristics are useful to a water manager because the dye behaves in much the same way as potential contaminants. However, data from a single dye trace generally reflects conditions for that particular trace, and especially for that particular discharge. Repeated dye traces between the same points during different flow conditions are needed to better define the relation between discharge and various dye-transport characteristics and to develop predictive capabilities for estimating time of travel, peak concentration, and persistence of a potential contaminant.

Perhaps the most useful information to be derived from the dye-recovery curves is information on the travel time of various components of the dye cloud such as the leading edge, peak concentration, dye centroid, and elapsed time for the passage of the dye cloud. In addition, the measured dye concentration of water samples collected during the passage of the dye cloud allows some estimates of concentration of a potential contaminant and persistence or the period of time a given concentration is equaled or exceeded.

Differences between the two dye-recovery curves, (traces 6 and 7) as shown in figure 12, reflect the different flow paths and flow conditions during the traces. During trace 6, with a flow path distance of about 14,200 feet and discharge of about 34 ft^3/s, the leading edge of the dye cloud arrived 47 hours after injection, with peak concentration at 56 hours. During trace 7, with a flow path distance of about 31,700 feet and discharge of about 18 ft^3/s, the leading edge of the dye cloud arrived 88 hours after injection with the peak concentration at 98 hours. Based on the earlier findings from repeated dye traces in the Elizabethtown area (Mull, Smoot, and Liebermann, 1988), it is likely that discharge is the controlling factor for determining dye-transport characteristics in the study area. However, repeated traces between the same points are needed to better define and confirm these relations in the study area.

The basic shape of the dye-recovery curves are similar, even though the curves are for dye traces during different flow conditions and distances (fig. 12). Each curve is a positively skewed, bell-shaped curve that is steeper on the rising limb than on the falling limb. This indicates dispersion of a contaminant entering the ground-water system draining to Pirtle Spring. Of special note is the fact that the dye is present for an extended period of time during the recession part of the dye-recovery curve. A water-borne contaminant entering the ground-water system draining to Pirtle Spring would likely behave in much the same way.

The dye cloud resulting from an instantaneous injection of dye (or contaminant) spreads as it moves, so the leading edge of the dye cloud passes the sampling point long before the trailing edge, with the time to peak dye concentration somewhere in between. The time to peak concentration gives an indication of the time of travel, but because of the typical asymmetry of the dye-recovery curve, it is not representative of the time of travel of the bulk of the dye cloud. For this reason, the time of travel is best represented by the centroid, or mass-weighted mean, of the dye mass. The time to the dye centroid ranged from 58 hours for trace 6 to 102 hours for trace 7.

A measure of the amount of spread or dispersion of the dye mass during transit is shown by the standard deviation of the time of travel. In other words, the standard deviation of time of travel indicates how much the dye cloud has spread out, in units of time, between the injection and recovery sites. Because it is a measure of the total amount of dispersion that has taken place, standard deviation of time of travel generally increases when the time of travel is long or when the rate of dispersion is great. The standard deviation of travel time for the traces 6 and 7 was 6.4 and 8.5 hours.

As mentioned previously, data from the semi-quantitative dye traces reflect conditions between a specific dye-input point and Pirtle Spring and for a specific discharge at the spring. Dye-transport characteristics are likely to be considerably different for different flow conditions and distances. Traces 6 and 7 were conducted under relatively low-flow conditions. In general, dye injected at greater distances from Pirtle Spring is likely to take longer to reach the spring, except during relatively high-flow conditions. During high-flow conditions, the velocity of ground-water flow increases and the time of travel decreases. In the karst terrane of the study area, the network of flow paths can be complex and flow can be highly variable. For these reasons, the application of the dye-trace data included in this report for the development of predictive capabilities needs to be used with caution.

GROUND-WATER QUALITY

Although extensive water-quality testing was not a component of this investigation, a brief discussion of ground-water quality is included because water from a karst aquifer is highly vulnerable to contamination. Selected historic water-quality data are included to provide background or baseline data for the comparison of results of future water-quality testing (table 3). Specific conductance and turbidity data that were collected during this investigation also are discussed below.

Specific Conductance

Specific conductance is a measure of the ability of water to conduct an electric current. It is related to the quantity and types of ionized substances in the water. Therefore, specific conductance can be used as an indicator of dissolved solids which is a general indicator of the quality of natural water (Hem, 1985). The larger the specific conductance value, the larger the concentration of dissolved solids. Under the geohydrologic conditions in the study area, dissolved solids generally are related to specific conductance by a factor of approximately 0.6.

Specific conductance is a simple and relatively inexpensive method of monitoring water quality. In general, the specific conductance can provide a base for indicating future changes in water quality of the springs. However, many potentially toxic, organic compounds do not become ionized in water; thus, measuring specific conductance will not detect the presence of these compounds.

The chemical quality and, thus, the specific conductance of water from karst springs or wells does not remain constant but changes in response to seasonal variations in recharge to the ground-water system. The largest and most rapid changes occur in water from springs or wells that tap conduits which are recharged directly from surface inputs such as open swallets or sinkholes. In general, the values of specific conductance are lower in water from conduit springs than from wells because surface runoff, which is a major recharge component to these springs, has relatively short contact time for the dissolution of various ions in soil and rock materials. During this investigation, values of specific conductance generally were highest during the dry periods when input from surface runoff was small (table 1).

Specific conductance was measured during each visit to all springs. Because most of these measurements were made during base flow conditions, the range of values is relatively narrow, from 280 to 440 μS/cm. Specific conductance ranged from 295 to 435 μS/cm at Pirtle Spring and from 280 to 440 μS/cm at Head of Rough Spring. Except for three measurements, the specific conductance of water from Head of Rough Spring was greater than that of water from all other measured springs.

To compare the specific conductance measurements from different springs, the specific conductance data are shown in a series of boxplots (fig. 13).

Table 3.--Water-quality data from springs

[<, less than; alkalinity and hardness as calcium carbonate; specific conductance, in microsiemens per centimeter at 25°C; total dissolved solids as residue on evaporation at 180°C; --, no data]

			Inorganics and trace elements																		
			Milligrams per liter								Micrograms per liter										
Site	Date sampled	Specific conductance	Nitrate	Hardness	Alkalinity	Dissolved solids	Sodium	Chloride	Sulfate	Fluoride	Antimony	Barium	Cadmium	Chromium	Copper	Iron	Lead	Manganese	Nickel	Silver	Zinc
Head of Rough	8-26-80	405	2.2	250	220	260	2.0	3.8	3.1	0.1	<30	50	<1	<50	<10	7	<3	<7	<50	<10	<5
Pirtle	8-26-80	350	1.5	240	210	251	1.8	3.1	4.4	.1	<30	50	<1	<50	<10	10	<3	<7	<50	<10	<5
Sanders	9-25-80	700	--	340	252	--	10	18	90	.3	50	70	3	<50	<10	40	<3	20	<50	10	10

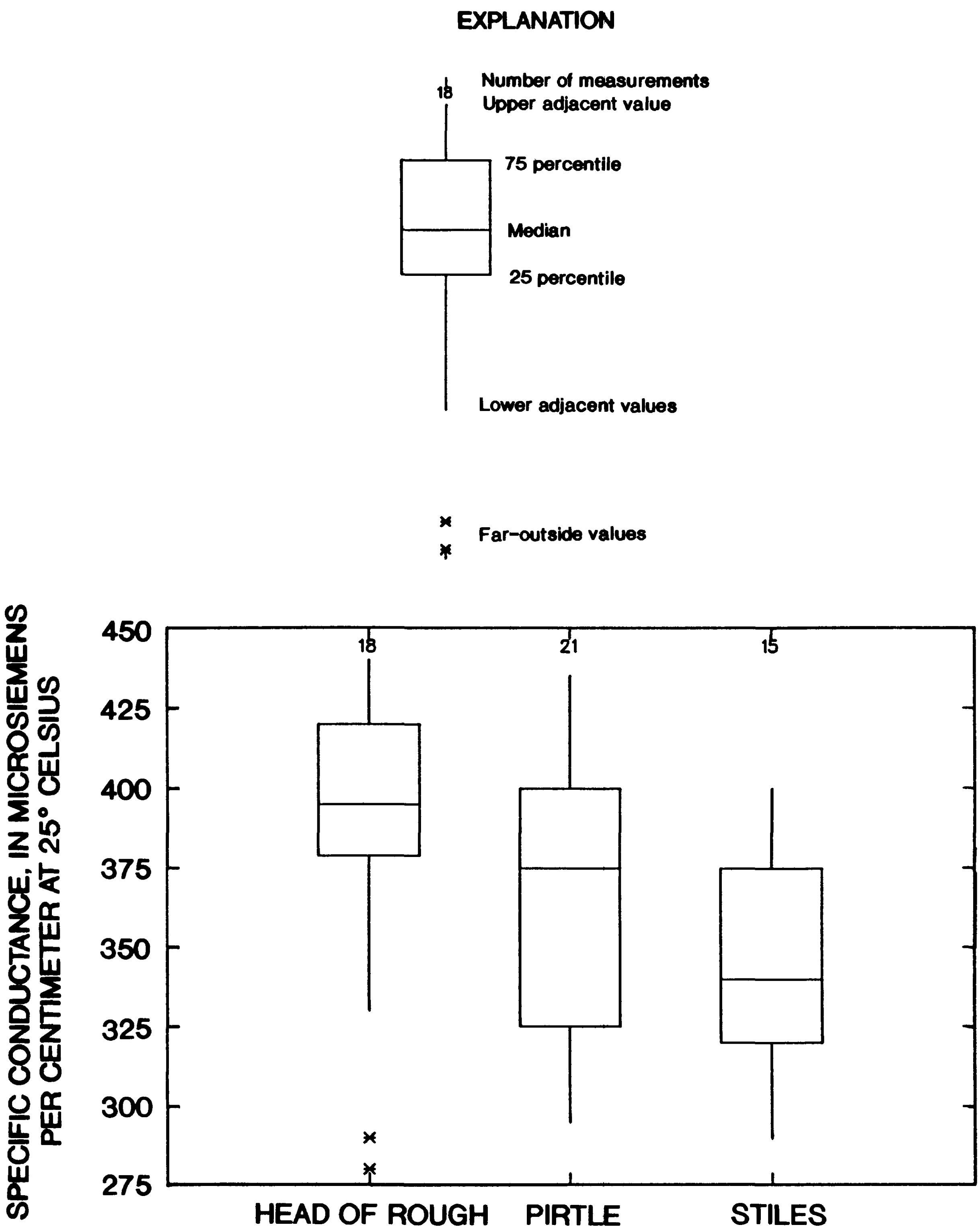


Figure 13.--Boxplots of specific conductance measurements for water from selected springs.

Boxplots provide visual summaries of the median, interquartile range, percentile skew, and extreme values and are often used to visually compare and contrast groups of data. A minimum of ten measurements from each site are necessary for boxplot construction.

The boxplot is constructed as follows: a box is drawn for the 25th percentile to the 75th percentile. Therefore the box length equals the interquartile range. A center line is drawn across the box at the median value. Whiskers are then drawn from the quartiles to two adjacent values. The upper adjacent value is defined as the largest data point less than or equal to the upper quartile plus 1.5 times the interquartile range. The lower adjacent value is similarly the smallest data point greater than or equal to the lower quartile minus 1.5 times the interquartile range. Values more extreme, in either direction, than the adjacent values are plotted individually. Those from 1.5 to 3.0 times the interquartile range beyond the box limits are called outside values and are usually plotted with an asterisk. Two outside values were recorded in samples from Head of Rough Spring. The occurrence of these values indicates that the data may not originate from a normal distribution. Further information on the construction and interpretation of boxplots can be found in Chambers and others (1983).

Visual comparison of the boxplots indicates that the samples are from three similar populations of samples or three springs. Although this distinction was expected for the samples from Head of Rough and Pirtle Springs, it was surprising that the samples from Stiles were not more similar to those from Pirtle Spring because dye tracing has confirmed that water from Stiles Spring flows to Pirtle Spring. However, results of dye tracing and discharge measurements indicates that Stiles Spring is not the only source of water at Pirtle Spring. Apparently the ground water draining to Pirtle Spring from other drainages has higher values of specific conductance than the water in Stiles Spring. This may be caused by water from more distant input points which results in longer flow paths and increased contact time between the ground water and rock materials.

Turbidity

Turbidity is the measurement of the interference of light passage through water due to insoluble particles which may scatter or absorb light. A turbidity measurement is expressed as a nephelometric turbidity unit (NTU) and is equivalent to the interference effect of a suspension of 1 mg of silica, of specified particle size, in one liter of water (Viessman and Hammer, 1985).

Turbidity in water from wells and springs in karst terrane usually originates as unconsolidated material on the land surface that has been carried into the subsurface by surface runoff. Turbidity is generally most noticeable after heavy rains. However, sediment deposited in conduits in the subsurface may be the cause of turbid water during periods of no precipitation or runoff. For example, muddy water from a pumped well during a relatively dry period in the Elizabethtown area was reported by Mull and Lyverse (1984). In this instance, heavy pumping of a well used for public supply for the city of Elizabethtown lowered water levels and increased turbulence which dislodged sediment in the ground-water flow system and resulted in turbid discharges from the well. The same effect can be observed in domestic water-supply wells, especially when water levels are lowered to the vicinity of the pump intake during periods of relatively high water use.

Rapid and widespread changes in turbidity are generally an indicator of conduit-type flow from springs in karst terrane. This is in sharp contrast to characteristic springs draining diffuse-flow parts of karst aquifers where turbidity typically is low and only slightly variable.

Turbidity was measured in water samples from Pirtle and Head of Rough Springs, primarily as an additional indicator of interconnection or separation of the ground-water basins. The results of these measurements are shown in table 4. Except for two samples, turbidity was consistently higher in water from Pirtle Spring than in water from Head of Rough Spring. Samples collected on August 1, 1989, from Head of Rough Spring had turbidity values more than five times higher than the samples collected on the same day from Pirtle Spring. The previous day, heavy thundershowers occurred in the area draining to Head of Rough Spring, but increases in turbidity caused by runoff from these storms did not occur at Pirtle Spring. On the basis of measurements of turbidity and specific conductance and the results of dye traces, the ground-water basins that drain to the Head of Rough and Pirtle Springs are separate, at least during low to medium flow conditions as observed during this investigation.

Table 4.--Miscellaneous turbidity measurements in water from selected springs

[Turbidity in nephelometric turbidity units]

Date of measurement	Pirtle Spring	Head of Rough Spring
6-15-89	52	26
6-19-89	150	77
6-23-89	20	6.2
6-26-89	25	7.2
6-29-89	17	21
7- 3-89	170	120
7-17-89	17	5
7-24-89	47	32
8- 1-89	23	120

SUMMARY AND CONCLUSIONS

* Ground water is presently the source of water for about 27,000 people in northwestern Hardin county. The Hardin County Water District Number 1 obtains water from four wells in the alluvial aquifer bordering the Ohio River near West Point, and from Pirtle Spring, a large karst spring near Howe Valley. Use of the alluvial aquifer as a source of usable water is threatened by elevated chloride concentrations and the flow of Pirtle Spring is inadequate to meet demands during periods of drought. Supplemental sources of good quality water are needed to meet the estimated daily needs of 4.6 Mgal/d by the year 2000.

* Wells drilled in the alluvial aquifer bordering the Ohio River near West Point have the best potential for high yield. However, present conditions indicate that concentrations of chloride are likely to increase and will limit the quantity of water available from wells drilled in that part of the aquifer available for public supply.

* The principal bedrock aquifer in the study area consists of limestone and dolomite of the St. Louis and Ste. Genevieve Limestones of Mississippian age. Well yields are controlled mainly by the nature of water-bearing openings penetrated by wells. High-yield bedrock wells were not inventoried in the study area. However, individual wells are known to yield about 500 gal/min from the same aquifers in the Elizabethtown area, about 8 miles east of the study area.

* The most favorable area for high-yield bedrock wells is near Pirtle Spring in the southwestern part of the study area and was identified on the basis of geology, water-level contours, and fracture-trace lineaments identified on aerial photographs. A single test well may not define the potential yield of bedrock aquifers in karst terrane. Additional test wells are needed to determine the yield of wells in this area.

* Potential surface water-supply sources are the Ohio, Rough, and Salt Rivers. Use of the Ohio River is limited because of State restrictions on the placement of public water supply intakes within 5 miles downstream of sewage treatment plant outfalls. The potential for the Rough River as a water-supply source is limited because of its relatively small watershed in the study area. Its 7-day, 10-year low flow is about 2.9 Mgal/d. Abundant water is available from the Salt River above its confluence with the Ohio River at West Point.

* Most of the study area is typical karst terrane with abundant sinkholes, karst windows, springs, and caves. Sinkholes and karst windows funnel surface runoff directly into the ground-water flow system. Qualitative and semi-quantitative dye traces defined the subsurface connection between selected sinkholes, karst windows, and springs and Pirtle Spring and Head of Rough Spring. Results of the tracer tests and quality of water data indicate that the ground-water basins draining to the Pirtle and Head of Rough Springs are not connected under flow conditions at the time of the tracer tests, and that runoff from farmlands as far as 6 miles to the east drain to Pirtle Spring. Hazardous and agricultural chemicals are potential sources of contamination to the springs.

* Results of qualitative dye traces generally confirmed that the direction of ground-water flow, as shown by a water-level contour map, is from the northeast and east to the vicinity of Head of Rough and Pirtle Springs.

* Results of tracer tests indicate that apparent ground-water velocity ranged from 5 to 15 ft/min during low-flow conditions and that most ground-water flow is through solution-enlarged conduits. This type of flow provides for rapid and widespread distribution of potential contaminants. Because of this vulnerability to contamination, predictive capabilities need to be developed for estimating time of travel, concentration, and residence time or duration of potential contaminants.

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APPENDIX

Dye Tracing Concepts and Techniques

The practice of tracing ground-water flow by adding distinctive substances to water draining underground and monitoring the downgradient resurgence of that water has long been a useful tool for investigating ground-water conditions. Given the hydrologic characteristics of karst terrane, dye tracing is generally the most practical and satisfactory method for collecting data on karst aquifers. Information from properly conducted dye traces can identify point-to-point connections between discrete recharge areas and discharge points such as springs and wells. In addition, analysis of dye-recovery data can provide critical information such as time of travel, peak concentration, and persistence of potential contaminants.

Dye tracing can generally be classified as qualitative, semi-quantitative, or quantitative, depending on the method of dye recovery, extent and method of analysis of the dye-recovery data, the number of dye traces between the same dye injection and recovery points, and the hydrologic conditions during repetitive dye traces. Typically, qualitative tracing uses visual observation or a passive detector and visual observation to detect dye at a discharge point. Generally, the distinguishing characteristics of semi-quantitative or quantitative tracing is instrumental analysis of various elutriants or detectors to confirm the recovery and to precisely measure the concentration of a particular dye used for tracing. Filter fluorometers or scanning spectrophotofluorometers are used to measure dye concentrations. Such instrumentation can measure dye concentrations well below the limits of visual detection. Quantitative dye tracing also requires accurate measurements of discharge from the spring during passage of the dye cloud. Dye traces may be classified as semi-quantitative if various data such as instrumental measurements of dye concentration or discharge are poorly defined or are not available.

The primary purpose of qualitative dye tracing is to determine the existence of a connection in the ground-water system between a specific inflow point, such as a sinkhole, and a discharge point located some distance away, such as a well or spring. Results of qualitative dye tracing can confirm the validity of water-level contours and, thus, the direction of ground-water movement. Qualitative dye tracing also can be used to identify the nature of the system draining to a particular spring, that is, whether the flow system is convergent to a single spring or distributary to several springs. If distributary, qualitative dye tracing is the most practical technique to identify the springs that drain the system. Qualitative dye tracing also can be used to efficiently show changes in flow routes when drainage from a particular sinkhole or karst window is traced to different or additional springs during high-flow conditions. Results of qualitative dye tracing, from the standpoint of water-supply protection, are especially useful for the identification of potential sources of contaminants detected in spring or wells and are almost always a necessary and efficient first step to quantitative dye tracing.

Useful hydrologic information such as time of travel and ground-water velocity may be determined from any dye trace depending on the frequency and method of sampling for the dye. However, if precise hydrologic information (time of travel and ground-water velocity) or potential contaminant transport characteristics (persistence, dispersion rates, and concentration) are needed, quantitative dye tracing using discharge measurements and precise measurements of the dye concentrations in the water are required. Traces may be classified as semi-quantitative if sampling does not properly define the dye-recovery curve, or if discharge was not accurately measured during the passage of the dye cloud.

The primary purpose of dye tracing during this investigation was to identify discrete input points, and, thus, to some extent the catchment area or ground-water basin draining to Pirtle Spring, which is part of the HCWD #1 public-water supply. All dye traces performed during this investigation were designed to be qualitative. However, through the cooperation and assistance of personnel at the water-treatment plant at Pirtle Spring, the collection of water samples was sufficient to define the dye-recovery curve for two traces and, thus, permit a more quantitative analysis of those dye traces. Quantitative analysis of the dye-recovery data did provide more precise information on time of travel, peak concentration, and duration of the dye cloud passing the water-treatment plant at Pirtle Spring. However, these traces are classified as semi-quantitative because sampling did not fully define the shape of the dye-recovery curve and flow conditions at Pirtle Spring were not defined during passage of the dye cloud. Also, repeat traces between the same points during different flow conditions were not performed.

The following discussion describes briefly the procedures used for dye traces during this investigation. In general, the procedures were similar to those used in the Elizabethtown area, Kentucky, by Mull, Smoot, and Liebermann (1988). Information on both qualitative and quantitative aspects of dye tracing are presented by Mull and others (1988).

Qualitative Dye Tracing

Qualitative dye tracing involves the tagging of a discrete sample of water with dye and monitoring the arrival of that water at various downgradient ground-water resurgences. The arrival of the dye may be observed visually or by appropriate analysis of passive detectors which have adsorbed the dye.

Several fluorescent dyes may be used for qualitative tracing. Fluorescent dyes generally are superior to non-fluorescent dyes because they can be detected at concentrations ranging from one to three orders of magnitude less than those required for visual detection of non-fluorescent dyes. Thus, traces with fluorescent dyes generally can be completed without the aesthetically unpleasant probability of unexpectedly discoloring a private- or public-water supply. Detailed discussions on the criteria for dye selection are given by Mull and others (1988). A primary reference on properties of dyes used for tracing is given by Smart and Laidlaw (1977).

The fluorescent dyes selected for use during this investigation were chosen because they are generally the most convenient and practical tracers, and they all, to some degree, are adsorbed on activated cocoanut charcoal or undyed cotton, material generally used in passive dye detectors. The fluorescent dyes used during this investigation included Tinopal (5BM-GX), rhodamine WT, and fluorescein (Colour Index Acid Yellow 73).

Tinopal (5BM-GX), an optical brightener, consists of yellowish-white, fine granules that dissolve and produce a milky color when first added to water. Optical brighteners are non-toxic, have low affinity for adsorption onto clays, and are readily adsorbed on undyed cotton. Optical brighteners are widely used in laundry detergents and soaps for enhancing fabric colors and are, thus, a common constituent of domestic wastewater. For this reason, checking for optical brighteners is a fairly efficient method of detecting effluent from domestic sewage systems. Thus, the effective use of optical brighteners for water tracing requires the definition of the background level of optical brighteners which can easily be determined by placing undyed cotton swatches in ground-water resurgences and testing for fluorescence before tracer dyes are injected. Optical brighteners were not detected in water from any of the monitored resurgences prior to water-tracing tests.

Optical brighteners are detected by viewing the exposed cotton detector under long-wave ultraviolet light. Cotton that has adsorbed Tinopal will characteristically fluoresce blue-white. The fluorescence of optical brighteners is enhanced if the exposed cotton is viewed under subdued lighting such as a darkened room or viewing box. A positive trace is indicated only if the entire cotton mass fluoresces relatively evenly. Scattered specks of fluorescence on the cotton should not be interpreted as a positive dye recovery. Swatches of undyed cotton used as dye-detectors are held in place by the same gumdrop anchors and fiberglass packets used for tracing with fluorescein which are described later.

Rhodamine WT is a liquid made specifically for dye tracing and has been widely used for quantitative studies such as time of travel and dispersion tests in streams (Hubbard and others, 1982). Because of the relative similarity between ground-water flow in karst terrane and streamflow in most areas, rhodamine WT generally is selected for quantitative studies in karst terrane and was used by Mull, Smoot, and Liebermann (1988) for quantitative dye-tracer studies in the Elizabethtown area, Kentucky. Rhodamine WT was used for one dye trace during this investigation, primarily to insure against the possibility of false positives caused by dye residue from an earlier trace with fluorescein. The presence of rhodamine WT was determined by fluorometric testing of water samples and analysis of activated cocoanut charcoal, which will be described later.

Fluorescein is a reddish-brown powder that turns vivid yellow green in water. Fluorescein has a low sorptive tendency, is photochemically unstable and may loose fluorescence in water with pH less than 5.0. Fluorescein was the principal tracer used in this study. Fluorescein dye was recovered by passive detectors consisting of packets of activated cocoanut charcoal suspended in suspected major ground-water resurgence points for a particular trace. Dye detectors also were placed in unlikely resurgences to define the background levels of fluorescence before the dye was injected.

The dye-detectors or bugs used during this investigation consist of a fiberglass bag containing about two teaspoons of activated cocoanut charcoal (6-14 mesh) attached to a length of wire imbedded in a gum-drop shaped concrete anchor about 6 inches in diameter and 3 inches high (fig. 14). The bag was fabricated from a 3- x 7-inch piece of fiberglass screening.

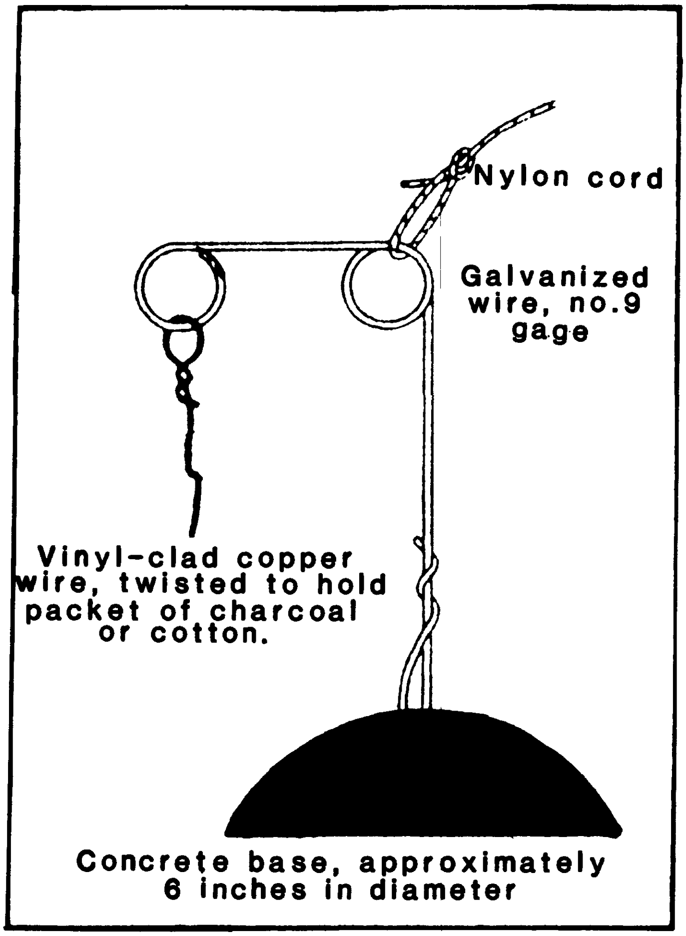
The gumdrop anchor was placed in an area of concentrated spring flow to maximize exposure to the dye-laden water and attached to the bank with a small nylon rope. The packets were left in place from 1 to 7 days but were changed more often when turbidity levels were high. The initial packets were replaced with new packets in all dye-monitoring points generally for a period of several weeks following the appearance of dye at a particular resurgence. The purpose of the replacement packet was to monitor for additional dye at the same resurgence or to allow for longer times of travel to distant resurgences.

The presence of fluorescein and, thus, a positive trace was determined by elutriating the exposed charcoal in a basic alcohol solution and visually checking for the characteristic yellow-green color above the charcoal. The elutriant consists of 6 to 7 grams of potassium hydroxide dissolved in 100 milliliters of 70 percent isopropyl (rubbing) alcohol. In strongly positive tests, the color develops almost immediately upon addition of the elutriant. In less positive instances, generally caused by dilution of the dye at the recovery points, longer exposure to the elutriating solution may be required before the characteristic dye color is observed. In instances where the typical fluorescein color is not obvious, detection can be enhanced by focusing a beam of sunlight or light from a microscope lamp through the solution. This technique increases the detectability of fluorescein where, for various reasons, the quantity of dye adsorbed by the detector is inadequate for a strongly positive dye color in the elutriant.

Quantitative Dye Tracing

As mentioned previously, quantitative dye tracing can provide knowledge about ground-water flow characteristics such as more exact time of travel or ground-water velocity, and contaminant transport characteristics such as persistence or duration and concentration of a potential contaminant. However, quantitative dye-tracer tests are more labor intensive and require more sophisticated equipment and techniques than qualitative dye tracing because the objective is to define dye concentration variations during passage of the dye cloud rather than simply to determine if the dye appeared at a particular ground-water resurgence such as a spring or well.

Quantitative dye tracing consists of the injection of a known quantity of dye and the measurement of the concentration of dye over time, at a particular spring that was identified as being hydraulically connected to the dye injection site by previous qualitative tracer tests. Determination of dye recovery requires measurement of both dye concentration and ground-water discharge. Water samples are collected during passage of the dye cloud and the dye concentration of each sample is measured with a properly calibrated fluorometer or spectrofluorometer. The calibration and use of a filter fluorometer is discussed in detail by Mull and others (1988).



(D.S. Mull and others, 1988, p. 31)

Figure 14.--Anchor used to suspend dye detectors (bugs) in springs or streams.

The initial result of quantitative dye tracing is a set of measured dye concentrations, each sampled at a selected time and place. These data are plotted against time to produce a dye-recovery (time-concentration) or breakthrough curve (fig. 15). Analysis of the dye-recovery curve provides insight into the flow characteristics of the aquifer such as effective time of travel and velocity of ground water between the swallet and the resurgence point. Additional analysis of the dye-recovery curve and discharge measurements from repeat dye traces between the same points, but under different flow conditions, provide estimates of peak concentration, duration or persistence, and dispersion. Because these data can be related to the velocity and dispersion of a potential ground-water pollutant, quantitative dye tracing is especially useful to water managers in karst terrane, where springs or wells might be affected by the accidental or intentional introduction of contaminants into the ground-water system.

A dye-recovery curve yields several quantitative characteristics by simple inspection. The time of injection is used as the beginning of the dye-recovery curve and is taken as zero. The measured dye concentration at the beginning of the dye response becomes the background concentration. Time to leading edge is the elapsed time, or time of travel, before concentration increases above background. Time to trailing edge is the elapsed time for dye passage. Time to peak concentration is the time of travel from dye injection to the peak of the dye-recovery curve. Other characteristics may be defined, such as time of travel from the leading edge until the concentration of dye has decreased to 10 percent of the peak value. A typical dye-response curve and its various features related to time of travel are shown in figure 16 (Mull and others, 1988).

The shape and magnitude of dye-recovery curves are influenced primarily by the amount of dye injected, the velocity and magnitude of flow, the mixing characteristics in the flow system, the sampling interval, and whether the discharge is diluted by water free of dye. The data from a single dye trace generally reflect conditions for that particular test, and especially for that particular discharge. Repeated quantitative dye traces between the same injection and recovery points are needed to describe the dye-recovery characteristics under different flow conditions. In particular, the analyses and interpretation of the results of repeated dye traces under different flow conditions are necessary to develop the predictive capabilities needed to monitor a karst water-supply spring when contamination of the water supply occurs or has the potential to occur.

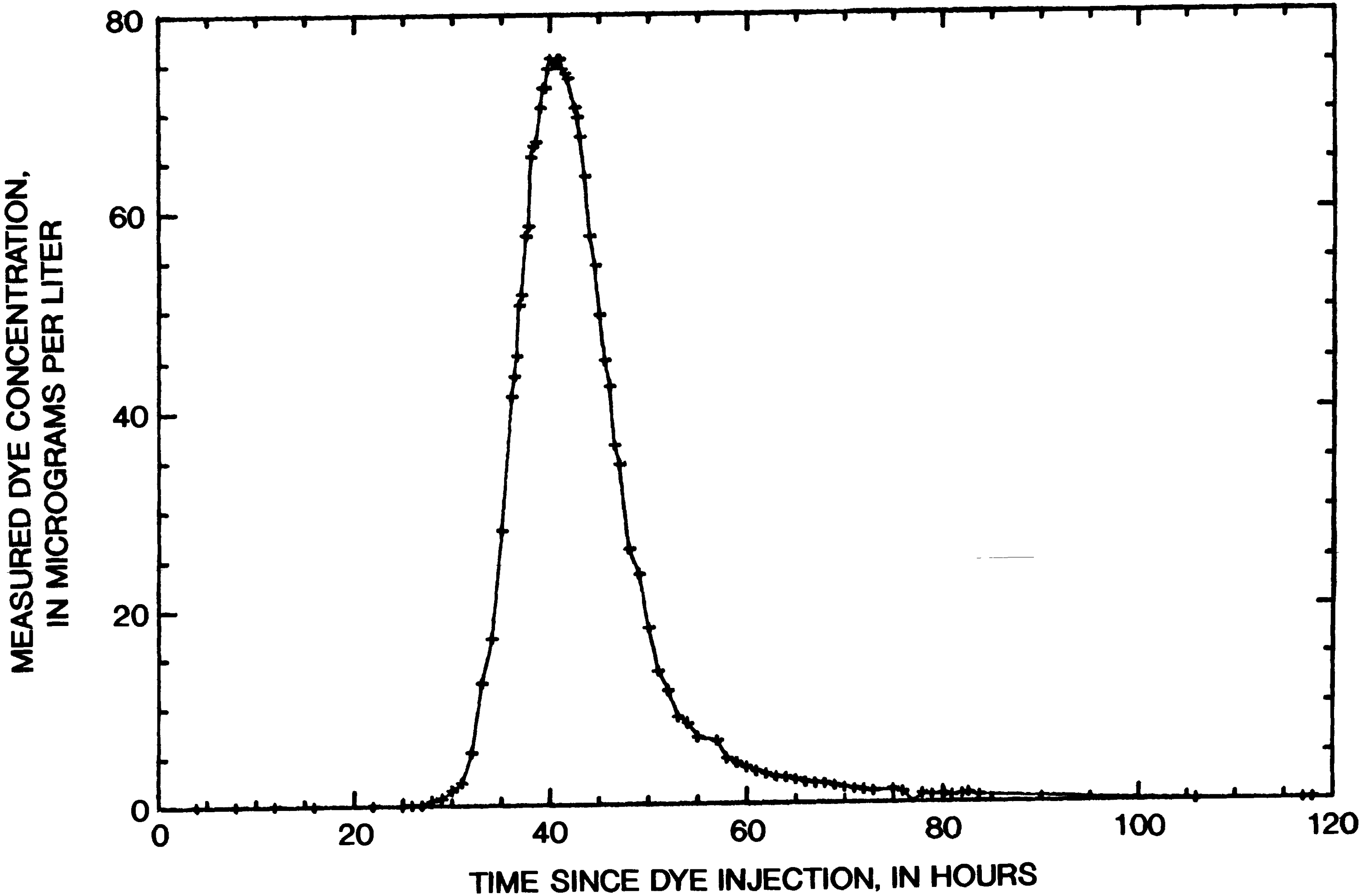


Figure 15.--Typical time-concentration response curve for dye recovery.

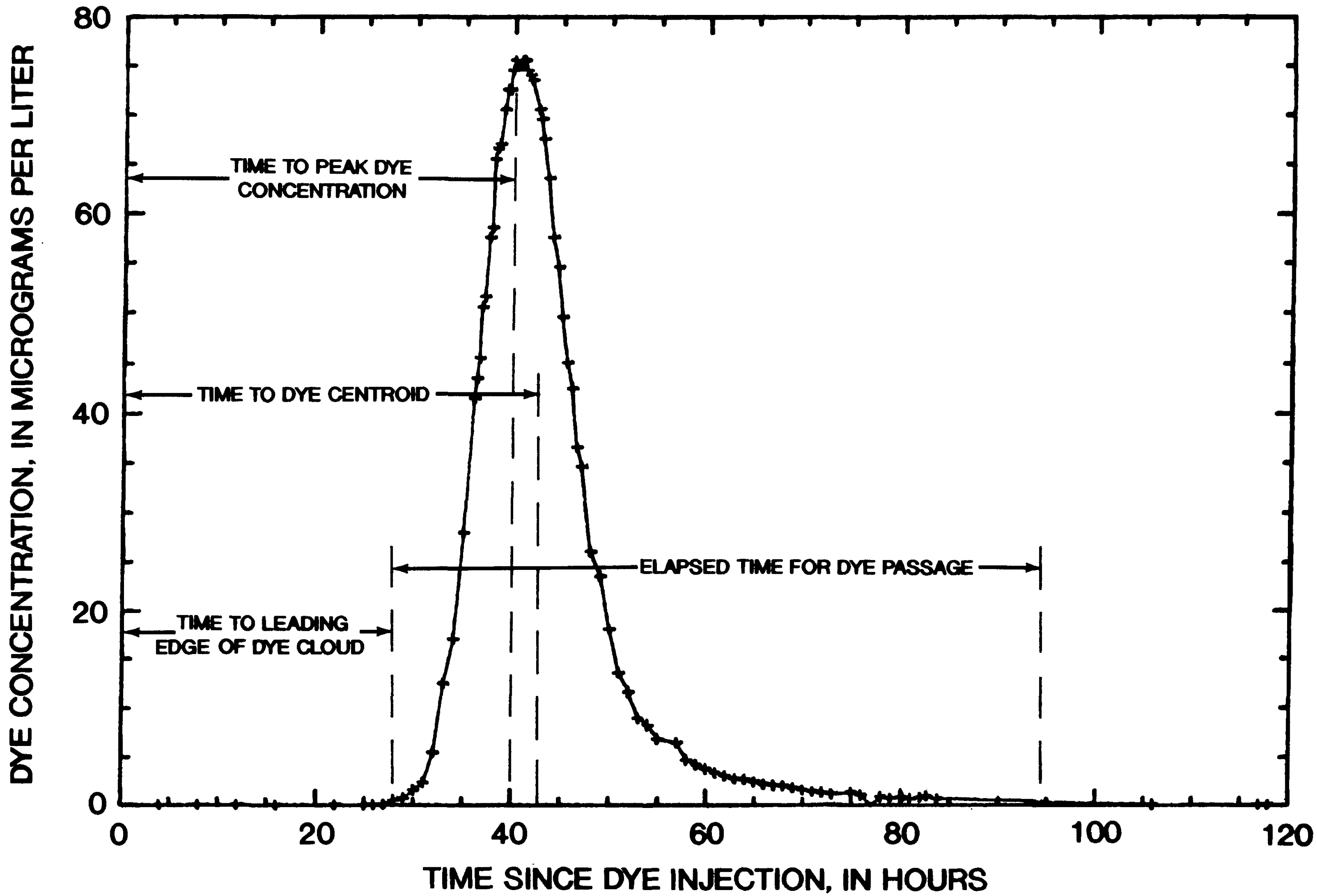


Figure 16.--Dye-recovery curve illustrating measures of elapsed time since dye injection.