DYE TRACING TECHNIQUES USED TO DETERMINE GROUND-WATER FLOW IN A CARBONATE AQUIFER SYSTEM NEAR ELIZABETHTOWN, KENTUCKY

By D.S. Mull, J.L. Smoot, and T.D. Liebermann

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CONVERSION FACTORS

For use of readers who prefer to use 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 SI Units
inch (in.)	25.4	millimeter (mm)
feet (ft)	0.3048	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)
million gallons (Mgal)	3,785	cubic meter (m^3)
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)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
micromhos per centimeter at 25° Celsius (μmhos/cm at 25 °C)	1.000	microsiemens per centimeter at 25° Celsius (μS/cm at 25 °C)

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

$$°C = (°F - 32)/1.8$$

<u>Sea level</u>: 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 "Mean Sea Level of 1929."

DYE TRACING TECHNIQUES USED TO DETERMINE GROUND-WATER FLOW IN A CARBONATE AQUIFER SYSTEM NEAR ELIZABETHTOWN, KENTUCKY

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ABSTRACT

Because of the vulnerability of karst aquifers to contamination and the need for water managers to know recharge areas and ground-water flow characteristics for spring and wells used for public water supply, qualitative and quantitative dye-tracing techniques were used during a ground-water investigation in the Elizabethtown area, Hardin County, in north-central Kentucky. The principal aquifer in the Elizabethtown area is thick nearly horizontal beds of limestone and thin beds of shale of Mississippian age. As much as 65 percent of all water pumped for the city water supply is obtained from two springs and two wells that obtain water from these rocks. Bedrock is overlain by unconsolidated residuum and surficial deposits that are hydrologically significant as a source of recharge to the bedrock aquifer through conduits developed in the unconsolidated material. The area is a typical mature karst terrane with sinkholes, springs, karst windows, and losing and sinking streams most of which receive runoff from interstate highways, railroads, and urban and rural areas.

Sinkholes were classified in this study according to their ability to funnel runoff directly into the ground-water flow system, based primarily on the nature of the swallet draining the sinkhole. The presence of bedrock in the sinkhole nearly always ensured a well defined swallet leading to the subsurface. Sinkholes that receive drainage directly from transportation routes have the greatest potential for contaminating ground water.

Qualitative and quantitative dye tracing techniques and equipment are discussed in detail. Qualitative dye tracing with fluorescein dye and passive dye detectors, consisting of activated coconut charcoal identified point to point connection between representative sinkholes, sinking streams, and karst windows and the city springs and wells. Qualitative tracing confirmed the presence of infiltrated surface water from a perennial stream, Valley Creek, in water from both city wells and generally confirmed the direction of ground-water flow as shown by a water-level contour map. In addition, qualitative tracing confirmed that part of the recharge area located 3,000 to 11,500 feet east of the springs underlies major transportation routes including interchanges of Federal and State highways.

Quantitative dye tracing with rhodamine WT, automatic samplers, discharge measurements, and fluorometric analyses was used to determine flow characteristics such as traveltime for arrival of the leading edge, peak concentration, trailing edge, and persistence of the dye cloud at the spring resurgence. Analyses of the dye-recovery curves for quantitative dye traces completed between the same sinkhole and a city spring, a distance of 3,000 feet, and during different flow conditions showed that the arrival time of the

leading edge of the dye cloud ranged from 5 to 24 hours and that the traveltime of the centroid of the dye cloud ranged from 6 to 31 hours when discharge was 4.6 and 0.53 cubic feet per second, respectively.

Repeat quantitative dye traces between a karst window and a city spring were used to develop predictive relations between discharge, mean traveltime, apparent ground-water flow velocity, and solute transport characteristics. Normalized peak concentration, mean traveltime, and standard deviation of traveltime were used to produce a dimensionless, composite type curve that was used to simulate solute transport characteristics for selected discharges. Using this curve and previously developed statistical relations, a water manager can estimate the arrival time, peak concentration, and persistence of a soluble conservative contaminant at a supply spring or well, on the basis of discharge and the quantity of spilled contaminant.

INTRODUCTION

Reports of contamination combined with increasing dependence on ground water has led to a growing awareness of the potential for ground-water degradation from surface runoff by way of sinkholes and sinking streams in the Elizabethtown area, Kentucky. Ground water is vulnerable to contamination where recharge areas are underlain by karstified limestone. It is particularly vulnerable where such recharge areas also contain urban areas and major transportation corridors as in the Elizabethtown area. Recognizing the serious potential for ground-water contamination and the need to identify the areas most likely to drain directly to the ground-water system, the U.S. Geological Survey and the city of Elizabethtown conducted a cooperative study to locate and classify sinkholes most susceptible to surface runoff; to identify point to point hydrologic connections by dye traces between selected sinkholes, losing and sinking streams and the city water-supply springs and wells; and to define the relation between precipitation, storm-water drainageways, streams, selected sinkhole drainage, ground-water movement, and down-gradient springs and wells.

Qualitative dye-tracing can identify point-to-point connections between selected sinkholes, losing and sinking streams, and water-supply springs or wells. Quantitative dye-tracing can provide the water manager with information on ground-water flow characteristics that are not readily obtainable in other ways. Thus, analysis of the results of quantitative dye tracing can be a valuable tool for the future management and protection of the ground-water resource.

Information gained from this study will help local, State, and Federal water supply, management, and protection agencies in their efforts to develop aquifer and well-head protection plans which incorporate land use controls around sinkholes whose drainage has been traced to public water-supply springs or wells. Techniques and concepts developed in the Elizabethtown area have transfer potential to other areas underlain by similar limestone aquifers.

Purpose and Scope

The purposes of this report are to explain dye-tracing techniques in karst terrane, demonstrate the use of the results of quantitative dye tracing for developing predictive capabilities for water-resource management, and to refine understanding of the hydrology of the carbonate aquifer near Elizabethtown using spring discharge measurements, precipitation records, low flow stream measurements, and results of dye tracing.

This investigation, begun in the summer of 1984, consisted of three phases of field operations: (1) field inventory of all sinkholes shown on 7-1/2 minute topographic maps with special emphasis on locating sinkholes not shown on these maps, (2) identification of point to point connection between selected sinkholes and the city springs and wells using qualitative dye tracing techniques, and (3) repeat dye tracing under variable flow conditions using quantitative dye tracing techniques. In addition, seepage measurements were completed in Valley Creek to define the gaining or losing nature of the stream in the study area. Discharge was measured at each water-supply spring during different flow conditions in order to define the stage-discharge relation for the spring. Daily precipitation was measured at 12 sites around Elizabethtown in order to quantify the relation between precipitation and spring discharge. This report discusses both qualitative and quantitative dye tracing techniques and presents an analysis and interpretation of the results from repeated traces that are used to describe the ground-water flow characteristics in the study area.

Location and Extent of Study Area

The Elizabethtown area, as defined for this report, consists of approximately 49 square miles in Hardin County in north-central Kentucky (fig. 1). The area is about 40 miles south of Louisville and is the hub for Federal interstate highways, State highways, and railroads. The area includes parts of the Cecilia and Elizabethtown 7-1/2 minute quadrangle maps.

Previous Investigations

Several published reports discuss the geology and water resources of the Elizabethtown area. Most recently, Mull and Lyverse (1984) described the occurrence, movement, and quality of ground water in a 50 square mile area around Elizabethtown. The ground-water and surface-water resources in a 240 square mile area around Elizabethtown are described by Lambert (1979). Similar discussions are in reports by Brown and Lambert (1963) and Otton (1948). The fresh-saline water interface is shown on a map of Kentucky at a scale of 1:50,000 (Hopkins, 1966). The U.S. Geological Survey published detailed geologic maps at the scale of 1:24,000 for the Cecilia (Kepferle, 1963) and Elizabethtown (Kepferle, 1966) quadrangles. McFarlan (1943) discussed the geologic and mineral resources of Kentucky, including the Elizabethtown area.

Methods of Investigations

Following a review of existing hydrologic data, a field reconnaissance of sinkholes was completed. Results of the sinkhole inventory were used to select dye injection points to define the hydrologic connection between sinkholes and the city water-supply springs and wells.

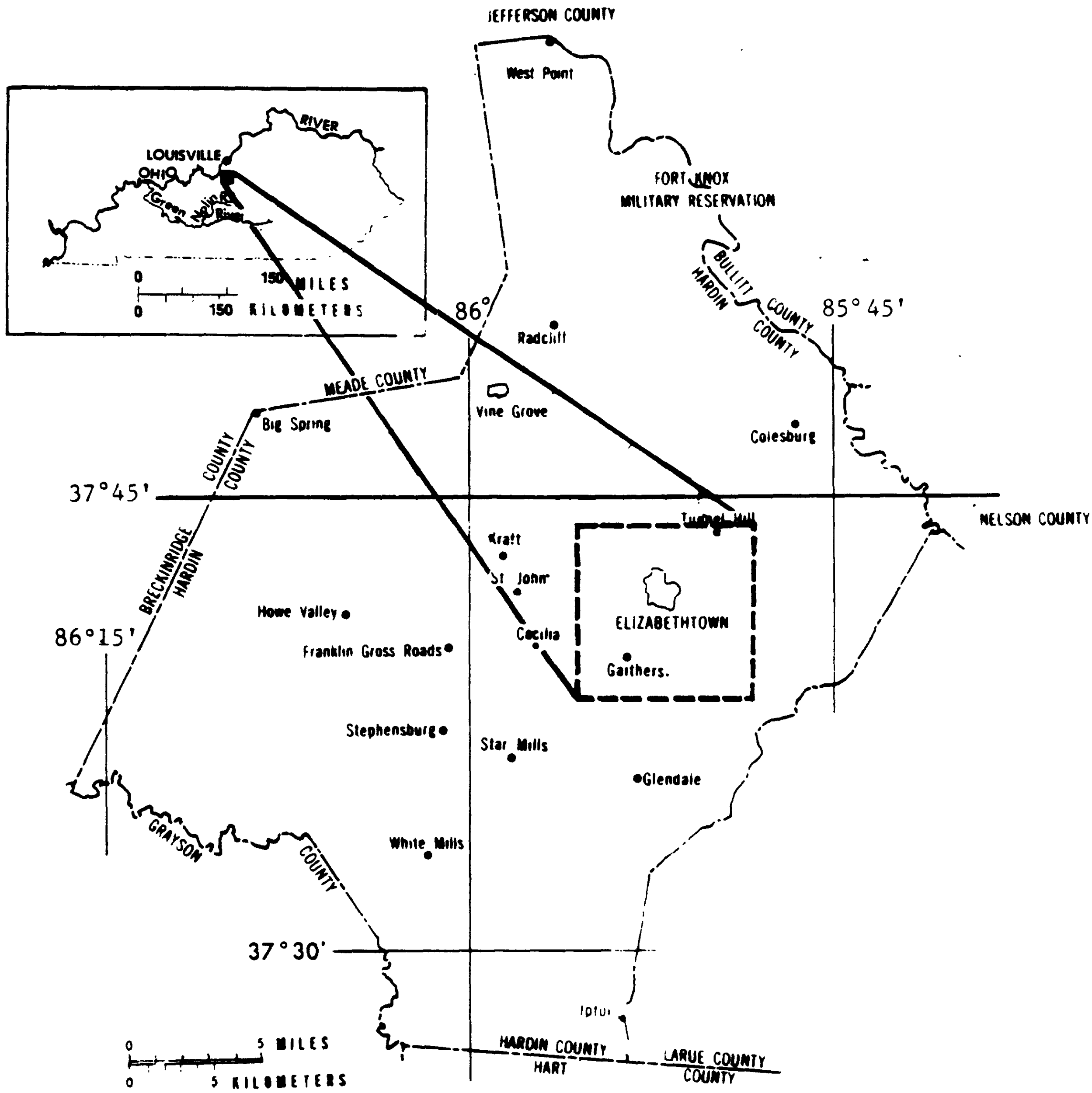


Figure 1.-- Location and extent of Elizabethtown study area.

The selection of sinkholes for the injection of dye was based on the presence of an open swallet or drain in the sinkhole, the susceptibility of the sinkhole to receive surface runoff directly from roadways or farmlands, and the apparent location of the sinkhole upgradient from the city spring and wells as shown by a water-level contour map. Initially, qualitative dye-tracing techniques were used to identify the connection between selected sinkholes and the city springs and wells. The water draining into a sinkhole was tagged with a fluorescent dye and the presence or absence of dye was monitored in water from springs and wells used for domestic, industrial, or public water supply. Quantitative dye tracing techniques using automatic water samplers, discharge measurements, and the mass balance relation of dye recovered to dye injected, were used to describe ground-water flow characteristics under various conditions. Procedures for conducting both types of dye tracing are described in detail in this report.

Miscellaneous discharge measurements and records from two continuous stage recorders were used to define the stage-discharge relation at each city water-supply spring. The stage-discharge relation is used to determine spring discharge without making discharge measurements. Two low-flow seepage measurements were completed in Valley Creek and its tributaries to identify the gaining or losing nature of the streams. The main stem of Valley Creek was checked for unknown springs, especially in the vicinity of the water-supply springs where dye recovery was monitored.

Precipitation was monitored at twelve sites throughout the area. Two sites had recording tipping bucket gages and ten sites had non-recording gages that were read daily. Records from these gages were used in combination with discharge measurements at the springs to define the relation between precipitation and discharge from the springs.

Gamma and caliper logs were run in two industrial water-supply wells, in one test well, and in one well used for the disposal of storm-water runoff. These records were used to determine the lithology of the rock and the presence and size of openings penetrated by the wells.

Because specific conductance can indicate differences in the source of water draining from a particular spring, specific conductance was measured with a Beckman[1] RB-3 meter each time a spring was visited. The number of measurements at each spring ranged from 29 to 32. The average interval between measurement was 17.4 days for the period between December 20, 1984 and July 9, 1986. Analysis of these data was used to confirm the connection between a cave under I-65 and a small unused spring upstream of the Elizabethtown Spring.

Acknowledgments

The authors are grateful to the many individuals and businesses 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

[1]Use of firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

inspecting springs, sinking streams, or sinkholes. Representatives of the Gates Rubber Company, Crucible Magnetics Division of Colt Industries, and Celeweve Systems Incorporated granted access to their wells and provided personnel to collect water samples during dye tracer tests. Personnel of the Elizabethtown Water Treatment Plant provided invaluable assistance with the construction of recorder shelters and installation of staff gages at each city spring. They also serviced automatic water samplers, manually collected water samples during dye tracer tests, and performed daily inspection of 10 precipitation gages in the Elizabethtown area. The assistance and cooperation of these individuals contributed significantly to the completion of this investigation.

WATER USE

The majority of water users in the study area are supplied by the Elizabethtown municipal water system which withdraws water from two wells, two springs, and a surface reservoir. In 1985, the average daily withdrawals were 1.15 million gallons from both wells and 0.75 million gallons from the springs. The average daily withdrawals from the reservoir were about 1.07 million gallons. Thus, the average daily withdrawals from all sources were 2.97 million gallons of which 64 percent was from ground water. Ground water was the sole source of water until the reservoir was completed in mid-1972. Except for 1978, more than 50 percent of all water pumped annually for municipal use was withdrawn from ground-water sources.

Mull and Lyverse (1984) reported average daily withdrawals of 3.14 million gallons in 1982 of which 65 percent were from ground water. The slight decrease in total withdrawals by the municipal water system in 1985 seems to reflect the fact that three industries developed their own ground-water supply wells. According to the water withdrawal permit file of the Kentucky Natural Resources and Environmental Protection Cabinet, Division of Water, the combined average daily withdrawals by these industries were 0.51 million gallons in 1985.

HYDROGEOLOGIC FRAMEWORK

Physiography

The Elizabethtown area lies within the Interior Low Plateaus physiographic province of Fenneman (1938) and consists of a sinkhole plain named the Pennyroyal (Sauer, 1927 p. 21). The Pennyroyal is a gently rolling broad upland (rough in places) that slopes to the southwest. It is underlain by soluble limestone, and is characterized by karst features such as sinkholes, sinking streams, springs, and subsurface drainage. A few caves are known but are not well developed.

The lowest altitude in the area, about half a mile south of Gaithers, is about 640 feet above sea level. The highest altitude, near Crest, is about 920 feet above sea level. The relief in most of the area is less than 150 feet and tends to lessen southwest of Elizabethtown, especially west of Valley Creek. The smaller streams usually flow in shallow channels less than five feet deep in residuum or alluvium. The main stem and larger tributaries of

Valley Creek, the only perennial stream in the area, flow directly on bed rock. In places, the channel of Valley Creek has incised more than 15 feet below the erosional land surface. In general, the distance of the Valley Creek channel below land surface increases in a southerly direction.

Geology

Because nearly all ground water in the Elizabethtown area is obtained from depths of 300 feet or less, only the near surface geology is discussed in this report. The geology is described in some detail in reports by Mull and Lyverse (1984), Lambert (1979), Brown and Lambert (1963), Otton (1948), and McFarlan (1943). Detailed stratigraphic columns, lithologic descriptions, and structural features are shown on 7-1/2 minute geologic quadrangle maps of the area. These maps are listed in the references. The following discussion proceeds from younger or uppermost geologic units to successively older and deeper rocks and has for the most part been extracted from previously mentioned works.

Alluvial deposits of Quaternary age that border Valley Creek and its tributaries are the youngest unconsolidated sediments in the Elizabethtown area. The alluvium ranges from 0 to 20 feet in thickness and consists of poorly sorted sand, silt, and gravel, interbedded with clay.

In most of the Elizabethtown area, bedrock is overlain by unconsolidated residuum or surficial deposits of slumped material. The residuum is not mapped, but it may be as much as 70 feet thick in places. It consists of clay and insoluble chert derived from weathered limestone and rests on an irregular karst surface of the underlying limestone. Chert is generally more abundant near the base of the residuum and called the "boulder zone" by local drillers.

According to the geologic maps, surficial deposits of slumped material, which range up to 330 feet in thickness, overlie bedrock or residuum in relatively broad areas south and west of Elizabethtown. The major areas of occurrence are shown on plate 1. Lambert (1979) suggests that this type of deposit may be more extensive than indicated on geologic maps because the deposits occur irregularly and tend to be masked by a thin veneer of loess. The deposits consist of poorly indurated sand and clay intermixed with scattered boulders of limestone. These deposits were derived from rocks overlying the Ste. Genevieve and St. Louis Limestones, probably during an early cycle of karstification (Kepferle, 1966).

The consolidated rocks underlying the Elizabethtown area are Mississippian in age and consist primarily of limestone and dolomite with minor amounts of siltstone and shale. The Ste. Genevieve and the underlying St. Louis Limestones are the most widespread rock units exposed at the surface. The Ste. Genevieve Limestone crops out south and west of Elizabethtown and averages about 80 feet in thickness. The formation is mostly limestone and dolomite but is locally shaly. Oolitic limestone in beds 0.5 to 4.0 feet thick is characteristic of the formation.

In this report, the Lost River Chert of Elrod (1899) is assumed to separate the two formations. The Lost River Chert is a 10-foot zone of limestone containing coarse fossil fragments and abundant chert, and crops out at the surface in the area south and east of Elizabethtown. The unit is commonly marked by rough-weathered blocks and slabs of chert which litter the land surface.

The St. Louis Limestone is the major bedrock unit in the study area. The formation crops out north and east of Elizabethtown and ranges from 200 to 310 feet in thickness. Limestone and dolomite are the predominate rock types, and shale occurs as scattered thin beds. The limestone is thin- to thick-bedded and has weathered to a mature karst topography. The massive beds of limestone have well-developed solution openings along fractures and bedding planes which form the conduits for ground-water movement. In nearby areas, core holes have penetrated about 50 feet of interbedded limestone, gypsum, and anhydrite in the lower part of the St. Louis Limestone (Kepferle and Peterson, 1964; Moore, 1964; McGrain and Helton, 1964). George, (1982) reported gypsum nodules in the lower part of the St. Louis Limestone and the upper part of the underlying Salem Limestone. It is the presence and subsequent dissolution of gypsum that has in part contributed to the extensive sinkhole plain development in the Elizabethtown area (Noger and Kepferle, 1985).

Limestone, shale, and dolomite of the Salem Limestone underlie the St. Louis Limestone but crop out only in the headwaters of several streams north of Elizabethtown. The Salem Limestone is about 35 to 110 feet thick, thin- to thick-bedded, and commonly shaly in the lower half. The upper part of the limestone is composed of rounded sand-sized limestone pellets and fossil detritus as much as 1/8-inch in diameter. The shaly sequence may reach a thickness of 50 feet but beds are discontinuous.

Occurrence and Movement of Ground Water

Ground water in the Elizabethtown area occurs in both unconsolidated sediments and consolidated bedrock that make up a complex interrelated aquifer system. Ground water in the unconsolidated sediments of the residuum and slumped surficial deposits occurs in intergranular (primary) openings and in conduits or pipe-like (secondary) openings. Although the tendency is to assume that all water in the unconsolidated material occurs in primary openings, Wright and Wilson (1984) report numerous voids and conduits and the presence of "piping in red clay" in the soil overlying bedrock. They reported that many of the test holes augered along the northbound lane of Interstate 65 near the Western Kentucky Parkway Interchange, penetrated water-carrying voids, in some cases, as much as 40 feet above bedrock. This suggests that, at least in some places in the Elizabethtown area, there is a well developed conduit system in the unconsolidated material that collects and funnels water to water bearing conduits in the underlying bedrock. The hydrologic significance of the unconsolidated material overlying bedrock is further indicated by Lambert (1979) who reported that a local well driller estimated that the material overlying bedrock is the principal source of water for one-third of the drilled wells in some areas.

Ground-water movement through unconsolidated material is generally considered to be relatively slow with possible quality enhancement through filtration and other physical and biological processes occurring in the soil material. However, the presence of pipe-like openings in the unconsolidated material suggests that the possibility exists for rapid ground-water movement with relatively little opportunity for water-quality improvement. Thus, potential ground-water contaminants placed on the surface or in depressions such as sinkholes, 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 Elizabethtown area is limestone. 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 the openings to allow more rapid movement of ground water. The enlarged openings may be vertical or horizontal and range in size from a fraction of an inch to cave-size, such as the opening that forms the mouth of the Elizabethtown Spring (site 1). Mull and Lyverse (1984) reported the presence of several zones of horizontal fractures or solutionally enlarged horizontal openings at various depths in wells. Most relatively high-yield water wells in the Elizabethtown area penetrate these horizontal sheet-like openings. The presence of these horizontal openings are shown by caliper logs that are discussed elsewhere.

There are generally two types of ground-water flow in the Elizabethtown area, diffuse (slow, laminar flow) and conduit (rapid, turbulent flow). Diffuse flow occurs in primary openings in unconsolidated sediments and bedrock and is a major component of ground-water recharge, especially where extensive deposits of unconsolidated sediments overly bedrock.

Conduit flow occurs in secondary openings that range from a few millimeters to cave-size. Water that moves through conduits can enter the subsurface through discrete points such as sinkholes or sinking streams or it can result from diffuse flow being concentrated into discrete conduits in the subsurface. The hydrologic significance of conduit flow is the rapid transmission of water through the aquifer. The relation between diffuse and conduit flow is shown by the generalized block diagram (Gunn, 1985) in figure 2.

In a mature karst aquifer such as occurs in the Elizabethtown area, master conduits concentrate direct-input, conduit flow from sinkholes and sinking streams. These conduits are dendritic or trellised and develop along horizontal and vertical openings. As the aquifer matures, flow becomes convergent to the conduits and thus to the springs that serve as natural discharge for the master conduits. Flow in master conduits is typically turbulent, with highly variable turbidity and temperature, and relatively flashy response to precipitation. These are characteristics of both the Elizabethtown and Dyers Springs that are the natural discharge points for master conduits draining separate ground-water basins in the Elizabethtown area.

Ground water in the Elizabethtown area moves in response to hydraulic gradients from points of recharge to points of discharge. The contours on plate 1 depict the shape of the water table and are based on the altitude of the water level in wells, springs, and streams in the fall of 1982 (Mull and Lyverse, 1984). The general direction of ground-water flow can be estimated by drawing flow lines perpendicular to the water-level contours. The lines

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

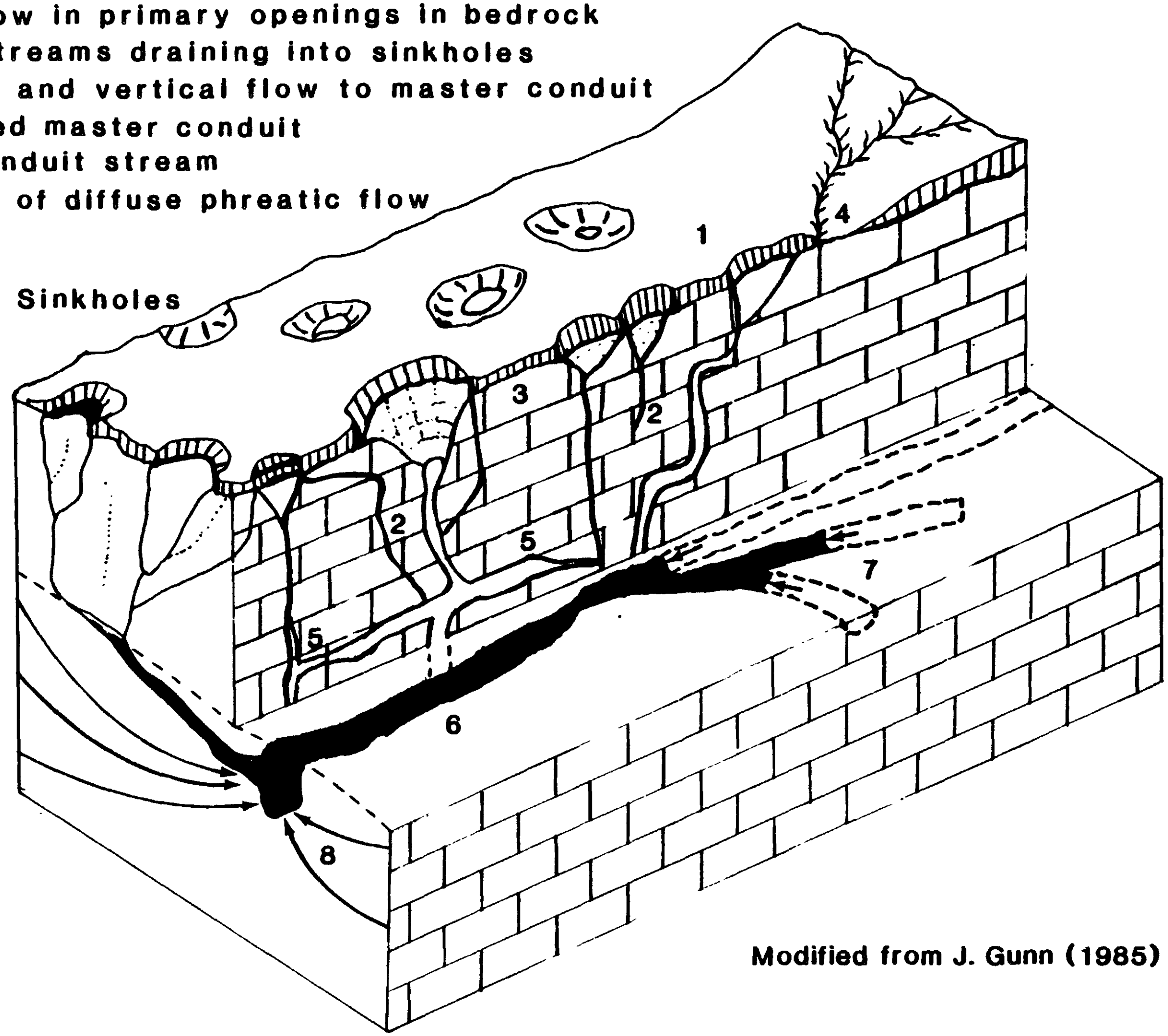


Figure 2.--Components of ground-water flow in a maturely karsted aquifer.

would show that the general direction of ground-water movement is towards Valley Creek from the surrounding area.

Direction of Ground-Water Flow

Results of dye traces completed during this investigation (described later in this report) generally confirm that the direction of ground-water movement is towards Valley Creek from the surrounding area. The water-level contour map (plate 1) shows a syncline dipping southwest and trending northeast-southwest roughly parallel to Valley Creek in the Elizabethtown area. Generally, the dye moved down the limbs and along the axis of the dipping syncline. In addition to the water-level contour map, there are other directional indicators of ground-water flow in the Elizabethtown area.

This study was designed primarily to use dye tracing to delineate ground-water flow paths and velocities in the Elizabethtown area. The trend of the dye traces (plate 1) suggests that there is a directional preference of ground-water flow. Additional data acquired during the study supports this interpretation. Joint measurements in outcrops, primarily in stream channels in the vicinity of Elizabethtown, indicate that the trend of joints is orthagonal, one set trending about N 50° E and the other about N 40° W (fig. 3). The northeasterly trending set coincides closely with axis of the syncline shown on the water-level contour map, plate 1.

Data from an aquifer test performed in September 1982 indicated anisotrophic ground-water flow during the pumping test. The test was conducted at site 12 located along the axis of the syncline of the water-level contour map (plate 1). Data from this test were used in a computer program (Maslia and Randolph, 1986) by Maslia to determine the two-dimensional transmissivity tensor components at the site. Results of the anisotropy analysis are plotted as the square root of the transmissivity (fig. 4) and indicate that the major axis of transmissivity is 34,900 ft^2/d, and the minor axis of transmissivity is 630 ft^2/d, giving an anisotropy ratio of 55:1. Storativity was calculated to be 5.9×10^{-4}. The angle of anisotropy of N 50° E in figure 4 is very close to the orientation of the one set of joints (fig. 3) and coincides closely with the axis of the syncline on the water-level contour map on plate 1.

There are several possible explanations for the apparent discrepancies in the direction of ground-water flow suggested by a comparison of the frequency of mapped fractures (fig. 3), results of the anisotropy analysis of the aquifer test (fig. 4), and the direction of dye traces shown on plate 1. The southwesterly direction of regional ground-water flow indicated by the water-level contours (plate 1) likely resulted in the solutional enlargement of the joint set trending N 50° E which coincides with the axis of the syncline and major axis of transmissivity determined from the anisotropy analysis of the aquifer test data shown in figure 4. Under natural flow conditions, the gradient of the water table along this regional direction is relatively small compared to that along the joint set of N 40° W which coincides with the limbs of the syncline. Thus, shallow ground-water movement as defined by the dye traces is down the steeper gradient on the limbs of the syncline to discharge points such as the springs along Valley Creek. However, when a cone of

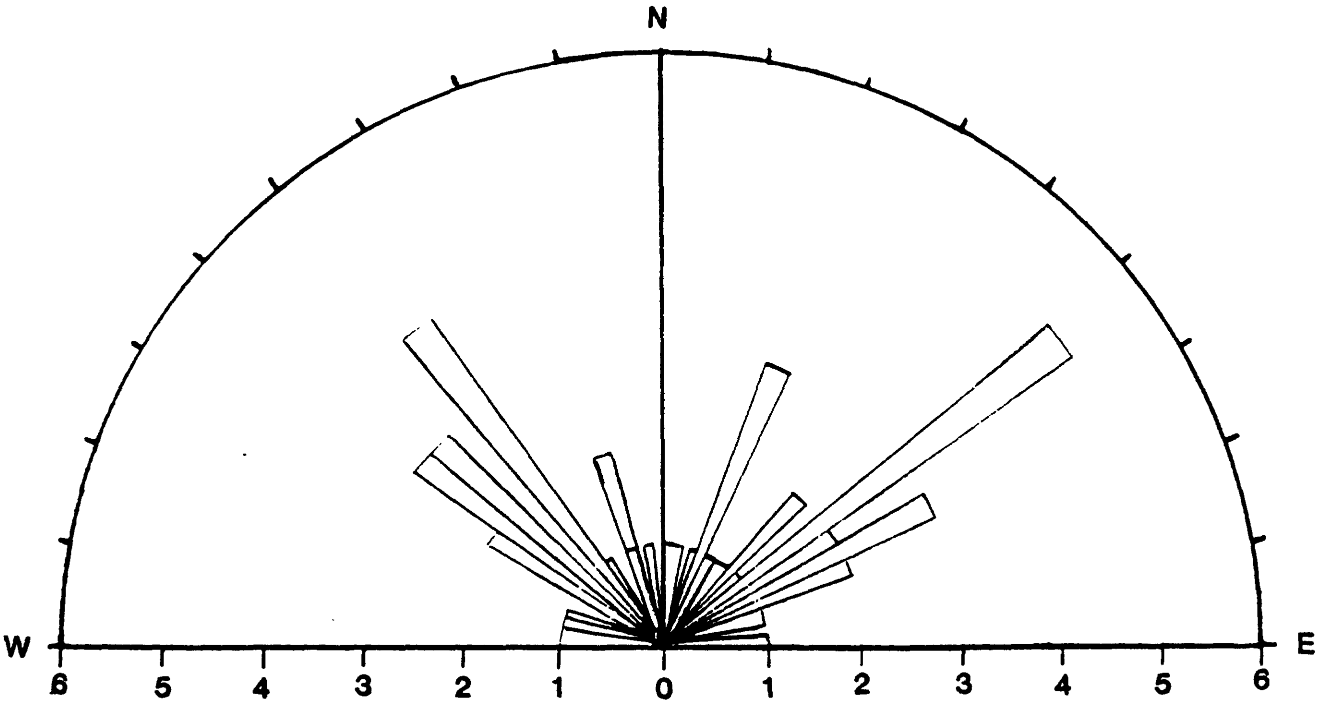


Figure 3.--Relative frequency and directional trend of measured fractures in the Elizabethtown area.

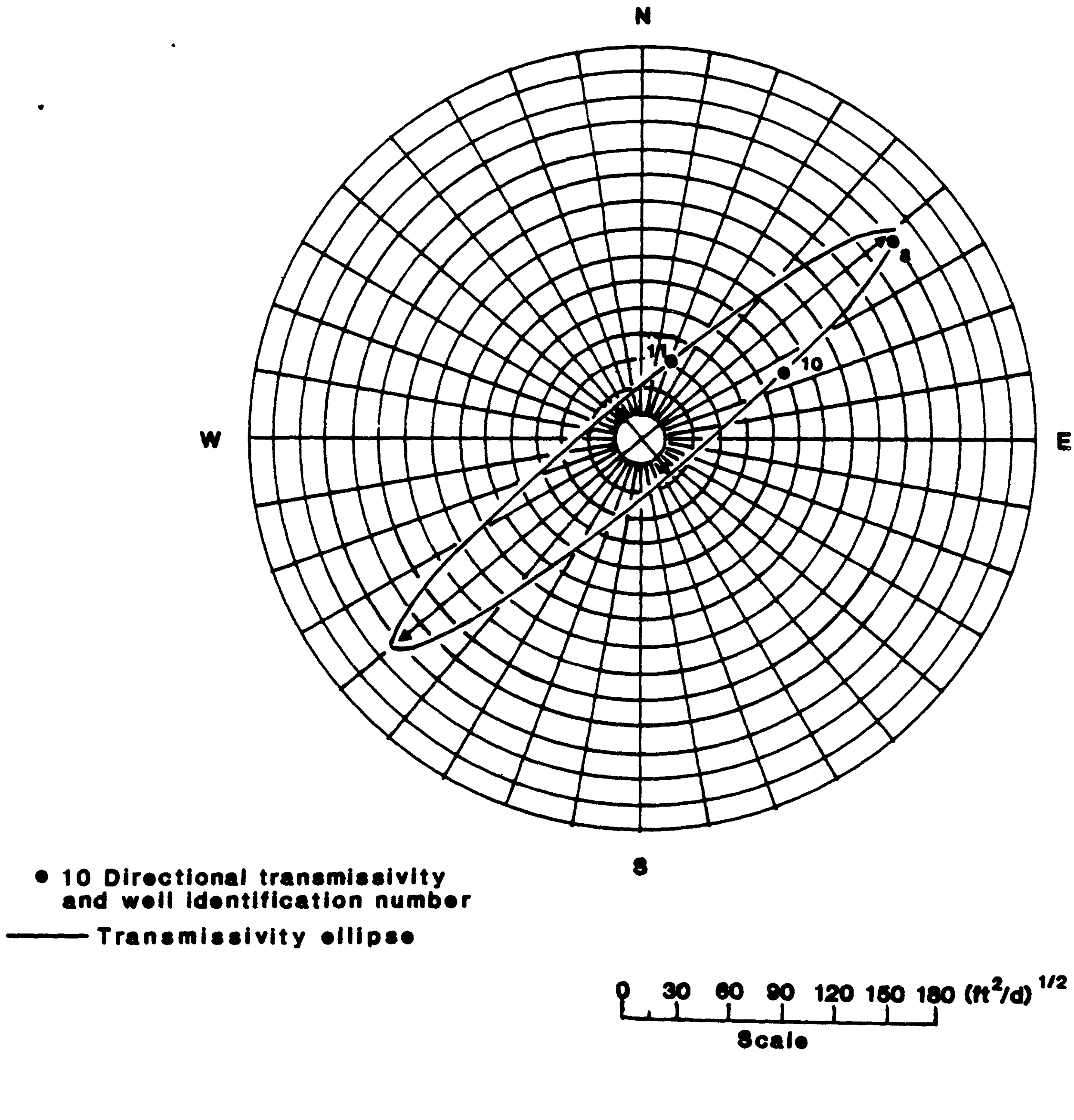


Figure 4.--Directional trend of transmissivity component for aquifer test, September 24, 1982.

depression was created by pumping during the aquifer test, the major axis of transmissivity was parallel to the regional direction of ground-water flow. This indicates that conduits are probably better developed and are more transmissive along the regional direction when stress is applied to the aquifer.

The rate of ground-water movement is important to the understanding and solution of many ground-water problems in karst terrane, but especially to those related to contamination of the ground-water system. For example, if a pollutant enters the ground-water system up-gradient from a supply well or spring, it is necessary to be able to predict when the pollutant will reach the water withdrawal point. It is important that water managers recognize that the rate of most ground-water movement in karst aquifers is typically much faster than ground-water flow in granular material. For example, the rate of ground-water movement in karst aquifers can be on the order of miles per day in contrast to feet per year in non-karst granular aquifers. Estimates of the rate of ground-water movement can be derived from quantitative dye tracing and monitoring the response of spring discharge to precipitation. These procedures are discussed later in the report.

Karst Features

The term karst refers to distinctive features developed on soluble bedrock. The geology and structure control, in part, the development of karst features. The principle requirements for karstification are soluble bedrock such as limestone or dolomite and the presence of primary openings along joints or bedding planes that permit the circulation of ground water sufficient to enlarge the primary openings through solution of the carbonate bedrock.

The karst features in the Elizabethtown area are developed on limestone and for the most part have formed as a result of the dissolution of carbonate material by percolating ground water. Although some karst land forms such as sinkholes may develop within the relatively thick zone of unconsolidated regolith overlying bedrock, it is the presence of solutionally enlarged openings in bedrock that ultimately controls the development of such features. Karst features such as sinkholes, springs, karst windows, losing streams, and caves are present in the Elizabethtown area.

Sinkholes

Sinkholes are the most common karst feature and develop as a result of the reduced support and the eventual collapse of surface or near surface material. In general, there are two types of subsurface collapse that form sinkholes: (1) collapse of limestone cave roofs and (2) slumping of surface material into solutionally 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 cave passage. Although reported in other karst areas in Kentucky, this type sinkhole is relatively rare in the Elizabethtown area.

The principle cause of sinkhole development in the Elizabethtown area is migration of regolith, which is unconsolidated material overlying bedrock, into openings in the underlying limestone 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 collapse of regolith arches have been reported in the Elizabethtown area. Such collapses generally occur where the regolith overlying bedrock is relatively thick and subsurface conduits have enlarged to the point that the roof collapses and creates sinkholes.

Sudden collapse of regolith arches can be triggered by construction and land use changes such as loading the land surface with ponded water or vibrating the surface by blasting or heavy traffic. Ponded water is reported to have caused the collapse of several sinkholes in the area south of Elizabethtown and west of U.S. Highway 31W, and also in the vicinity of the interchange of Interstate 65 south and the Western Kentucky Parkway.

The development of solutionally enlarged openings in limestone bedrock below regolith 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 infiltration and transport of sediment from the surface that results in sinkhole formation. It is this same network of subsurface openings that provides avenues for rapid ground-water movement that creates the potential for pollution from sinkhole drainage.

Sinkholes in the Elizabethtown area are circular to irregular in outline and range in diameter from 15 to about 1,500 feet. A few are as deep as 60 feet below the surrounding area. In general, increasing sinkhole size is accompanied by complexity of form such as an elongation of the depression or the coalescing of smaller sinks. Mull and Lyverse (1984) indicated that the trend of the long dimension and groups of sinkholes in the Elizabethtown area is in a northwest and northeast direction. This alignment, which is similar to the trend of vertical joints, suggests that sinkhole development is influenced by ground-water movement along joints in bedrock.

Sinkholes in the Elizabethtown area were classified into five types based on their relation to surface runoff and the water table (Mull and Lyverse, 1984). Following a reconnaissance of sinkholes during this investigation, additional criteria, which better describe sinkhole potential for collecting and draining surface runoff into the ground-water system were selected for sinkhole classification. The criteria for sinkhole clarification are based on the following characteristics: (1) sinkholes developed in unconsolidated material overlying bedrock with no bedrock exposed in the depression, but with well developed, open swallets, (2) sinkholes that have bedrock exposed in the depression and a well developed swallet that empties directly into bedrock, and (3) sinkholes or depressions in which the bottom is covered or plugged with sediment and in which bedrock is not exposed. Because of its impact on the rate of ground-water recharge, the principal criteria for classification of sinkholes in the Elizabethtown area is the presence and nature of the opening draining the sink. Therefore, all sinkholes inventoried during this investigation were classified according to the presence of an open or plugged swallet and are shown on plate 1. In about 95 percent of the inventoried sinkholes, the presence of exposed bedrock ensured an open drain. These sinkholes with an open drain are thought to have the greatest potential for polluting ground water because the open drain is usually connected to subsurface openings that lead directly to the ground-water system. Thus, surface runoff can drain directly to the subsurface without the benefit of filtration and other physical, chemical, or biological processes that occur as the water percolates through the soil plug in the bottom of the sinkhole.

Springs

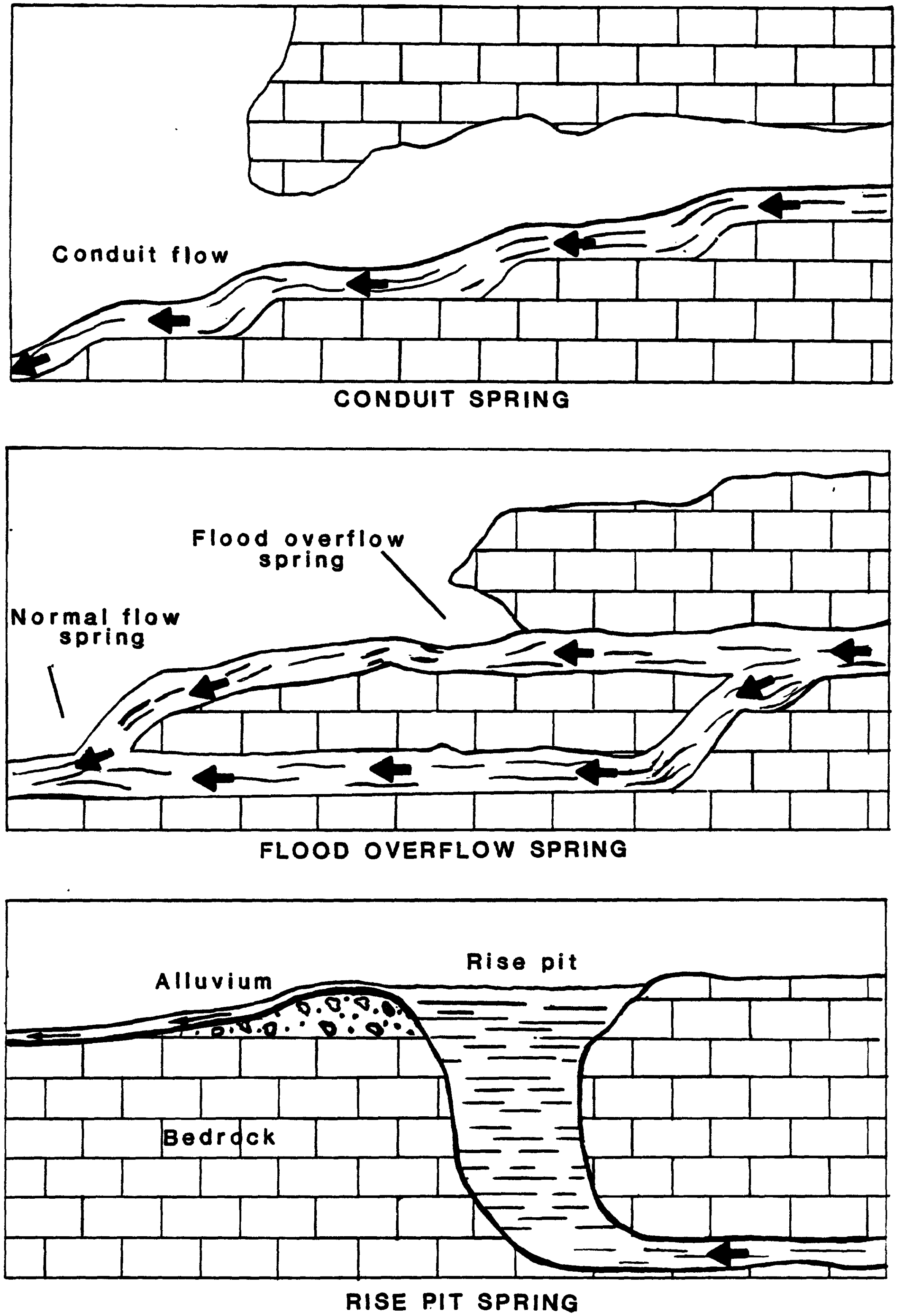
A spring is a natural point of discharge from the ground-water reservoir where the land surface intersects the water table or water-bearing cavities. Springs in the Elizabethtown area range from "wet weather springs" that flow only during or after a rainy period, to relatively large springs that discharge from cave-like conduits in limestone and generally are perennial. Wet-weather springs range from "seeps" to relatively large openings that act as overflow springs when lower passages are filled during heavy rain. Water from a seep is generally shallow ground-water discharge but water from an overflow spring is part of the integrated drainage from a ground-water basin. Flows from the wet-weather springs in the study area were not measured during this investigation because the wet-weather springs represent relatively local ground-water conditions. However, most of these springs were monitored for dye recovery during various traces. The location of all known springs are shown and numbered on plate 1.

The largest springs in the area, Elizabethtown Spring (site 1) and Dyers Spring (site 16), are fed by a converging subsurface drainage system that can be considered as a large branching pattern of openings that collect water over an extensive area, funnel the water to the main conduit of the spring, and thence to the surface at the mouth of the spring. These springs are developed in the upper third of the St. Louis Limestone.

Elizabethtown Spring

The Elizabethtown Spring (site 1) is a conduit spring (see fig. 5). Water flows from a cave-like opening and, except during floods, has a free surface with the atmosphere. The opening and cave conduit is sufficiently large to permit exploration, and penetrations by cavers of several hundred feet have been reported. The Spring discharges on the east bank of Valley Creek.

A smaller conduit-flow spring (site 2) enters Valley Creek about 100 feet upstream of the mouth of the Elizabethtown Spring (see plate 1). Although water from this spring is unused, the spring is hydrologically significant because of its relation to the larger Elizabethtown Spring (site 1). Water from the smaller spring (site 2) issues from several small openings at the base of a limestone cliff at the level of Valley Creek. The mouth of the spring is frequently flooded by backwater from the Creek. During medium- to high-flow conditions water can be heard cascading behind the cliff to the mouth of the spring. Various tracer tests have shown that the unused spring (site 2) and the Elizabethtown Spring (site 1) are connected under certain flow conditions, usually during low flow. Based on a series of specific conductance measurements that are discussed in detail later, high flow from the unused spring does not overflow to the larger spring (site 1) but rises in the conduit system to a flood overflow relief spring at site 5.



From J. N. Jennings (1985)

Figure 5.--Principal types of springs in the Elizabethtown area.

Dyers Spring

Dyers Spring is a "blue-hole" rise pit type spring (fig. 5) that discharges on the east bank and about 100 feet from Valley Creek. Rise-pit springs are called a "blue-hole" spring because of the blue color of the water in the pit. The rise pit and the channel draining to Valley Creek are about 10 feet below the surrounding land surface. The pool was about 8 feet deep during low-flow conditions on October 24, 1984 when scuba-equipped divers tried to determine the nature of the conduits draining to the spring (George, 1984).

Boiling Spring

Another type of a rise-pit spring found in the Elizabethtown area is known locally as a "boiling" spring. Water in a boiling spring wells upward under sufficient pressure to agitate the bottom sediments and the surface in the rise pool to produce the boiling appearance that gives the spring its name. Stark's Spring (site 21) is a boiling spring on the west bank of Billy Creek above the bridge on State Highway 1357, and about one mile west of its intersection with the U.S. Highway 31W bypass. Discharge from this spring rises through alluvium and flows about 40 feet to Billy Creek in a channel incised about 4 feet below the surrounding land surface. Bedrock is not exposed in the rise pool or in the channel draining to Billy Creek. Although discharge was only measured during tracer tests, the land owner states that this is a perennial spring and that discharge is clear to highly turbid.

Flood Overflow Spring

The flood overflow spring at site 5 is about 600 feet northeast of the mouth of the unused spring at site 2 (see plate 1). The altitude of the mouth of the overflow spring is about 15 feet higher than the mouth of the unused spring. Water flows from the spring at site 5 only after intense or prolonged precipitation. Water from this spring (site 5) is frequently very turbid and turbulent. As the conduit systems feeding the spring drains, however, flow becomes clear and less turbulent. The rise point at the overflow spring (site 5) is obscured by a large brush pile so the nature of the opening is not known. The channel leading from the rise point enters Valley Creek about 400 feet upstream of the mouth of the unused spring (site 2). The channel from the flood overflow spring to Valley Creek is incised about three feet into alluvium or residuum and bedrock is not exposed. The relation between the flood overflow spring (site 5) and the unused spring (site 2) is shown in figure 5.

Karst Windows

An unusual type of karst landform that is relatively rare in the Elizabethtown area is a karst window, a depression that has part of a subterranean stream flowing across its floor (Monroe, 1970). Thus, the depression has features of both a spring and a sinkhole. Two karst windows are known in the study area and are shown as springs (sites 15 and 22) on plate 1. In each case a spring or stream emerges at the upper end of the sinkhole, flows about 250 feet and drains into a swallet at the lower end of the sinkhole. The two karst windows receive relatively little runoff because of the small area that drains directly into the sinkhole. However, the karst windows are hydrologically significant because the streams in each sinkhole provide a direct path to the subsurface for any contaminant deposited in or near the sinkhole. This fact has special significance in the case of the karst window at site 15 because flow from this site has been traced to Dyers Spring, part of the Elizabethtown public water supply.

Losing and Sinking Streams

Losing streams are those having streambeds above the water table and are contributing to the zone of saturation. Streams may lose all or part of their flow to the ground-water system at points along their course through fractures or other openings that intersect the streambed. Streams may gain flow in one reach and lose in another reach depending on local geologic and hydrologic conditions. A stream may either gain or lose at different times of the year depending on the seasonal changes of the water table. For this report losing streams are distinguished from sinking streams on the basis of the quantity of streamflow that drains underground and the presence of a swallet through which water drains underground.

Sinking streams are those that terminate and usually drain underground through one or more well developed swallets and losing streams are those that lose only part of their flow underground. Three sinking streams are known in the area of this investigation and shown on plate 1 (sites 23, 24, and 40). Flow in all three sinking streams is intermittent. Thus ground-water recharge through these swallets is limited to periods of runoff following precipitation. Although the above mentioned sites are the largest sinking streams in the study area, many sinkholes function as swallets for sinking streams that exist for varying periods following precipitation.

All water reaching the ground-water system by way of losing or sinking streams is subject to contamination from the surface. Surface contaminants can be transported directly into the ground-water system in this way. Therefore, there is little chance for quality enhancement before the water enters the aquifer. Thus it is important to identify losing and sinking streams, especially in areas where karst aquifers are the source of water for public supply such as the Elizabethtown area. Sinking streams were located during the sink-hole inventory and are shown as open sinkholes on plate 1. Most of the urban area of Elizabethtown is drained by Valley Creek and its tributaries. Consequently, the losing nature of Valley Creek, the perennial stream that flows past the Elizabethtown water-supply wells and springs, should be known because this stream has the potential to introduce into the ground-water system contaminants originating throughout the urban area.

Sinkholes - Potential for Pollution

Sinkholes can provide a direct path for surface runoff to drain to the subsurface because they are commonly drained by open swallets that lead directly to the aquifer system. Sinkholes act as collection and retention basins for surface runoff. Thus, depending upon the drainage area to the sinkhole, relatively large amounts of water can enter the aquifer system in a short time. Therefore, any pollutant carried by surface runoff has the potential for rapid transport to the ground-water system. However, 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. Drainage from sinkholes is also controlled by the nature of sediment and debris washed into the swallet. Heavy sediment loads, such as are common from freshly disturbed construction or cultivated sites, coupled with larger debris can partially obstruct or plug the swallet resulting in the ponding of water in the sinkhole. Mull and Lyverse (1984) reported several instances following periods of rapid runoff in which water collected in and overflowed sinkholes because the sinkhole-drain was partially plugged.

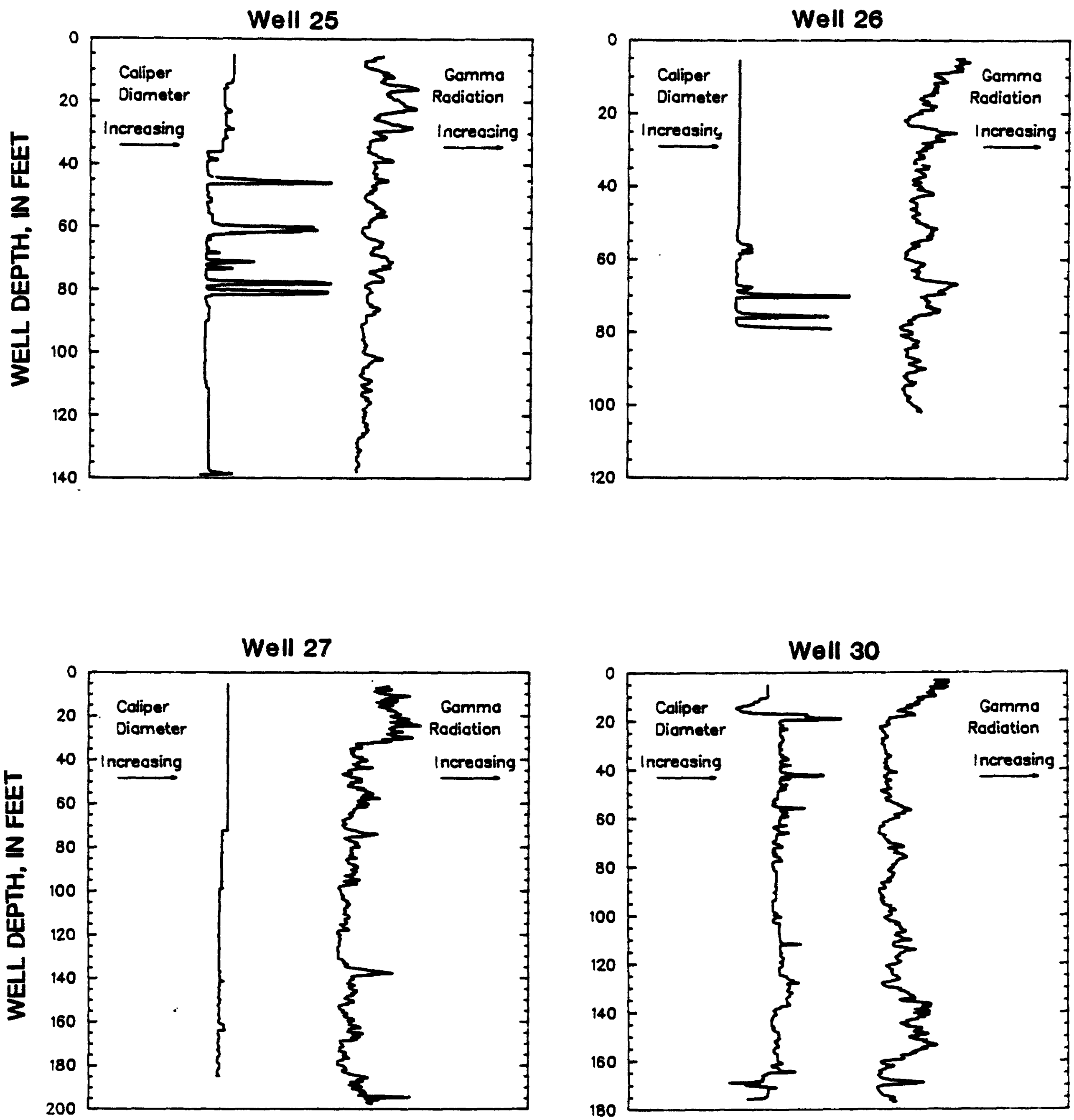
Ponding can also occur in sinkholes with open swallets if runoff exceeds the drain capacity of the swallet or if the subsurface system of conduits which receives sink-hole drainage is filled. The collection and possible retention of surface runoff can be expected in virtually all sinkholes or depressions throughout the Elizabethtown area.

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. The percolation of water through sediments may provide some filtration and purification before the water reaches the aquifer. Because the nature of the contaminants entering the aquifer is, for the most part, related to man's activities, virtually all sinkholes or depressions in the Elizabethtown area have the potential for polluting the underlying ground water. In general, however, the sinkholes having the greatest potential for polluting the ground-water system are those drained by open swallets which receive surface runoff directly from the various transportation routes that traverse the Elizabethtown area. Inspection of plate 1 shows many sinkholes with open swallets, especially in the area south of Elizabethtown, that receive drainage from railroads and highways.

Subsurface Openings

A unique feature of karst terrane is the network of subsurface openings that store and transmit ground water. The presence and size of openings and the lithology of the rocks penetrated by a borehole can be determined by caliper and gamma logging within the borehole. Caliper logs of the uncased portion of the borehole measure variations in the diameter of the well bore and provide qualitative information on the lithology and permeability of the formation. Gamma-ray logs measure the natural radioactivity of a rock unit and are used to identify the lithology of the rocks penetrated. Gamma rays are emitted in proportion to the concentration of radioactive elements in the rock. For example, shaly carbonates that contain large quantities of clay and organic materials are more radioactive than other carbonates within the aquifer (Keys and MacCary, 1971).

Mull and Lyverse (1984) reported that caliper logs from wells in the Elizabethtown area showed that horizontal openings are more numerous and larger in wells south of the city. Caliper logging during this investigation support those results. Caliper logs of wells 25, 26, 27, and 30 are shown in figure 6. Wells 25 and 26 were drilled for industrial water supply. The



Well numbers refer to plate 1.

Figure 6.--Geophysical logs for selected wells in the Elizabethtown area.

caliper log of well 25 shows that this well penetrated five zones of horizontal openings and the deepest was about 80 feet below land surface. The presence of these openings probably explains the relatively high, continuous yield from this well, which has been about 250 gals/min since the well was completed in the spring of 1985. The log of well 25 is similar to logs of the Elizabethtown water-supply wells (Mull and Lyverse, 1984) and suggest that these wells have all penetrated horizontal opening of similar size and depth.

The caliper log of well 26 shows that this well only penetrated three zones of horizontal openings. However, only about 50 gal/min were needed from this well so it was intentionally drilled to a lesser depth than well 25.

Well 27 located about 1,200 feet northeast of well 26 produced little water although the well was drilled to a depth of 185 feet. However, the caliper log of this well (fig. 6) suggests that the well casing may have closed off the water-bearing openings in this well.

Well 30, about 175 feet deep, was drilled as a storm-water disposal well. However, the well reportedly functions only marginally for this purpose. On the basis of the caliper log (fig. 6), this well did not penetrate horizontal openings similar to those found in wells south of the city. In this case, the absence of enlarged horizontal openings precludes the ability of the well to effectively discharge large quantities of storm-water runoff into the aquifer.

HYDROLOGIC CONDITIONS

Precipitation

Precipitation is the source of nearly all water in the Elizabethtown area. Mean annual precipitation for the study area is 49.05 inches. Mull and Lyverse (1984) calculated that, on the average, 32 inches or 65 percent of the mean annual rainfall was lost to evaporation and transpiration. The remaining 17 inches consist of 11 inches of overland flow and 6 inches of base flow which is recharged to and discharged from the aquifer system in a typical year.

Precipitation in different parts of the basin and its effect on discharge from both city water-supply springs was of special interest to this investigation. Precipitation and spring-discharge data were analyzed to determine the effect of various precipitation events on discharge at both water-supply springs.

Precipitation data for the period April 1985 through April 1986, obtained from 10 non-recording gages located around the city, one tipping-bucket recording gage located along Valley Creek about 3.6 miles east of the Elizabethtown Spring (site 1) and one recording gage located on New Glendale road, 1.65 miles east of Dyers Spring (site 16). Due to location and malfunction of the equipment, data from the gage on New Glendale Road was inadequate and was not analyzed. The location of all precipitation gages is shown on plate 1. Daily precipitation readings were made about noon each day at all non-recording gages. Analyses of these data show that precipitation was uniformly distributed over the study area and that differences in daily precipitation between gages were not significant.

Analyses of precipitation data were used to indicate the hydrologic conditions during the study period relative to historic trends. Analysis of precipitation data collected within the study area showed that precipitation was below normal during the study period. Thiessen's pologon method (Fetter, 1980), using data from each non-recording precipitation gage, was used to compute area weighted composite precipitation values for the study area. The weighted precipitation during the study period was 19-percent less than the normal precipitation for the region (U.S. Department of Commerce, 1985). Monthly total composite precipitation was less than the normal monthly precipitation totals during 8 of the 12 months of the study period when precipitation data were obtained (fig. 7). The largest deviation from normal occurred in December 1985 and January 1986 when the monthly total composite precipitation was approximately 1 inch and the normal monthly precipitation total is approximately 4.5 inches.

Relation of Precipitation to Ground-Water Discharge

Ground-water discharge at the Dyers and Elizabethtown Springs is highly responsive to precipitation events. Because of the nature of the karst conduit system, response of spring discharge to precipitation more closely resembles surface-water than ground-water flow in that peak discharge generally occurs on the same day as the precipitation. Large day-to-day changes from baseflow to peak flow to recession flow, and a rapid return to baseflow conditions also occur (see figs. 8 and 9).

Peak discharge from the springs is related to the intensity and magnitude of the precipitation event. High flows may result from intense storms in any season. The most rapid flow response occurs during high-intensity events, with peak discharge often occurring within one hour of the peak precipitation intensity. In winter and spring, even a small amount of rain falling on wet ground can result in a substantial and rapid response.

Baseflow during the study period was higher during the winter months and was greatest in November 1985 and February 1986, when precipitation was above normal. Baseflow was lowest during July through September 1985, when precipitation was below normal and soil moisture was depleted.

Stage-discharge Relations for Elizabethtown and Dyers Springs

One objective of this investigation was to define a simple stage-discharge relation at each of the city water-supply springs. This relation can be used to estimate the discharge directly from the stage height rather than doing a discharge measurement. Discharge is used with the results of quantitative dye tracing, which is discussed later, to estimate flow characteristics of a ground-water contaminant.

The term stage or gage height refers to the water-surface elevation referenced to some arbitrary datum. A simple stage-discharge relation is based on the fact that for a given discharge the stage or surface of the water being measured will reach a particular point or stage relative to an assigned

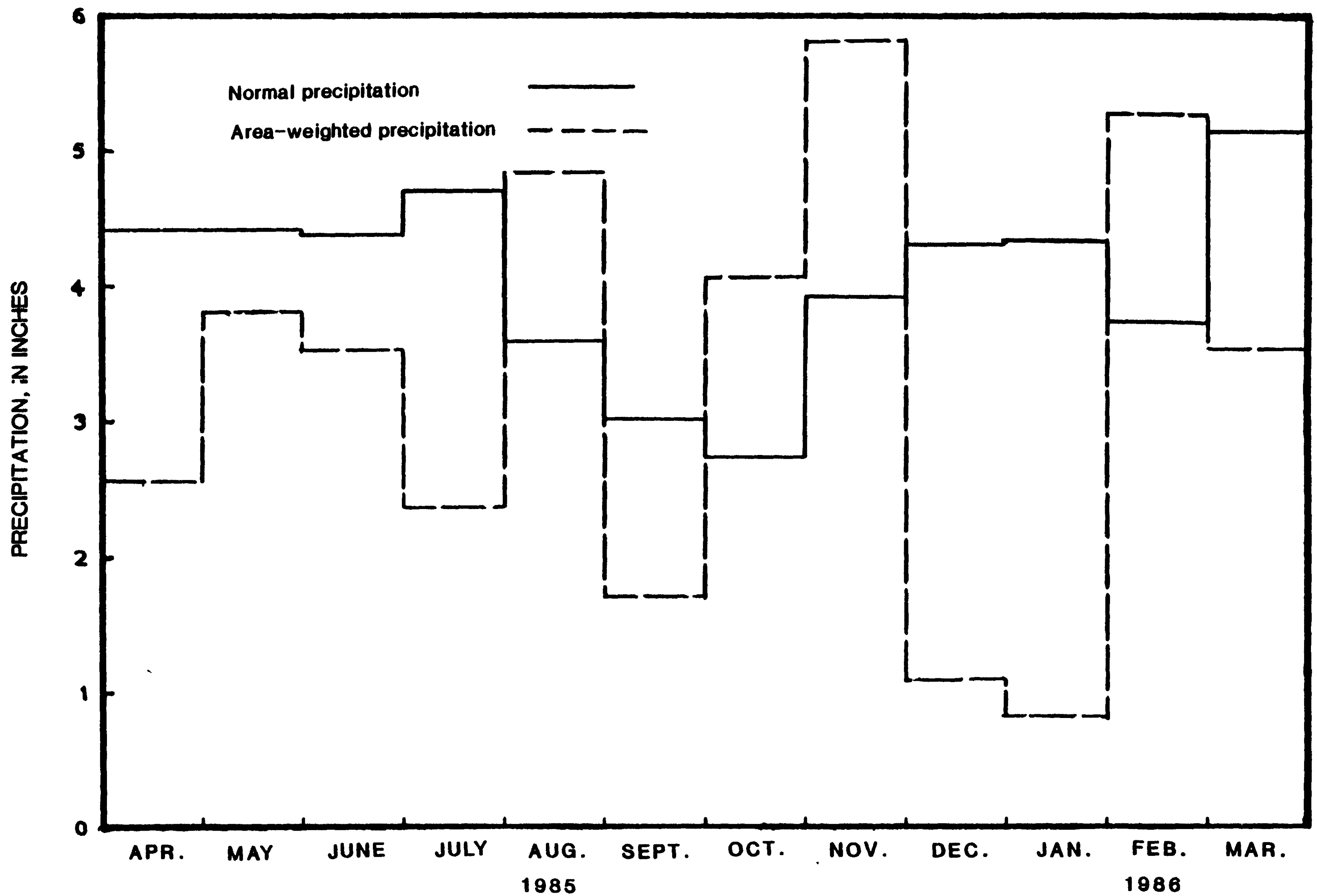


Figure 7.--Comparison of monthly normal precipitation and the area-weighted monthly precipitation at Elizabethtown, for the period April 1985 through March 1986.

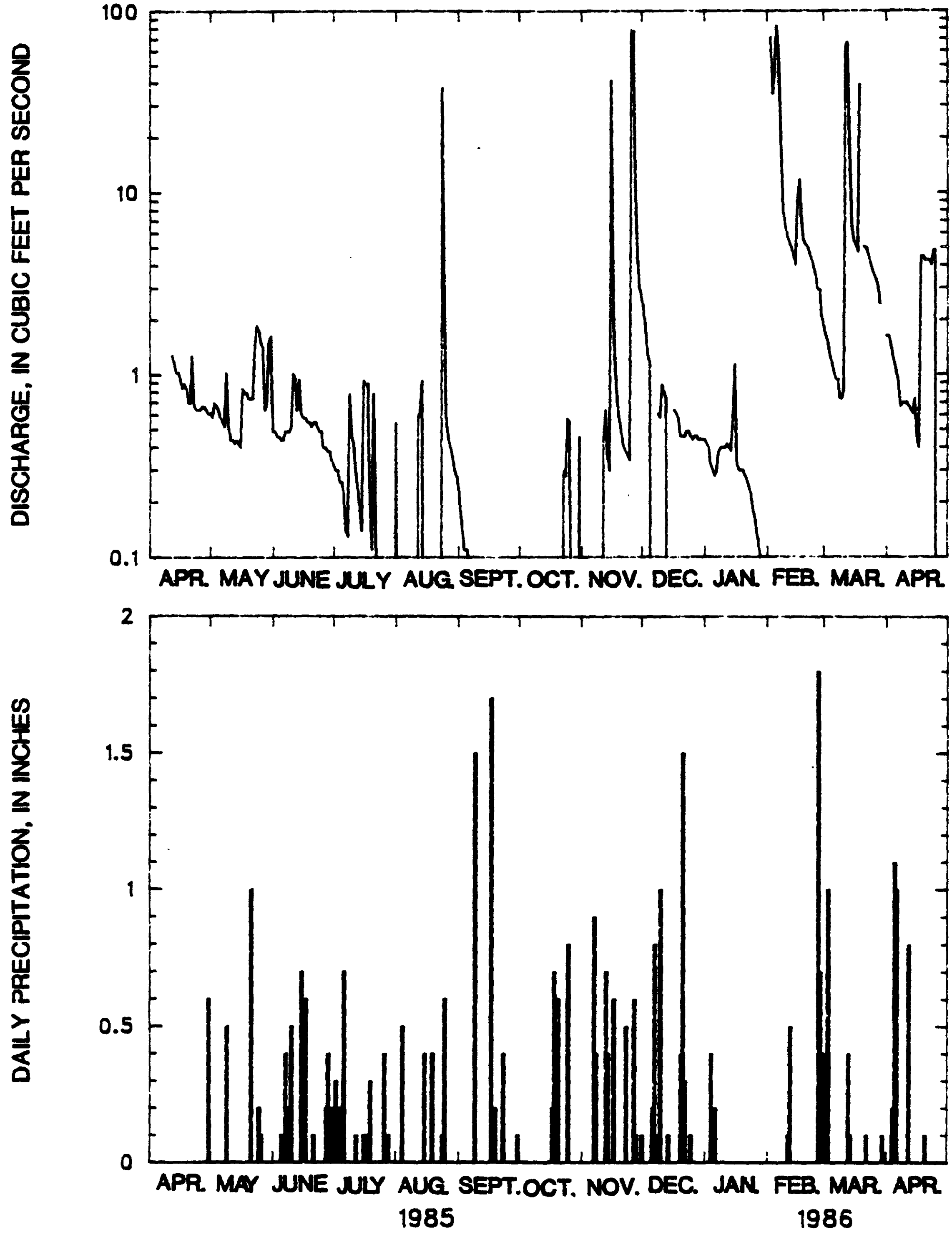


Figure 8.--Daily precipitation and maximum daily discharge from Dyers Spring, April 1985 through April 1986.

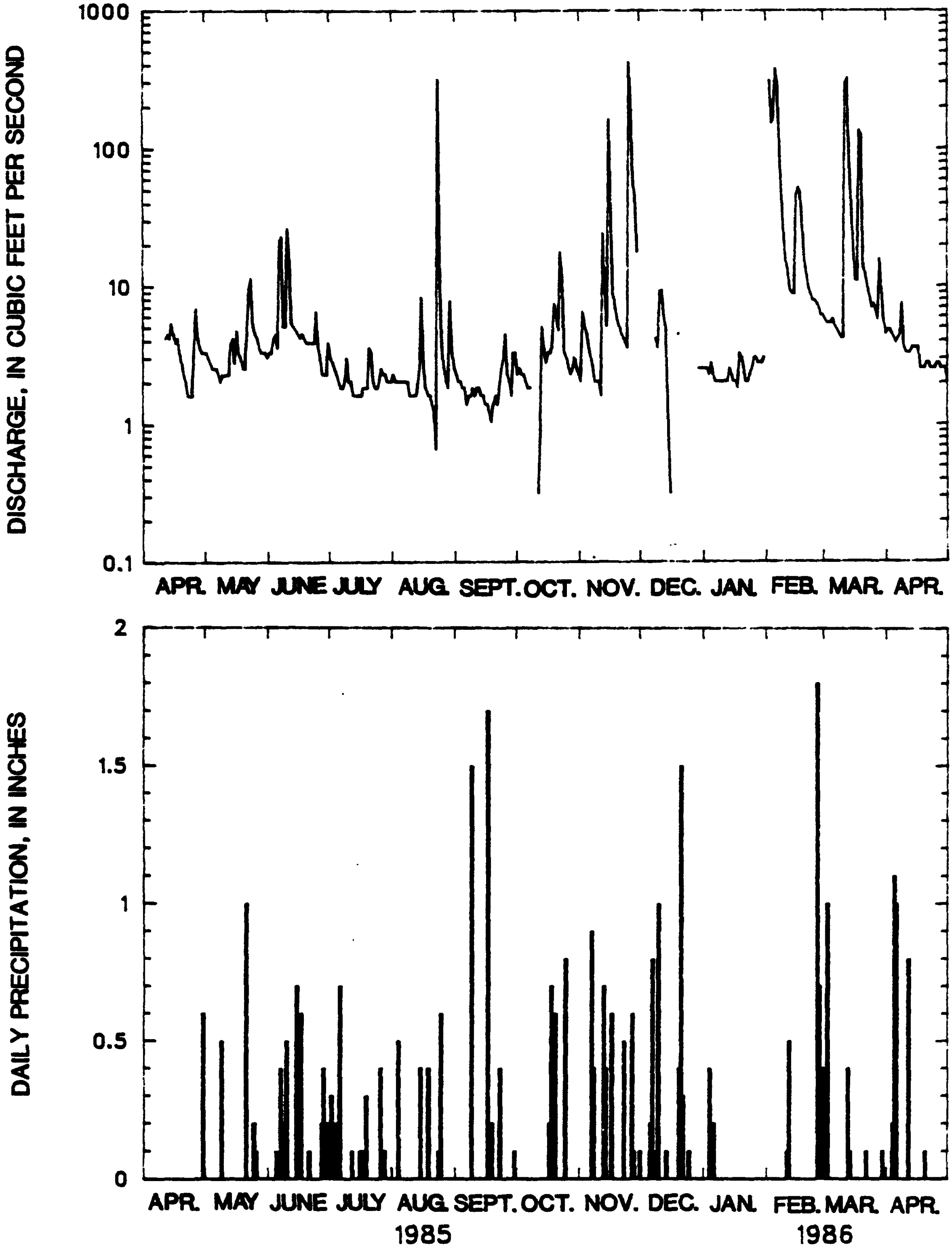


Figure 9.—Daily precipitation and maximum daily discharge from Elizabethtown Spring, April 1985 through April 1986.

datum (Kennedy, 1984). Discharge and stage measurements made during different flow conditions permit the development of a rating curve. Thus, discharge can be determined by reading the stage and converting that reading to discharge based on the stage-discharge rating curve.

The stage-discharge relations developed at a site are usually not permanent nor do they often represent historic conditions. Changes in the stream channel caused by scour and fill, aquatic growth, debris, or backwater, all result in changes in the stage-discharge relation. Thus, a stage-discharge curve will retain its original shape only so long as the elements that control it retain their original physical characteristics or as long as the changes in characteristics are compensating with respect to their effects on the stage of water at the measurement site.

If the stage-discharge rating curves presented in figure 10 are to be used, direct measurements of discharge should continue to be made periodically in order to verify the relation. When measured values begin to diverge significantly from the curves, new relations should be defined. At the Elizabethtown Spring, discharge estimates would be more reliable and less subject to change over time if a stage-discharge relation were developed for the dam rather than the channel. Discharge could then be computed as a function of headwater and tailwater elevations at the dam, and would not be affected by changing conditions in the channel.

Miscellaneous, direct discharge measurements made by current meter were used to define the stage-discharge relation at the Elizabethtown and Dyers Springs. Although water was being pumped from each spring before the start of most discharge measurements, the pumps were stopped for at least one hour and discharge allowed to stabilize before it was measured.

Automatic recorders were installed at the mouth of Dyers and Elizabethtown Springs to provide a continuous record of stage. Although other hydrologic investigations have been completed in this area, (Mull and Lyverse, 1984 and Lambert, 1979) this was the first attempt to collect a continuous record of stage that was used to define flow characteristics at each Spring.

To compute spring discharges, the graphical records of water-surface elevations from the stage recorders were digitized. A computer program then used the digitized water surface elevations and a digital rating to compute discharge. No adjustments were made to shift the theoretical stage-discharge rating to the measured discharge. The instantaneous discharges were summarized and a plot of the mean daily discharges for the Dyers and Elizabethtown Springs are shown in figures 11 and 12, respectively.

Elizabethtown Spring

The stage-discharge relation at the Elizabethtown Spring is defined for discharges less than 28.0 ft^3/s (fig. 10). To extend the stage-discharge rating beyond 28.0 ft^3/s, a straight-line extension of the rating curve was used. The slope of the extension is 122 ft^3/s for each foot rise in water-surface elevations. A straight line extension was assumed because the upper limits of the rating curve approximate a straight line and the slope of channel banks above the concrete liner are fairly steep and uniform.

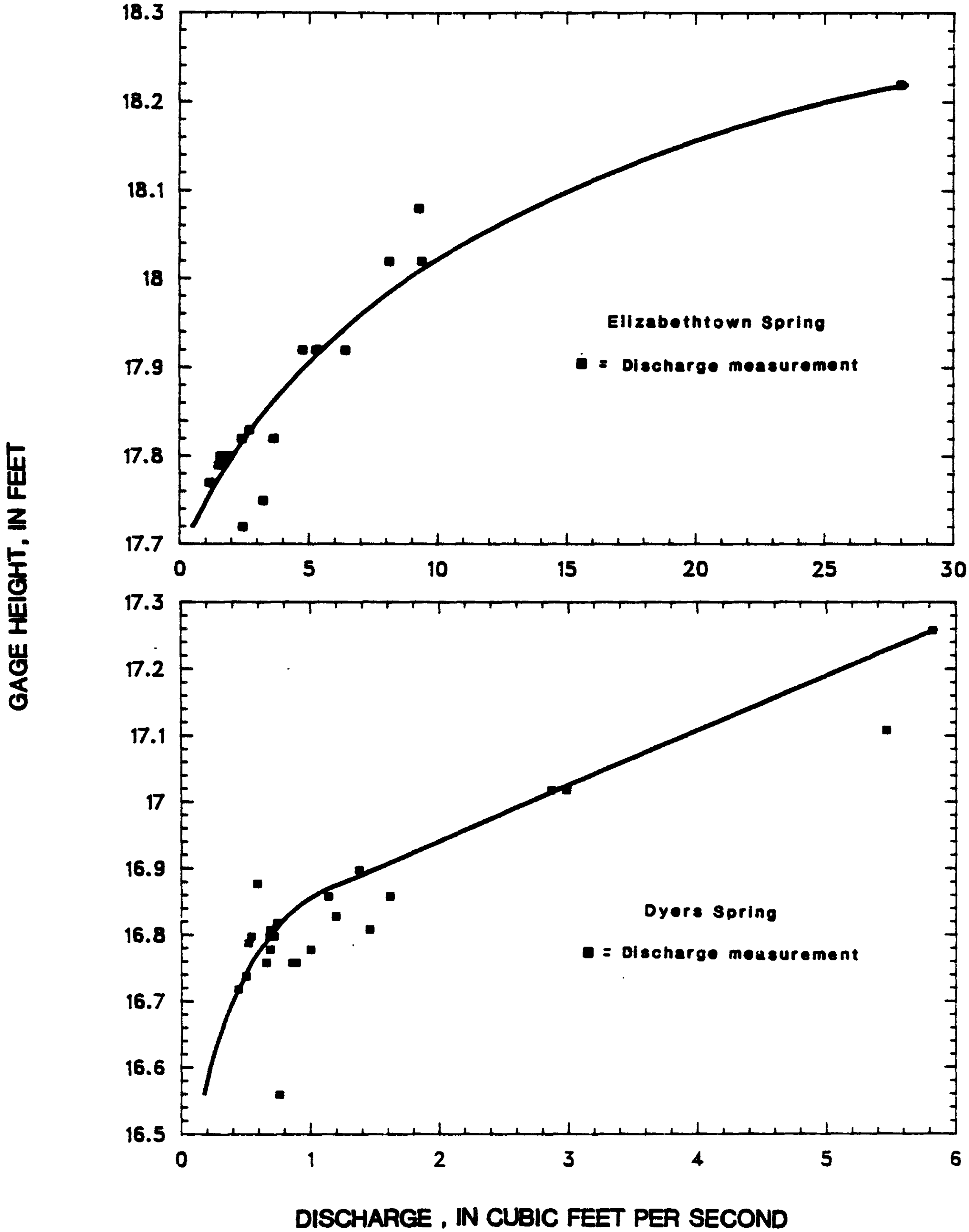


Figure 10.—Stage–discharge relation at the Dyers and Elizabethtown Springs.

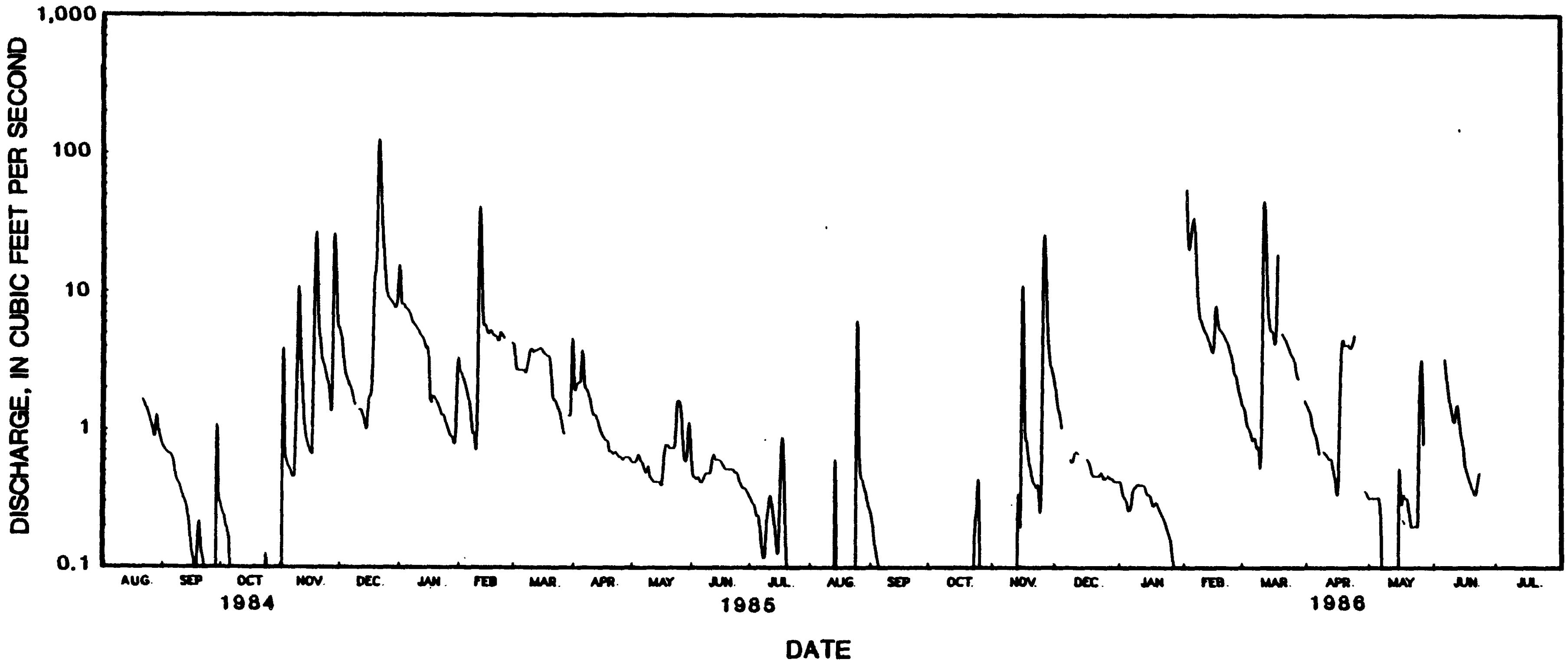


Figure 11.--Mean daily discharge at Dyers Spring, August 22, 1984 to June 24, 1986.

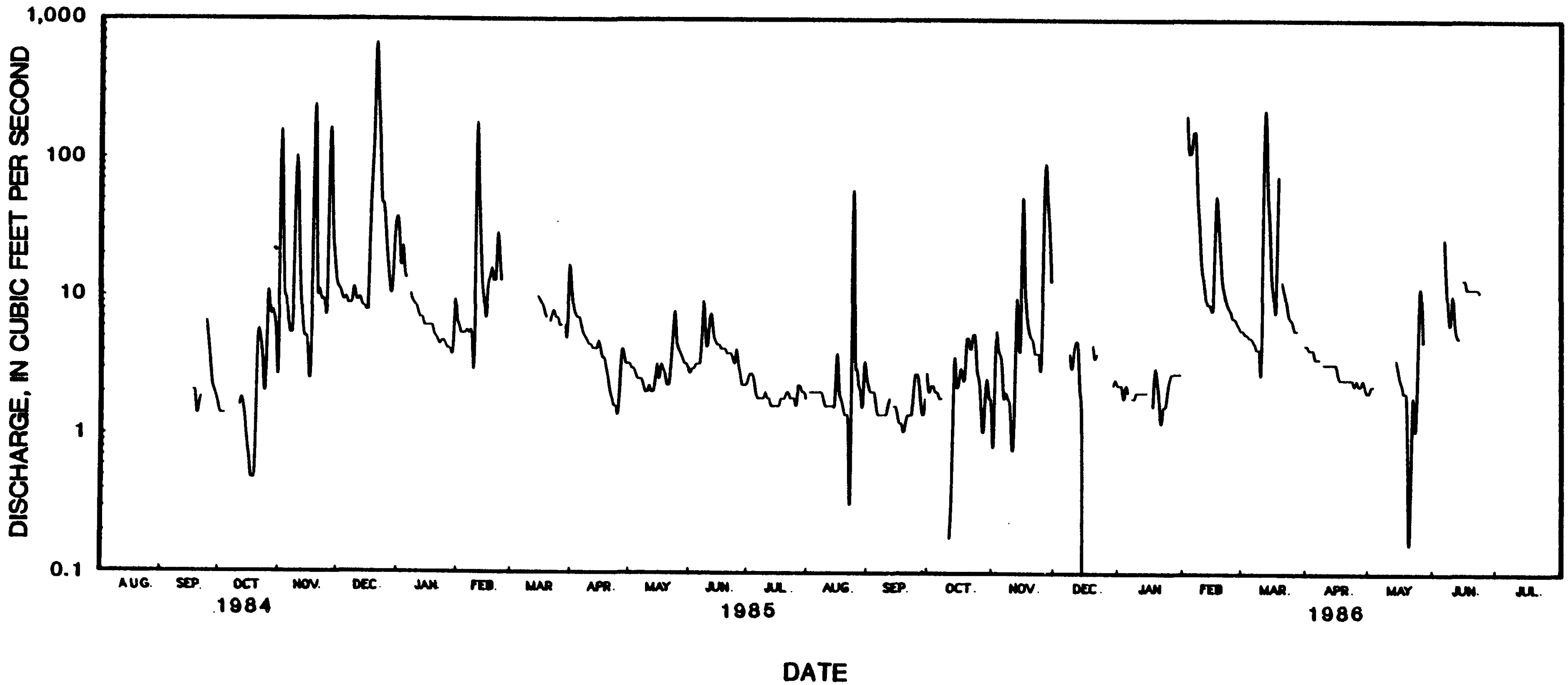


Figure 12.--Mean daily discharge at Elizabethtown Spring, September 18, 1984 to June 24, 1986.

The spring discharges by way of a basin that has been excavated about 60 feet from the edge of the creek. The basin is about 40 feet wide and the bottom and sides are concrete lined. The sides are about 4 feet high, there is a center divider about 3.5 feet high. A dam about 18 feet high forms the lower end of the basin. Water flows through the dam in two, 30-inch diameter pipes that have flapper gates on the downstream side of the dam. A reservoir for pumping is formed by a second dam which is about 3 feet high, about 10 feet from the creek and about 15 feet downstream from the high dam. The reservoir and the basin and cave conduits behind the high dam are subject to back water and flooding from Valley Creek.

The control for the Elizabethtown Spring is a low overflow dam. However, the dam does not eliminate the effects of changing conditions such as scour and fill, aquatic growth, debris, on backwater. This fact is illustrated by the distribution of the points used to define the stage-discharge relation for this spring (fig. 10). If the stage-discharge relation in the channel were controlled entirely by the low dam, the points representing various discharge measurements would plot more closely along the stage-discharge curve.

Dyers Spring

The stage-discharge relation at Dyers Spring is defined for discharges less than 5.93 ft^3/s (fig. 10). A straight-line extension of the rating curve was also used to determine discharges greater than 5.93 ft^3/s. A straight-line extension seemed valid in this case, as with the Elizabethtown Spring, because the channel banks are fairly steep and the slope of the channel banks are fairly constant.

Discharge from Dyers Spring creates a pool about 50 feet in diameter. The city's water-pump intake is at the lower end of the pool about 50 feet from the rise pit. An automatic water-level recorder monitored stage in the same pool. Thus, discharge values below about 0.1 ft^3/s are not shown because the effects of pumping in addition to decreased natural discharge causes zero flow from the pool (fig. 11).

Water level in the pool is controlled by natural riffles and to some extent by a concrete dam located about 80 feet downstream of the rise pit. The dam is about 10 feet high and is about 20 feet from Valley Creek. The bank at the left side of the dam has eroded so that the dam is ineffective when water depth exceeds about two feet. A single pipe, 20 inches in diameter with a flapper gate on the down-stream end, drains to Valley Creek. The channel and rise pit are flooded by backwater from Valley Creek during relatively low flood-flows.

Because the control for Dyers Spring is a natural riffle, the rating could easily be affected by natural scour and fill, aquatic growth within the channel, or backwater from Valley Creek. The volume of sediment transported and deposited in the rise pool of Dyers Spring requires periodic dredging to prevent blocking of the pump intake. Such maintenance was performed once during this investigation, however, the dredging was confined to the rise pool and did not affect the natural riffle. Future sediment removal or other channel modification could remove or modify the riffle and markedly affect the stage-discharge rating at this site.

Valley Creek Seepage Measurements

To determine the losing or gaining nature of Valley Creek, seepage measurements were made in Valley Creek during different flow conditions. Seepage measurement consists of discharge measurements made at selected sites throughout the reach of interest. The measurements are made as quickly as possible, preferably on the same day, and the resulting measurements compared to identify gaining or losing reaches of the stream. Three sites on Valley Creek and one site on Freeman Creek, the major tributary to Valley Creek were selected where discharge measurement were made. The sites are shown on plate 1 and the results of the measurements are shown in table 1.

The lower-most site for seepage measurements in Valley Creek was selected upstream of the point where water from the Elizabethtown Spring enters Valley Creek (site 47). Comparison of discharge at this site with the sum of discharge in Freeman Creek (site 48) and Valley Creek at Highway 62 (site 50) shows the gaining or losing nature of streamflow in this reach. The low-flow measurement on August 8, 1985 shows that Valley Creek was losing about 1.4 ft^3/s. However, the measurement on May 6, 1985, showed a slight gain in streamflow in the same reach. Low flow seepage measurements were also completed by Mull and Lyverse (1984). The results of those measurements are also included in table 1 and show that Valley Creek was losing 1.62 ft^3/s and 0.06 ft^3/s on August 4, and August 10, 1983, respectively, but was gaining in November 1, 1982.

These discharge measurements do not consistently show that Valley Creek is a losing stream in the reach between sites 47 and 48. Thus, characterizing this reach solely on the basis of discharge measurements could be misleading. However, when the seepage measurements are considered with the results of dye tracing that are discussed later in this report, Valley Creek can be described as a losing stream in the reach between Freeman Creek and the Elizabethtown Spring (site 1), at least at times. Dye from trace 29 and 29-A was recovered in both city water-supply wells following the injection of dye into Valley Creek at a point about 2,100 feet upstream of the wells. This shows that not only is Valley Creek losing water in this reach, but that water from the stream is infiltrating to the city water-supply wells.

DYE TRACING CONCEPTS AND TECHNIQUES

The practice of tracing ground-water flow by adding distinctive substances to water draining underground and monitoring the down-gradient resurgence of that water has long been a useful tool for hydrologic investigations. One of the earliest reported water-tracing experiments took place almost 2,000 years ago when chaff was thrown into Ram Crater Lake in order to identify springs at the headwaters of the Jordan River (Mazor, 1976). In general, the materials used for tracers have been limited only by the creativity of the experimenters and in recent years has included such diverse items as computer card chips, dog biscuits, plastic pellets, oranges, food coloring, and a "geobomb" that was set to detonate underground at some predetermined time (Milanovic, 1981). Accidental or intentional dumping of distinctive substances has often served to identify point to point connections between input points and resurgences such as springs or pumped wells. For

Table 1.--Miscellaneous stream discharge measurements, Elizabethtown area

Stream	Map or station number[1]	Date	Discharge (ft^3/s)
Valley Creek at Pierce Street at Elizabethtown	53	May 6, 1985	2.6
		Aug. 8, 1985	.45
Unnamed tributary to Yellow Creek at East Poplar Street at Elizabethtown	52	Aug. 8, 1985	.17
Valley Creek at State Highway 61 at Elizabethtown	51	Aug. 4, 1983[2]	1.01
		Aug. 10, 1983[2]	1.81
		May 6, 1985	4.55
		Aug. 8, 1985	.80
Valley Creek at U.S. Highway 62 at Elizabethtown	50	Nov. 1, 1982[2]	2.52
		Aug. 4, 1983[2]	1.25
		Aug. 10, 1983[2]	1.17
		May 6, 1985	4.50
		Aug. 8, 1985	.86
Freeman Creek at State Highway 251 at Elizabethtown	48	Nov. 1, 1982[2]	1.34
		Aug. 4, 1983[2]	2.06
		Aug. 10, 1983[2]	.74
		May 6, 1985	2.70
		Aug. 8, 1985	2.10
Valley Creek at Elizabethtown	47 03310210	Nov. 1, 1982[2]	4.01
		Aug. 4, 1983[2]	1.69
		Aug. 10, 1983[2]	1.85
		May 6, 1985	7.30
		Aug. 8, 1985	1.55

[1]Refers to plate 1.

[2]Mull and Lyverse, 1984.

example, Quinlan and Rowe (1977) report the dumping of an estimated 340 tons of whey into a sinkhole that contaminated water from public-supply wells at Smiths Grove, Kentucky, about five miles away. Aley and Fletcher (1976) reported that water from a sinkhole was traced to a nearby high school in Tennessee when revenue agents dumped 2,000 gallons of illegal whiskey into the sinkhole. During the Elizabethtown investigation, drainage from a salt storage yard that flows into a cave was traced to an unused spring about 1.4 miles away.

Although perhaps unintentional, in all cases mentioned above the primary objective of water tracing was successfully accomplished. That is, the existence of a connection via the ground-water system between a specific inflow point and a discharge point located some distance away was verified. If the identification of a hydraulic connection is the sole purpose of the water tracing experiment, then a variety of tracers and techniques such as mentioned above, may be adequate. In general these types of techniques are known as qualitative tracing. However, if hydrologic information such as traveltime and ground-water flow velocity, or potential contaminant characteristics, such as persistence, dispersion rates, and concentration are needed, then quantitative tracing methods incorporating more sophisticated tracers and techniques are required.

Both qualitative and quantitative tracing technique were used during this investigation in the Elizabethtown area. The following discussion describes the procedures used. Other reports give additional information on the theory and techniques of dye tracing. In particular, the papers by Aley and Fletcher (1976), Quinlan (1986), and Smart and Laidlaw (1977) provide detailed discussions of qualitative dye tracing techniques. Basic information on the quantitative aspects of dye tracing are presented by Wilson, Cobb, and Kilpatrick (1984), Hubbard and others (1982), Kilpatrick and Cobb (1985), and Jones (1984).

QUALITATIVE DYE TRACING TECHNIQUES

Qualitative dye tracing techniques involve the tagging of a discrete in situ sample of water with dye and monitoring the arrival of that water at various resurgences with passive detectors. Fluorescent dyes were chosen because they are readily available and generally, the most practical tracers. Fluorescent dyes are generally 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 usually can be completed without the aesthetically unpleasant and potentially unsafe practice of discoloring a domestic or public water supply.

Although many different fluorescent dyes are used as ground-water tracers, present usage is centered on four: rhodamine WT, optical brighteners, Direct Yellow 96, and fluorescein. In general, rhodamine WT is not used for qualitative tracing because of the difficulty of visually separating the pink color of the dye from that of other organic compounds that can easily be sorbed by the activated coconut charcoal commonly used for dye recovery. Rhodamine WT was the tracer for several qualitative tracer test during this investigation. However, these traces were designed to be quantitative but were classed as qualitative based on the results of each trace. The use of rhodamine WT as a tracer is discussed in a later section on quantitative dye tracing.

Optical brighteners and Direct Yellow 96 are detectable in low concentrations, are non-toxic, have low affinity for adsorption onto clays, and are readily adsorbed on undyed cotton used to recover dye in passive detectors. Optical brighteners are, however, widely used by the laundry detergents for enhancing fabric colors and are thus a common constituent of domestic waste water. For this reason, the effectiveness of optical brighteners for water tracing can be limited in areas where effluent from domestic septic systems is present. The background levels of optical brighteners can easily be determined by placing undyed cotton "bugs" in ground-water resurgences and testing for fluorescence before tracer dyes are injected. Optical brighteners can be detected by viewing cotton detector samples under long-wave ultraviolet light. If relatively high levels of optical brighteners are present as background, the choice and amount of brightener used for tracing can be affected. Optical brighteners have been successfully used for water tracing in some areas. For example, Quinlan and Rowe (1977), Thrailkill and others (1982), and Spangler and others (1984) have reported successful tracing with optical brighteners in the Mammoth Cave and Inner Blue Grass regions in Kentucky.

Because of its distinctive fluorescence, Direct Yellow 96 is ideal for water tracing in areas where background levels of optical brighteners are present. Unlike optical brighteners, Direct Yellow 96 does not undergo significant photochemical decay. Direct Yellow 96 is a powder that must be mixed thoroughly with water before injection into the ground-water system and, like optical brighteners, is adsorbed onto undyed cotton detectors.

The presence of both optical brighteners and Direct Yellow 96 is confirmed by viewing the cotton detectors under long wave ultra-violet light after the cotton has been washed thoroughly with a high-speed jet of water to remove sediment and trash. The fluorescence of these tracers is enhanced if the exposed cotton is viewed under subdued lighting such as a darkened room or viewing box. Cotton that has adsorbed optical brighteners will characteristically fluoresce blue white, while the fluorescence of Direct Yellow 96 is canary yellow. A positive trace is indicated only if the entire cotton mass fluoresces relatively evenly. Scattered spots of fluorescence on the cotton should not be interpreted as a positive dye recovery.

Fluorescein dye was selected for qualitative tracing during this investigation based on its safety, availability, and its ready adsorption onto activated coconut charcoal used for dye recovery. Fluorescein is a reddish-brown powder that turns vivid yellow green in water. Although fluorescein has a low sorptive tendency, is photochemically unstable and may loose fluorescence in water with pH less than 5.0, it is one of the most widely used water-tracer in karst areas in the United States (Quinlan, 1986).

The procedures and equipment used for qualitative dye tracing during this investigation were based on those used in the Mammoth Cave area by Quinlan and Ewers (1981). The amount of fluorescein dye used for each injection was based on estimated flow conditions and the straight line distance of the trace. For initial traces in the Elizabethtown area, about one pound of dye per mile of trace was used. As knowledge of the flow system developed, this amount was reduced to about one-half pound per mile. This amount proved adequate if the flow was primarily in a major conduit between the injection and recovery points. All fluorescein dye was added to water draining directly into an open swallet. Thus, less dye was required than if the dye had been injected through soil such as in the bottom of a plugged sinkhole.

In order to simplify dye injection, especially during windy conditions, the fluorescein powder was mixed with water at the approximate ratio of one-half pound per gallon. The dye solution was poured into water draining directly into a swallet in order to lessen dye loss due to photochemical decay or absorption by organic debris at the surface. While mixing and injecting the dye, extreme care was taken to avoid contaminating clothing or the injection site because of the possibility of contaminating future traces. Disposable, plastic gloves were worn during all dye handling operations.

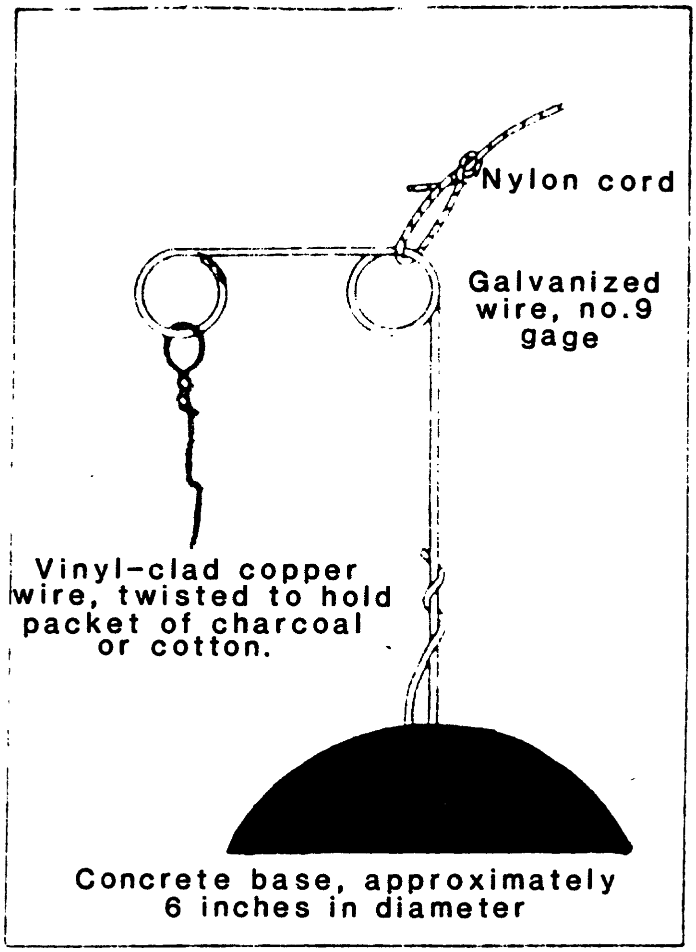
Fluorescein dye was recovered by passive detectors consisting of packets of activated coconut charcoal suspended in all suspected ground-water resurgence points for a particular trace. In addition, detectors were placed in unlikely resurgences in order to define the background levels of fluorescence.

The dye-detectors or "bugs" consist of a bag of activated coconut charcoal attached to a length of wire imbedded in a gum-drop shaped concrete anchor about 6 inches in diameter and 3 inches high (fig. 13). The anchor was made by pouring concrete into plastic bowls lined with plastic film. A piece of wire, about 18 inches in length, was imbedded in the wet concrete. A bag for holding the activated coconut charcoal was attached to the wire. The bag was fabricated from 3x7 inch piece of fiberglass screening. Only activated coconut charcoal (6-14 mesh) was used for detectors. Charcoal intended for water-treatment processes, aquariums, or home barbecue does not sorb the dye and is not acceptable for use as a detector. Because the coconut charcoal loses its sorption ability upon exposure to the atmosphere, it must be stored in air-tight containers at all times. For this reason, charcoal was not placed in the fiberglass packets until placement at each site.

The gumdrop anchor was placed near the center of flow from the suspected dye-resurgence point in order to maximize exposure to the dye. In cases where the channel was too shallow for the anchor, a u-shaped wire pin was driven into the channel bottom to hold the packet in place. However, this technique tends to hold the packet on the bottom of the channel where the packet may be covered with sediment or damaged by benthic invertebrates.

The anchor was secured to the bank with a small nylon rope. Use of a tan colored rope lessened the chance of discovery and tampering. In addition, a business card or information about the investigations could be encased in plastic and attached to the anchor to help satisfy the curiosity of potential vandals. If velocities were high, the detector was placed in a sheltered area to prevent the loss of either the anchor or charcoal and the resulting loss of data from the trace. In addition to streams and springs, packets of charcoal were also suspended in toilet tanks in selected private homes and in the stream of water discharging from one city public-supply well (site 3).

The packets were left in place from 1 to 9 days but were generally



From J. F. Quinlan (1986)

Figure 13.--Anchor used to suspend dye detectors (bugs) in springs or streams.

changed more often when turbidity levels were high or if traveltime was to be estimated. When the packets were retrieved, each packet was rinsed in the stream to remove accumulated sediment. The packet was sealed in a lock-top plastic bag, labeled, and returned to the laboratory in a light-tight case. If the packets were not processed immediately, they were refrigerated in order to decrease bacterial action that could reduce fluorescence. Packets processed this way could be stored several days without adversely affecting the fluorescence of sorbed dye.

The presence of fluorescein dye 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. Before removing the charcoal from the fiberglass bag, the charcoal was rinsed with a jet of water to remove sediment which can interfere with the analysis. The charcoal was then placed in a small jar or beaker and covered with about 30 ml of elutriant solution consisting of 38 percent ammonia hydroxide, 43 percent 1-propanol, and 19 percent distilled water (Smart, 1972). A simpler elutriant was also used that consisted of a saturated solution of about five percent potassium hydroxide (Quinlan, 1986). This solution consists of 6 to 7 grams of potassium hydroxide dissolved in 100 ml of 70 percent 2-propanol (rubbing alcohol). After the potassium hydroxides dissolves, the solution separates into a super saturated and saturated solution. The lighter, saturated solution is decanted into the containers to cover the charcoal. The advantage of this elutriant is that additional solution can be made by adding either constituent to the original solution so long as only the lighter, unsaturated part of the solution is used to elutriate the charcoal. However, Quinlan (1986) reports that the potassium hydroxide and alcohol solution has a limited shelf-life and should not be used if more than a few days old. The ammonia hydroxide, propanol, and distilled water solution has a shelf-life of several months.

In strongly positive tests, the maximum color intensity develops almost immediately upon addition of the elutriant and then slowly decreases (Jones, 1984). All charcoal samples collected for qualitative dye tracing during this investigation were elutriated for four hours and then examined for the yellow-green color under focused sunlight or a high intensity beam of light such as that from a microscope light. Identification of a strongly positive test is generally obvious. However, weakly positive tests require special care and experience lest the presence of algae and organic matter, which can occur as background, be incorrectly interpreted as fluorescein. Persons unfamiliar with the color of dye elutriated from charcoal detectors should prepare laboratory test solutions before running first-time dye traces.

Additional quality-control procedures which were incorporated in the study during qualitative tracing included the following. Repeat traces to the same point using the same dye usually were not performed until after the occurrence of a major storm in order to allow any residual dye to be flushed from the system. This reduced the possibility that a later storm might flush slow-moving or trapped dye-laden water from the first trace and cause an incorrect positive trace. Repeat traces during low-flow conditions were delayed sufficiently to ensure that residual dye had drained from the system. In the case of quantitative traces discussed later, this was confirmed by near zero dye concentrations measured at the beginning of each trace. In addition, passive detectors were kept in place for at least a week, or until the start of another trace, after the arrival of the first dye cloud. A secondary dye cloud was detected during only one trace (trace 27) and is discussed later.

Detectors or "bugs" were always fabricated and placed before the dye was handled or injected. This lessened the possibility of contamination and also produced a reconnaissance of the potential recovery points just before dye injection. The visitation of each "bugged" dye-recovery site was a convenient time to review changes in water use from resurgence such as intermittent withdrawals by farmers for irrigation purposes. This was also a convenient time to explain to the land owner or water user the nature and purpose of the pending dye trace which is especially important if the possibility exists that the dye may discolor the water.

As mentioned earlier, careful handling of the dye was observed in order to prevent contamination of the charcoal or packets which would result in erroneous or misleading positive traces. The dye powder was stored in a different room from the charcoal and transferred to plastic, lock-top boxes for transit to the injection site. The charcoal was stored in screw-top glass jars both in the laboratory and during transit to the field. At the beginning of each trace, all charcoal packets were installed before a dye container was opened.

QUANTITATIVE DYE TRACING TECHNIQUES

Quantitative dye tracer tests generally require higher levels of effort and more sophisticated equipment and techniques than qualitative dye tracing. Quantitative dye tracing consists of the injection of a known amount of dye and the measurement of the amount of dye recovered over time. Determination of dye recovery requires measurement of both water flow rate and dye concentration. Measurements were made at each dye resurgence site that was identified as being hydraulically connected to injection locations by previous qualitative tracer tests. Water samples were collected, usually with automatic samplers, during passage of the dye cloud and the dye content of each sample was measured with a properly calibrated fluorometer. These data were plotted against time to produce a dye-response or breakthrough curve. A typical dye-response or dye-recovery curve and its various features related to traveltime are shown in figure 14.

The shape and magnitude of the dye-recovery curve is determined by: (1) the amount of dye injected, (2) the characteristics of the dye, (3) discharge of the resurgence, (4) longitudinal dispersion of the dye, and (5) the cross-sectional mixing of the dye before the sampling point. The apparent shape of the dye recovery curve can also be affected by the sampling interval. Analysis of the dye recovery curve provides insight into flow characteristics of the aquifer such as effective traveltime between the swallet and the resurgence and velocity of ground water. Additional analysis of the recovery curve and discharge measurements 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 located in karst terrane, where springs or wells might be affected by the accidental or intentional introduction of contaminants into the ground-water system. The following discussion summarizes techniques for quantitative dye tracer studies

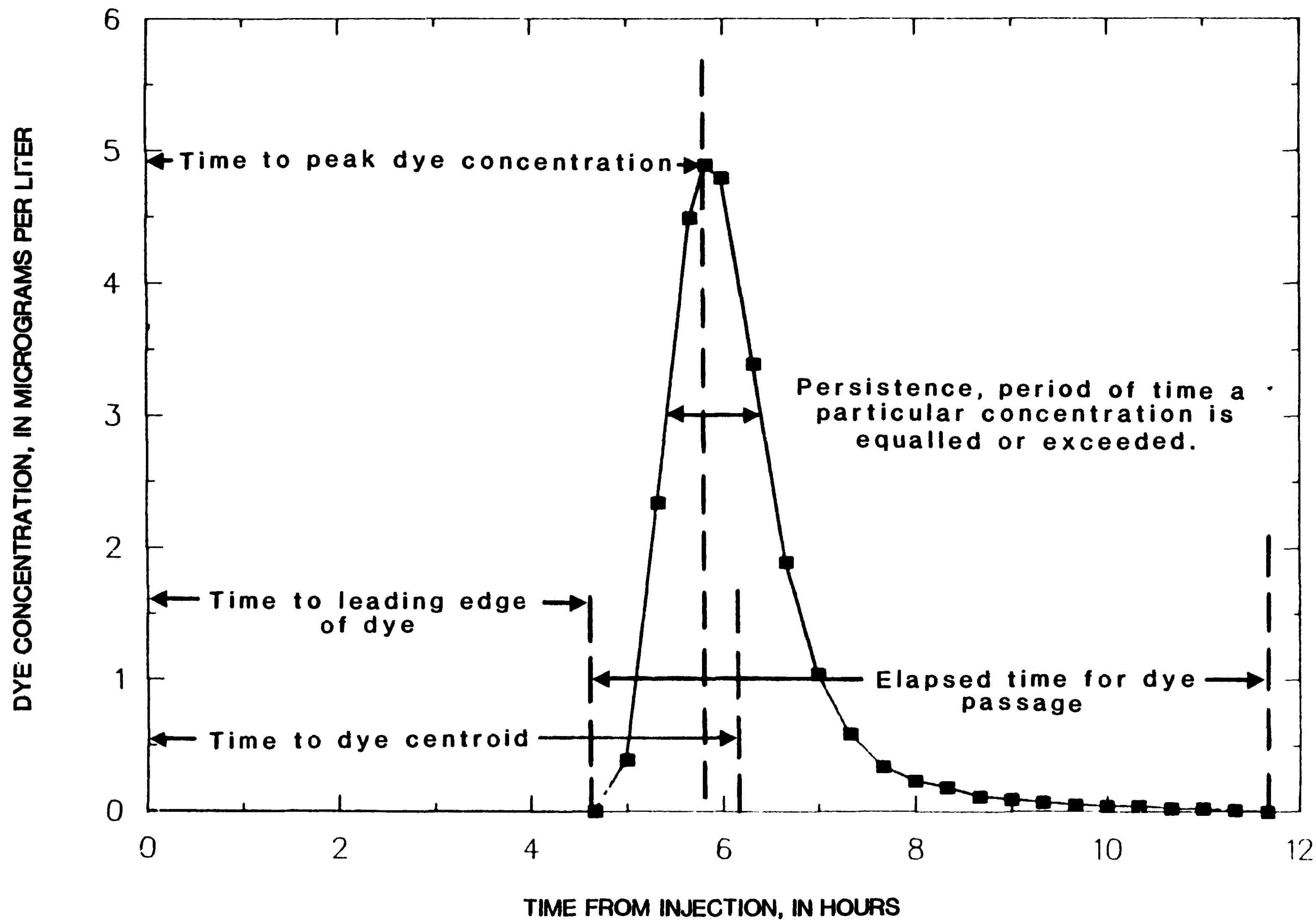


Figure 14.--Typical time-concentration response curve for dye recovery.

and presents references that describe, in detail, the procedures used. The discussion will describe each phase of quantitative dye tracing, generally in operational sequence.

The primary criteria for the selection of a fluorescent dye for quantitative tracing are its (1) water solubility, (2) detectability in low concentrations - strongly fluorescent, (3) separability from background fluorescence, (4) stability or conservancy in the karst environment, (5) non-toxicity in low concentrations, and (6) cost. Generally, detection limits are controlled by background conditions such as turbidity, the presence of substances that fluorescence such as algae, and the calibration of the fluorometer. During this investigation, the minimum observed dye concentration was 0.01 µg/L which was considered background for some tests. Conservancy refers to the stability of the dye in the environment. No dye is 100 percent conservative because some dye is lost to sorption or chemical decay. Therefore, dye loss must be considered during quantitative analysis of the dye-recovery data.

Several available dyes meet the above requirements for quantitative tracing. Rhodamine WT has been widely used for time of travel and dispersion tests in streams (Hubbard and others, 1982). Because of the similarity between ground-water flow in karst terrane and streamflow, in addition to meeting the other requirements, rhodamine WT was selected for all quantitative dye traces in this investigation.

After identifying and selecting input and resurgence points on the basis of earlier qualitative traces, the amount of dye for injection must be determined. The amount of dye required for a quantitative trace depends on flow conditions and the distance of the trace. Considerable experimentation may be required before the correct amount of dye can be determined consistently. In general, the amount of dye injected must be adequate to produce detectable dye concentrations at the monitored resurgence but ideally, remain below the levels of visual detection. In addition, it is the policy of the U. S. Geological Survey that the amount of fluorescent dye injected into a water course does not result in dye concentrations exceeding 10 µg/L at water-user withdrawal points (Hubbard and others, 1982).

During this investigation, most of the tracing was from an injection point to one or more springs used for public water supply. Through the cooperation of the Elizabethtown water treatment plant operators, water from the springs was diverted and not used during the passage of the dye cloud. This procedure was initiated and followed for all traces and was especially worthwhile in the early part of the investigation when the relation between the amount of dye injected and recovered was less predictable.

For initial quantitative traces, the amount of dye per injection was based generally on an equation for estimating the dosage of rhodamine WT, 20 percent solution, needed for a slug injection, stream discharge measurement developed by Kilpatrick and Cobb (1985). The equation adapted to dye recovery from a spring is as follows:

$$V_s = 3.79 \times 10^{-5} \frac{Q(1.5L)}{v} C_p \qquad \text{(eq. 1)}$$

where C_p = the peak concentration at the sampling site, in micrograms per liter;
L = the apparent length of the trace, (map distance) in feet;
Q = discharge from the spring, in ft^3/s;
V_s = the volume of rhodamine WT, 20 percent solution, in milliliters; and
v = the apparent ground-water flow velocity, in ft/sec.

In order to adjust for the meanderings of the subsurface flow passages, the apparent length of the trace (straight-line map distance) was multiplied by 1.5 (Sweeting, 1973).

Handling, transporting, and injecting dye for quantitative tracer tests requires even more care than that for qualitative tests. Considering that dye concentrations are commonly measured in parts per billion, or less, the slightest contamination can cause erroneous or misleading data. As with fluorescein dye, disposable plastic gloves were worn during all handling of the rhodamine WT and extreme care was taken to avoid contaminating clothing or the area around injection points. The rhodamine WT was stored and transported to the injection site in one-liter, opaque, polyethelene bottles. The dye to be injected was measured with a 100 mL glass, graduated cylinder and mixed with about two gallons of water in a metal pail. This mixture was carefully poured into water draining directly in a swallet or into the center of flow if water was ponded over the swallet. One dye injection was by way of water ponded over a swallet that was the flooded drain point for a sinking stream (site 40). In this case the dye mixture was poured into the pool at a point located approximately over the known swallet.

Analysis of dye-recovery data is based on mass balance relation that essentially compares the mass of the dye recovered to the mass injected (Hubbard and others, 1982). Therefore, a critical element of this analysis is the determination of the mass of dye injected which is calculated by the equation:

$$\text{mass} = \text{volume} \times \text{density} \times \text{purity}. \qquad \text{(eq. 2)}$$

Thus, for a 10 mL injection of rhodamine WT 20 percent solution, the mass is computed by multiplying the volume (10 milliliters) by the density (1.19 grams per cubic centimeters) by the strength or purity (20 percent) so that in this case the mass injected is 2.38 grams.

Calculation of the mass of dye recovered is based on the time-concentration or dye-recovery curve and on the discharge of the monitored resurgence. The time-concentration curve is a plot of time versus the dye content of water samples collected during the passage of the dye cloud. The dye-recovery curve is typically bell-shaped but skewed to the right, such that it is steeper on the rising limb than on the falling or recession limb of the curve. For the conditions of a variable flow rate the mass of dye recovered is:

$$M = \int_0^\infty QCdt \qquad \text{(eq. 3)}$$

If the flow rate is steady the mass of recovered dye is:

$$M = Q\int_0^\infty Cdt \text{ or } M = QA \qquad \text{(eq. 4)}$$

where discharge is constant and

M = mass of dye recovered, in micrograms per liter
Q = discharge, in ft^3/s
C = dye concentration at time t, in minutes
A = area under the time-concentration curve.

The dye content of each sample was measured with a properly calibrated fluorometer. Fluorometer calibration is discussed in detail in the next section. The samples were collected by hand or by automatic samplers. Equipment required for sampling by hand will vary depending on the sampling site, that is, from a bridge, or a boat, or by wading. Glass sample bottles are recommended in preference to plastic bottles because the dye may have a slight affinity for the plastic, resulting in dye loss. An 8-dram (approximately 32 milliliter or 1 ounce) polyseal-cap glass bottle was used for all hand sampling during this investigation. Hand sampling was only used to determine the presence of dye and not to measure the passage of the dye cloud. The location of each sample in the cross section should be approximately the same for each sample.

Automatic samplers are usually preferred because sampling is often required for periods of several days or during inclement weather. The chance of missing part of the dye cloud is reduced because automatic samplers can sample for long periods prior to the arrival of the dye cloud. In addition, simultaneous sampling from multiple sites is generally more efficient and less costly with automatic samplers. However, there are some disadvantages to the use of automatic samplers such as excessive sampling on the recession where fewer samples are needed to define the dye cloud and poor definition of the dye cloud near the peak if the selected sampling interval is too long.

There are several types of automatic samplers available commercially. Crawford (1979) gives a description of a "homemade" sampler. Automatic samplers are generally of two types: (1) bank-mounted sampler having a small diameter suction tube leading to the sampling point in the water, and (2) a floating, boat-like sampler (Kilpatrick, 1972) that is partially immersed in the flow. Commercially produced, bank-mounted samplers which collected samples in glass bottles were used during this investigation. The sampler could collect as many as 28 samples with a sampling interval from 1 to 999 minutes.

Adequate definition of the time-concentration curve is dependent on an appropriate sampling interval that is based on an assessment of flow conditions and hydrology of the test site. The sampling interval chosen during initial traces to a particular resurgence was frequently adjusted for better definition of the time-concentration curve during repeat traces. Sampling intervals during this investigation ranged from 20 to 120 minutes.

The degree to which the dye is laterally and vertically mixed in the flow, at the sampling site, affect the sampling strategy. A single point sample taken from a laterally unmixed concentration distribution cannot be used to properly calculate the mass of recovered dye for the sampling interval.

A mixing length may be defined as the distance needed for nearly complete lateral mixing of the dye tracer in the test stream. In the application of dye tracer techniques to surface water investigations, the mixing length can be calculated using techniques described by Kilpatrick and Cobb (1985) and the distance to sampling sites can be selected accordingly. In ground-water applications of quantitative dye tracer techniques, however this calculation has little application because the mixing length is typically the distance between the dye injection point such as a sinkhole, and the point of dye recovery from a ground-water resurgence such as a spring. This distance is fixed unless dye is sampled well downstream of the resurgence point. Thus, for the two major springs in the study area, Dyers and the Elizabethtown Spring, the mixing length for dye traces from specific input points is relatively fixed because of the short distance between the resurgence and the receiving stream.

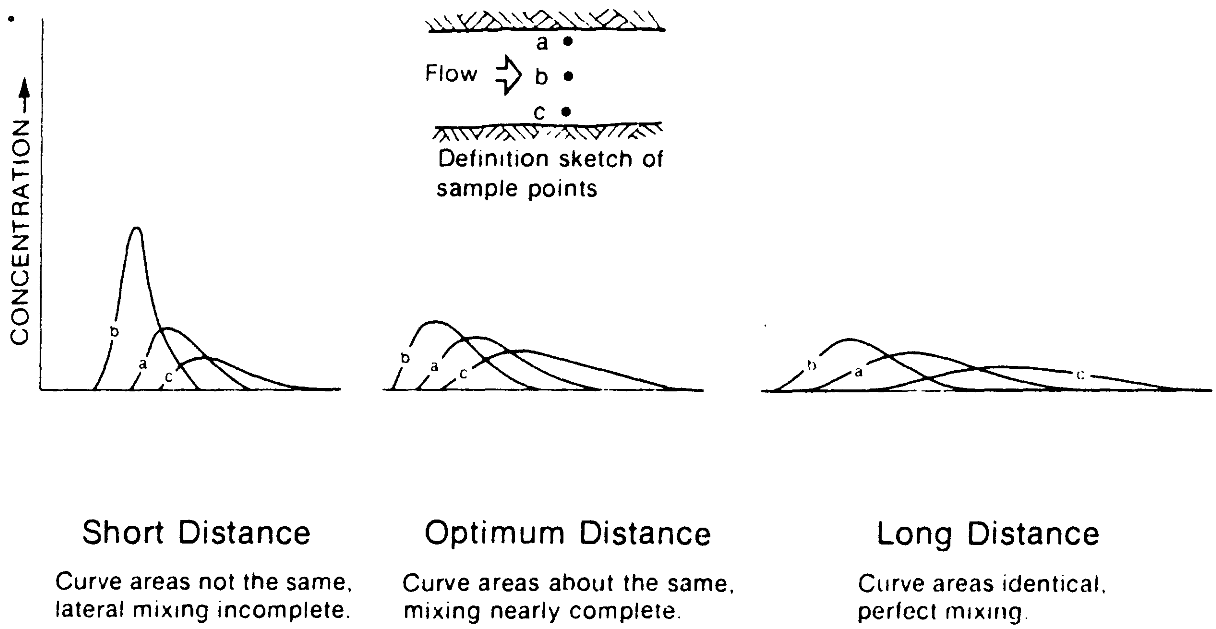
Incomplete lateral mixing is usually the result of a short mixing length. Incomplete mixing can also occur when undyed ground water enters the flow system between the injection point and the sampling point at short distances above the sampling point. The addition of undyed water to the flow system above the sampling point, usually results in incorrectly high estimates of recovered dye.

During quantitative dye tracing, a preliminary trace is usually needed to assess the degree of lateral mixing of dye at the recovery point. Dye is recovered from at least three points in the cross section at the resurgence and time-concentration curves plotted for each section. Complete lateral mixing is reached when the areas under the time-concentration curves for each lateral position sampled are the same, regardless of curve shape or magnitude of the peaks. Kilpatrick and Cobb (1985) found that the optimal level of mixing for dye tracings purposes was about 95 percent of complete and single-point sampling should adequately represent the mass of dye cloud at that point. The relation of mixing length to curve areas is illustrated by figure 15.

In order for samples to represent the dye cloud with incomplete lateral mixing, the dye cloud must be sampled at several points, laterally such as at a, b, and c as shown in figure 15. Selection of these sampling points is based on equal increments of flow as determined from a stream discharge measurement made with a current meter. For example, if three points in a section are to be sampled, the samples should be collected at 1/6, 3/6, and 5/6 points of cumulative flow across the section (Kilpatrick and Cobb, 1985).

Single-point sampling was used for all dye recovery measurements during this investigation. Preliminary estimates based on straight line map distance and estimated ground-water velocity suggested that the distance between injection and recovery points was adequate for complete mixing of the tracer. The shortest map distance for any quantitative trace was about 3,000 feet.

Although sampling points were selected on the basis of the estimated mid-



From F. A. Kilpatrick and D. D. Cobb (1985)

Figure 15.--Typical response curves observed laterally and at different distances downstream from a dye injection point.

point of flow, subsequent analysis revealed that some samples were affected by incomplete lateral mixing of the dye tracer at the recovery point, especially during periods of high flow. Because analysis of the dye recovery data showed more nearly complete mixing during periods of low to medium flow, the most likely cause of apparent incomplete mixing was probably the addition of undyed water to the main water-bearing conduit near the ground-water resurgence.

Specific procedures are required for the handling of water samples after collection because improper handling can affect the determination of dye content. All samples were transported and stored in light-proof containers in order to prevent reduction of fluorescence due to photochemical decay. Although some samples were checked for fluorescence in the field, primarily as a guide for sampling, most were returned to the laboratory for final determination. Because fluorescence activity is significantly affected by temperature (fluorescence is inversely related to temperature) temperature effects must be accounted for in data analysis (Wilson and others, 1984). However, temperature effects can be ignored if the fluorometer used for measuring dye content does not increase temperature during analysis and if the samples and calibration standards are allowed to temperature equilibrate before analysis. Thus, the water samples that were collected for dye analysis were allowed to temperature equilibrate, usually overnight, before the dye content was measured with a properly calibrated filter fluorometer.

Because the dye is not completely conservative (that is some of the dye is lost during the trace) the measured dye concentrations are adjusted to eliminate the effects of dye loss. This adjustment is required if the results of different traces are to be compared. In this procedure, the measured dye concentrations are multiplied by the ratio of the dye mass injected to the mass of dye recovered.

Because the concentration of dye recovered is affected by the quantity of tracer injected, it is necessary to "normalize" the dye recovery data by dividing observed concentrations by the mass of the tracer injected. The resulting concentrations are therefore, adjusted to a particular unit of tracer, for example, milligrams per liter per kilogram. This procedure compensates for variations in the mass of dye injected during different traces and simplifies analysis of the time-concentration data.

Although, all dye-concentration data used for quantitative analysis in this report were adjusted for dye loss and normalized to a unit mass of tracer, both procedures assume that none of the dye flows to other resurgences or is trapped in the subsurface. This fact can usually be established with qualitative tracer tests and confirmed with discharge measurements during the time of the quantitative test. However, the complexities of ground-water flow in karst terrane are such that some dye may escape detection by flowing to an unmonitored resurgence, especially during traces performed under high-flow conditions.

A filter fluorometer is an instrument that measures the intensity of light from a water sample containing a fluorescent substance. The intensity of fluorescence is proportional to the amount of fluorescent substance present. Fluorescence can also be measured with fluorescence spectrometers or spectrofluorometers (Udenfriend, 1962 p. 62-86). These instruments are especially useful if different dyes are being used for tracing to the same point. Although other brands of fluorometers may be used, all fluorometric analysis during this investigation was done with a Turner Designs Model 10 filter fluorometer. This portable meter provides direct reading of dye content based on meter calibration, reaches operational temperature in about 15 minutes, can be powered with either 115 volt a.c. or 12 volt d.c. current, and does not adversely increase the temperature of the test sample.

A filter fluorometer consists of six basic components shown in figure 16 (Wilson and others, 1986). The light source and filters are selected for maximum sensitivity to the particular fluorescent tracer being used. Detailed information about fluorometers and fluorometric operation, including calibration, is given by Wilson and others (1986). However, the calibration procedure is reiterated here because dye recovery data acceptable for quantitative analysis is dependent on the use of a correctly calibrated fluorometer.

The preparation of calibration standards is basically the process of step by step reduction of the stock dye solution until concentrations that are expected during dye recovery are reached. This reduction is generally known as a serial dilution and is explained in detail by Kilpatrick and Cobb (1985). Precise measurements of the initial volume of dye, added diluent, and distilled water in each step of the procedure are necessary in order to prepare a set of standards for an accurate calibration of the fluorometer. The serial dilution procedure is based on the equation:

$$C_n = C_i \left[\frac{W_d}{V_w + V_d}\right] + C_i\ S_g \left[\frac{V_d}{V_w + V_d}\right] \qquad \text{(eq. 5)}$$

where C_i = the initial dye concentration, in micrograms per liter

C_n = the new dye concentration, in micrograms per liter,

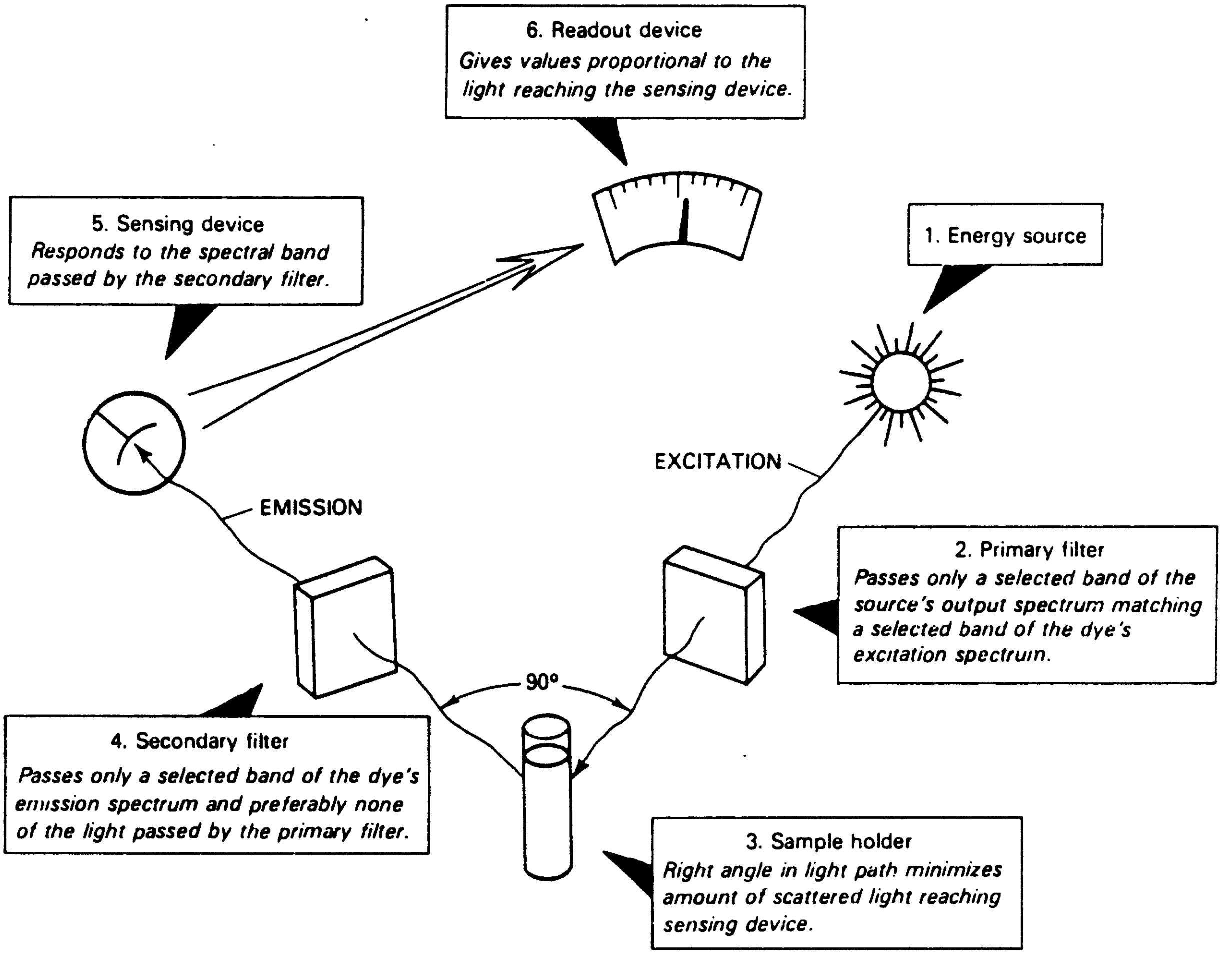
S_g = the specific gravity of the initial dye solution, 1.19 for rhodamine WT, 20-percent solution;

V_d = the volume of the dye solution added, in milliliters,

V_w = the volume of the added diluent, in milliliters, and

W_d = the weight of the initial solution, in grams.

For rhodamine WT, 20-percent solution, (200 g/L or 200,000,000 µg/L) three serial dilutions are required to obtain concentrations on the order of 100 µg/L (see table 2). In each step, the preceding C_n becomes the new initial concentration, C_i. This third dilution (100 µg/L) should be retained in quantity as a "working solution" and is used for further dilution if standards below 100 µg/L are needed. The use of the working solution eliminates the necessity to perform complete serial dilutions each time the fluorometer is calibrated so long as the same dye lot is being used. The same working solution was used throughout this investigation because all rhodamine WT used was from the same dye lot. The working solution should be sealed and stored out of light.



From J. F. Wilson, E. D. Cobb, and F. A. Kilpatrick (1986)

Figure 16.—Basic structure of most filter fluorometers.

Table 2.--Three-step serial dilution for preparation of a working solution for fluorometer calibration

[μg/L, microgram per liter; g/cm³, gram per cubic centimeter; ml, milliliter]

	Initial concen-tration (μg/L)	Specific gravity (g/cm³)	Volume of dye (mL)	Volume of diluent (mL)	New concen-tration (μg/L)
First dilution	200,000,000	1.190	20	2,068	2,280,000
Second dilution	2,280,000	1.002	20	3,000	15,100
Third dilution	15,100	1.000	20	3,000	100

Although an infinite number of combinations of water and dye may be used to prepare standards, table 2 shows the combinations for three dilutions used to produce the working solution of 100 μg/L used as a calibration standard during this investigation. Distilled water was used for calibrating to zero background. Calibration was checked with temperature equilibrated solutions before the final measurements for all dye samples.

DYE TRACING IN THE ELIZABETHTOWN AREA

For this report, dye traces are classed as qualitative, quantitative, and semi-quantitative based on the purpose of the trace, the field techniques used, and the nature and analysis of the data collected. The traces were intended to be quantitative but were classed as qualitative or semi-quantitative if the nature of the dye recovery during these traces was such that quantitative analysis was not possible. All traces are summarized in table 3, 4, and 5; injection and recovery sites are shown on plate 1. The traces are listed chronologically in each table and numbered sequentially, beginning with the first trace in table 3. Although the traces are shown on the map (plate 1) as straight lines, the lines are not intended to indicate the exact path of ground-water movement.

One of the reasons for dye tracing in the Elizabethtown area was to identify point to point connection between sinkholes and sinking streams and the springs and wells used for the Elizabethtown public water supply. Therefore, the early part of this investigation concentrated on identifying these connections by qualitative dye traces. The use of qualitative methods continued during quantitative traces to confirm connections during different flow conditions, to confirm passage of the dye cloud in case the selected sampling interval missed the dye cloud entirely, and to modify and improve the techniques being used.

Quantitative traces were performed between selected ground water input and recovery points whose connection had been defined by prior qualitative traces. Although rhodamine WT was the only dye used for quantitative traces, several traces using rhodamine WT were classed as qualitative due to

Table 3.--Summary of qualitative dye tracer tests

Trace No.	Injection date	Injection Site	Injection Feature	Major recovery sites	Other sites monitored	Tracer and quantity injected	Remarks
1	10-12-84	36	Cave	1, 2	16, 3	fluorescein, 1 pound	Strongly positive at site 1; weakly positive at site 2.
2	11-06-84	15	Karst window	16	-	do	Dye detected visually.
3	12-11-84	40	Sinking stream	1, 2	3, 16	rhodamine WT, 40 mL	
4	02-11-85	41	Sinkhole	1, 3	2, 16	fluorescein, 0.5 pound	Drainage turbid, flow 150 gal/min, est.
5	03-07-85	36	Cave	1, 2	3, 16	rhodamine WT, 95 mL	Flow in cave, 100 gal/min, est.
6	03-15-85	36	Cave	1, 2	3, 16	rhodamine WT, 200 mL	Flow into cave, 150 gal/min, est.
7	04-02-85	38	Cave	58	1, 2, 3, 16, 39	fluorescein, 2 pounds	Flow in cave, 200 gal/min, est.
8	04-12-85	34	Sinkhole	2	1, 3, 6	rhodamine WT, 20 mL	Weakly positive. Water from hydrant used to flush dye underground.
9	05-17-85	15	Karst window	16	1, 2, 3	rhodamine WT, 10 mL	Water clear.
10	09-11-85	40	Sinking stream	1	2, 3, 16	rhodamine WT, 20 mL	Dye flushed into swallet with 2,500 gals hauled water.
11	11-04-85	36	Cave	2, 3	1, 5, 16, 17	rhodamine WT, 100 mL	Flow into cave, 75 gal/min, est.
12	11-26-85	29	Sinkhole	48	1, 2, 3, 16, 18, 25	rhodamine WT, 200 mL	Stormwater runoff injection.
13	01-14-86	22	Karst window	21	1, 2, 3, 16, 18, 20, 25, 48	rhodamine WT, 80 mL	Nearby domestic water-supply wells also monitored for dye.
14	02-06-86	31	Sinkhole	3, 29, 48	1, 2, 3, 5, 13, 17, 18, 20, 25	rhodamine WT, 400 mL	Stormwater runoff, water turbid.
15	05-15-86	36	Cave	1, 2	3, 4, 5, 13, 17, 18, 20, 25	fluorescein, 0.5 pound	Weakly positive at site 2. Dye detected in water sample at site 1.

Table 4.--Summary of quantitative tracer tests with rhodamine WT dye

Trace No.	Injection date	Injection Site	Injection Feature	Major recovery sites	Other sites monitored	Quantity injected (milligrams per liter)	Remarks
16	02-22-85	40	Sinking stream	1	2, 3, 16	120	Sinkhole flooded. Dye recovered on charcoal at sites 2 and 3.
17	02-28-85	15	Karst window	16	1, 2, 3	10	Water clear, base flow.
18	03-01-85	15	Karst window	16		10	Water clear, base flow.
19	05-23-85	15	Karst window	16	1, 2, 3	15	Water clear, base flow.
20	05-30-85	15	Karst window	16	1, 2, 3	15	Water clear, base flow.
21	07-16-85	15	Karst window	16		10	Water clear, base flow.
22	08-12-85	15	Karst window	16		10	
23	09-30-85	40	Sinking stream	1	2, 3, 16	100	Storm-water injection. Water turbid. Dye detected in water at sites 2 and 3.
24	01-22-86	22	Karst window	21	1, 2, 3, 14, 16, 18, 20, 25, 48	200	Water clear.
26	02-26-86	15	Karst window	16	1, 2, 20	30	Water clear.

Table 5.--Summary of semi-quantitative tracer tests with rhodamine WT dye

Trace No.	Injection date	Injection Site	Injection Feature	Major recovery sites	Other sites monitored	Quantity injected (milliliter)	Remarks
25	02-03-86	42	Sinkhole	1, 2, 3	5, 13, 16, 18, 20, 25, 43	300	Storm-water injection. Dye detected in water from site 3 and on charcoal at site 2.
27	03-12-86	14	Sinkhole	15, 16	1, 2, 5, 13, 45	100	Storm-water injection. Dye detected in water from site 15.
28	04-08-86	29	Sinkhole	4, 44, 45	1, 2, 3, 16, 17, 18, 20, 25, 32, 33	2,000	City-water injection. Dye detected in water at recovery sites.
28-A	04-08-86	29	Sinkhole	3, 44, 45	1, 2, 4, 16, 17, 18, 20, 25, 32 33	2,000	City-water injection. Dye detected in water at recovery sites.
29	04-22-86	28	Stream	4, 42	1, 2, 3, 16, 17, 18, 20, 25, 32, 33	150	Valley Creek, low base-flow.
29-A	04-22-86	28	Stream	3, 42	1, 2, 4, 16, 17, 18, 20, 25, 32, 33	150	Valley Creek, low base-flow.

conditions that prevented sampling of the dye cloud with sufficient accuracy to define the dye-recovery curve. Unless otherwise noted in table 3, all dye was recovered on activated coconut charcoal in passive detectors. The presence of fluorescein in the elutriant was determined visually but fluorometric analysis rather than visual detection of red color of the dye was used to confirm the presence of rhodamine WT during qualitative traces.

Because the large springs represent the discharge points for a ground-water basin and because the Elizabethtown (site 1) and Dyers (site 16) Springs are part of the Elizabethtown water supply, one or both of these springs were monitored for dye recovery during all dye traces. Wells pumped for public (sites 3 and 4) and industrial (sites 18, 20, and 25) water supply were also monitored in addition to the small (sites 17 and 43) and intermittent (sites 2 and 13) springs. In addition to the ground-water sites, Valley Creek was monitored for dye at sites above the points where flow from the Elizabethtown, Dyers, and the unused spring at site 2, joined Valley Creek. The Valley Creek sites were monitored for all traces in order to locate previously unknown ground-water discharge to Valley Creek. The fact that no dye was recovered from Valley Creek upstream from the springs suggests that the springs are the major points of discharge from their respective ground-water basins.

Qualitative Dye Traces

Only the positive qualitative traces that were not later repeated using quantitative techniques are presented here. Qualitative dye traces are summarized in table 3. The traces are numbered sequentially and include traces from 4 sinkholes (sites 29, 31, 34, and 41), 2 caves (sites 36 and 38), two karst windows (sites 15 and 22), and a sinking stream (site 40).

Traces 1, 5, 6, 11, and 15 originated in a cave-like opening (site 36) under the southbound lane of Interstate Highway I-65 about 500 feet north of the Western Kentucky Parkway. Repeat traces were performed from this site because of its susceptibility to receive contaminated runoff from the accidental spillage of hazardous substances due to transportation related accidents. The cave collects runoff from about 0.7 square mile of urban and industrial development which includes major transportation routes that carry the heaviest traffic in the Elizabethtown area. The cave is at the end of a y-shaped, concrete box culvert that collects runoff from the east and west sides of I-65. During periods of heavy runoff both the cave and the culvert are flooded. Water drains underground through several swallets at the end of the culvert. During all traces, dye was poured directly into these swallets and was underground within a few minutes.

The dye from trace 1 was strongly positive at the Elizabethtown Spring (site 1) and weakly positive at the unused spring (site 2). This pattern generally was repeated for subsequent traces from the cave (site 36). However, dye trace 11 was not recovered from the Elizabethtown Spring (site 1). Although traces 1, 5, and 6 indicate a connection between the cave (site 36) and the Elizabethtown Spring (site 1) attempts to define the dye-recovery curve during traces from the cave (site 36) were unsuccessful at site 1. None of the traces from the cave (site 36) were positive at Dyers Spring (site 16), the industrial supply wells (sites 18, 20, and 25), or in Valley Creek above the unused spring (site 2). However, dye from traces 4 and 11 was detected in water samples from one city water-supply well (site 3).

Trace 4 originated in a sinkhole (site 41) located west of U.S. Highway 31W about 3,500 feet south of State Highway 61, south of Elizabethtown. The sinkhole drains about 0.14 square mile of woodland and light commercial land use and also receives runoff from US 31W. About one-half pound of fluorescein was injected at 1100 hours on February 11, 1985. The dye was poured into water draining into the swallet at the estimated rate of 100 gal/min. Although water was slightly ponded over the swallets, the dye drained underground minutes after injection. Flow into the swallet consisted primarily of snowmelt with a slight sediment load. At the time of injection, flow from both city springs was clear. Passive detectors monitored for dye at both city springs and the unused spring (site 2) and were recovered 9 days later. Dye recovery was strongly positive at the Elizabethtown Spring (site 1) and was weakly positive in water from one city well (site 3). Dye was not detected at any other monitored site.

The results of traces 1 and 4 confirm the existence of at least two input points for the spring at site 1 and also that the ground-water basins draining to the Elizabethtown and Dyers Springs are not interconnected. The results also indicate that, under some flow conditions, flow to the Elizabethtown Spring at site 1 is separated from the smaller, unused spring located at site 2, which is located only 100 feet upstream of the mouth of the larger spring (site 1).

Trace 7 was from a cave (site 38), north of Cole Creek about 4 miles east of the Elizabethtown Spring. About 2 pounds of fluorescein dye was poured into a stream flowing at the rate of approximately 100 gallons per minute; all dye was underground within minutes after the injection. In this cave, water flows in a conduit about 4 feet high that extends in a northeasterly direction and drains underground through swallets at the southwest end of the conduit. In addition to the routinely monitored sites, passive detectors were also installed in a spring (site 39) about half a mile below the dye injection point and also in Cole Creek at the bridge on highway 567 (site 58). Dye recovery was strongly positive at site 58 but not at any of the other monitored sites, including the spring at site 39. Subsequent reconnaissance of Cole Creek revealed a spring flowing from the right bank, about 50 feet upstream of the bridge at site 58. However, discharge from this spring was only about 3 gal/min, much less than the flow in the cave at the injection site. On the basis of the difference in flow between the cave and the spring it seems unlikely that the spring is the principal output point for the cave and that flow from the cave into Cole Creek probably occurred upstream of the sampling point above the bridge.

Dye was injected into a sinkhole (site 34) south of US 31W bypass for trace 8. The sinkhole drains an area of approximately 0.05 square mile and receives drainage from the highway and urban area. Water drains underground through several open swallets that are large enough to admit cavers. Twenty milliliters of rhodamine WT was injected during low-flow conditions on April 12, 1985. About 60,000 gallons of water from a fire hydrant was used to flush the dye which was injected about 15 minutes after water began flowing into a swallet. Water continued to flow into the swallet for almost an hour after the dye was injected. A slightly positive dye recovery on coconut charcoal was observed at the unused spring (site 2) upstream from the Elizabethtown

Spring but not at the Elizabethtown Spring (site 1), water-supply well (site 3), or Dyers Springs (site 16). However, this trace was not considered conclusive because the dye recovery was questionable.

Dye from trace 12 was injected into a storm water disposal sinkhole (site 29) and was recovered in Freeman Creek at Highway 251 (site 48). However, the dye recovery was weak so this trace was not considered positive until the low-flow dye injection during trace 28 which produced a very positive dye recovery in Freeman Creek at south Mantle Street (site 49), downstream at site 48, and in the city water-supply wells 3 and 4. Trace 12 is one of several traces from site 29 that were attempted with increasing quantities of dye following storm events which produced drainage into the sinkhole. Apparently the quantity of dye injected during earlier attempts was insufficient for detection at various recovery points because of dilution from the storm water in Freeman Creek.

Trace 14 was from a stormwater disposal sinkhole (site 31) on the north side of Poplar Street, under a church parking lot. The sinkhole drains about 0.2 square mile of urban area. Storm water runoff was used to inject 400 mL of rhodamine WT on February 6, 1986. The dye was recovered in a water sample from site 29, thus, confirming a ground-water connection between sinkholes 29 and 31, a map distance of about 900 feet. Dye from this trace was also recovered from one city water-supply well (site 3). However, a later trace (29) confirmed that the dye that was recovered in the city production well (site 3) from trace 14 was in water which had infiltrated from Valley Creek to the well, rather than by way of a subsurface connection between the sinkhole at site 31 and the city well (site 3). Trace 29 began with dye injected directly into Valley Creek and is discussed in more detail in the section on semi-quantitative traces.

Only those traces with positive dye recovery are listed in the tables and shown on the map (plate 1). Additional traces were attempted that did not result in positive dye recovery. Unsuccessful attempts were made during the early part of the investigation when the ground-water flow system was less well understood and techniques were being refined. Selected traces that did not yield positive dye recovery are briefly described in order that future tracing attempts might benefit accordingly.

Two traces were attempted using hauled water to flush the dye into the ground-water flow system during low-flow conditions when surface runoff from precipitation was absent. About 1,600 gallons of raw water was dumped into the sinkhole in the southern cloverleaf of the I-65 and Western Kentucky Parkway Interchange (site 37) and the cave (site 36) under the southbound lane of I-65 on August 29 and September 26, 1984, respectively. Rhodamine WT was used for both injections and water samples were collected from the Elizabethtown Spring (site 1). Although this technique of flushing dye underground with water from a hydrant or tank has been successful in other areas (Jones, 1984) and was successful during later traces in this investigation, dye was not recovered from these two injections.

Several factors could explain the failure to recover dye during these traces such as insufficient quantity of water to flush the dye into the conduits draining to the spring, too little dye to be detected in water samples from the spring, inadequate duration of sampling, or some combination of all of these. Considering the quantity of dye injected, 40 mL on August 29 and 100 mL on September 26, and the fact that successful traces were performed with similar quantities of injected water during this investigation, the most probable explanation is that sampling was discontinued before the dye arrived at the Elizabethtown Spring (site 1).

A trace was attempted from a well located on Poplar Street that is used for the disposal of storm-water runoff (site 30). The well is 180 feet deep, 6 inches in diameter and is open at land surface. The mouth of the well is about 6 inches above land surface and is protected by a pipe grate with 6-inch openings between the pipes. The well is located in a topographic depression that collects runoff from about 0.02 square mile of urbanized area. Runoff drains from the depression into the well and also to a sinkhole (site 29) on the south side of Poplar Street. During periods of heavy precipitation nearby structures may be flooded by the accumulation of stormwater that exceeds the drainage capabilities of both the sinkhole (site 29) and the well (site 30). The primary purpose of this trace was to identify the sites receiving drainage from this well. In addition, a positive trace from the well would indicate the degree to which the well was functioning as a storm-water drain and whether or not the well was tapping the same fracture system draining the nearby sinkhole (site 29).

On December 26, 1984, 200 mL of rhodamine WT was injected into the well. Although recent rains had flooded the depression around the well, water did not cover the well at the time of injection and the dye was poured directly into the well bore.

Following this injection, daily water samples and passive detectors monitored for dye at both city springs (sites 1 and 16), Valley Creek above each spring, one water-supply well (site 3), and two small springs (sites 2 and 17) through January 31, 1985. Dye was not recovered at any of these sites nor in water samples from the nearby sinkhole (site 29). These results suggest that the well does not penetrate sufficient openings within the ground-water flow system to function efficiently as a drainage well. This interpretation was substantiated by caliper logs (see fig. 6) that show that well 30 does not penetrate horizontal openings similar to those found in wells 25 and 26 or in other high-yielding wells located near the city well field (Mull and Lyverse, 1984).

In order to lessen the possibility that slow drainage of dye from the well might interfere with later traces, the well was dewatered on January 28, 1985. Water was pumped from the well into the nearby sinkhole (site 29). The water was a deep pink color from the dye remaining in the well. Although not confirmed from this dye injection, drainage from the sinkhole (site 29) was later traced to Freeman Creek at South Mantle Street (site 49).

Quantitative Dye Traces

For this investigation, dye traces were classified as quantitative if the dye-response curve was well defined and discharge at the recovery site was accurately measured. Traces classed as quantitative are summarized in table 4. In the following discussion, quantitative traces to public water-supply springs are discussed first followed by a discussion of a quantitative trace to an unused spring located about 1.5 miles northwest of the city well field.

Two quantitative traces (sites 16 and 23) were completed from a sinking stream (site 40) to the Elizabethtown Spring (site 1). The sinking stream drains approximately 1.3 square miles that includes agriculture, industrial, and urban land uses. The area that drains to the sinking stream is traversed by heavily-traveled State Highway 61. Water drains underground through swallets that are partially plugged by loose debris which is common to surface runoff. The channel leading to the swallets is incised 8-10 feet below the adjacent land surface. Except in periods of intense or prolonged precipitation, all runoff drains underground. Flooding causes water to overflow the channel into an adjacent field. However, all surface runoff that accumulates in the channel and depression around the swallet eventually drains underground because there are no over-flow routes from the site.

The area around the swallet was flooded when dye for the first quantitative trace (site 16) from site 40 was injected. Dye was poured into ponded water over the approximate location of the swallet at 1200 hours on Feb. 22, 1985. Water samples were collected hourly at the Elizabethtown Spring (site 1) and at Dyers Spring (site 16). Passive detectors were installed in Valley Creek upstream of each spring, and in the discharge from the unused spring (site 2) and one city well (site 3) nearest to the injection site. The leading edge of the dye cloud arrived at the Elizabethtown Spring (site 1) 8 hours after injection and the peak dye concentration arrived 4 hours later. The straight-line distance between the injection site and the spring is approximately 11,500 feet. Thus, the apparent velocity of water carrying the leading edge of the dye was about 24 feet per minute, the highest apparent velocity measured during this investigation. The apparent velocity of the leading edge of the dye cloud is described here in order to emphasize the velocity of ground-water flow in a karst aquifer. However, the apparent velocity of the centroid of the dye cloud or simply, mean traveltime is used for quantitative analysis that is discussed later.

The second quantitative trace (site 23) between sites 40 and 1 was begun at 1435 hours on September 30, 1985. Although this trace also used storm-water runoff, the trace is representative of low-flow conditions. The swallet was dry until runoff from a thunderstorm began draining underground at 1420 hours. Dye was poured into the swallet about 15 minutes later and was flushed underground almost immediately. Water samples were collected at two-hour intervals from the Elizabethtown and Dyers Springs and one city well (site 3). Passive detectors monitored for dye in Valley Creek upstream of each spring and in the discharge from the unused spring at site 2. In addition, daily water samples were collected from the unused spring. After 26 hours the leading edge of the dye cloud appeared at the Elizabethtown Spring (site 1) and the peak dye concentration arrived 22 hours later. Based on the straight-line map distance of 11,500 feet, the apparent ground-water velocity during this trace was about 7.3 feet per minute.

Dye was not recovered at Dyers Spring (site 16) nor from Valley Creek during either trace from site 40. However, traces of dye were recovered in discharge from both the unused spring (site 2) and the city well (site 3). Dye was detected on charcoal in the passive detectors at sites 2 and 3 during trace 16 and in water samples from both sites during trace 23.

Based on the results of these traces, the Elizabethtown Spring (site 1) is the major resurgence point for water draining underground at site 40 during both low and high flow conditions. Some water from site 40 also drains to sites 2 and 3. The significance of these results is that both the spring (site 1) and one well (site 3) used for public water supply by the city is recharged by drainage from the sinking stream (site 40) and that recharge to the well (site 3) from site 40 flows under, but does not intersect Valley Creek. Additional analysis of the quantitative data from these traces are discussed in a later section on the interpretation of dye-trace characteristics.

Seven quantitative traces were completed between Dyers Spring (site 16) and a karst window (site 15) about 3,000 feet east of the spring. The existence of this connection was suggested by Mull and Lyverse (1984) and was confirmed by qualitative traces on November 6, 1984 (trace 2).

In the karst window at site 15, a spring emerges from crevices in limestone at the upper end of the sinkhole, flows about 250 feet and drains into a swallet at the lower end of the sinkhole. The stream is about 40 feet below the surrounding farmland and is unused except for watering livestock, which have direct access to the spring. The area draining to the spring collects runoff from the adjacent farmland, which is cultivated for corn, soybeans, and various cover crops.

Although limestone is exposed at the lower end of the sinkhole, the mouth of the swallet was covered by ponded water for all flow conditions observed during this investigation. There is no external drainage, thus, except for evaporative losses, all water that enters the depression, either as discharge from the spring or as surface runoff from the area draining into the sinkhole, eventually drains underground through the swallet. The karst window receives relatively little direct runoff because of the small area that drains directly into the sinkhole, but the contributing area is hydrologically important because the sinkhole offers a direct path to the subsurface for any contaminant placed in the area draining to the sinkhole. Thus, agricultural chemicals associated with nearby farming and farm-animal wastes can drain directly into the ground-water system. In the case of this karst window (site 15), both qualitative and quantitative dye traces showed that flow from this site resurges at Dyers Spring (site 16), which is part of the Elizabethtown water supply.

Dye was poured into the stream above the swallet during each quantitative trace from site 15. All dye drained underground minutes after the injection except during traces 17 and 18, which were made during high base-flow conditions when the sinkhole was partly flooded. Automatic samplers collected water samples at Dyers Spring (site 16) and at the Elizabethtown Spring (site 1) during all traces from the karst window at site 15. In addition, passive detectors were installed in Valley Creek upstream of each spring. Dye injected into the karst window at site 15 was not recovered in Valley Creek nor from any other monitored site other than Dyers Spring. The fact that dye injected in site 15 was only recovered from Dyers Spring indicates that Dyers Spring is the major discharge point for the conduit system draining site 15 and also confirms that the ground-water basins draining to the Elizabethtown Spring and Dyers Spring are not interconnected, at least not under flow conditions that existed during dye traces performed during this investigation.

The apparent traveltime for the leading edge of the dye cloud between the karst window, site 15 and Dyers Spring (site 16) were 5 and 24 hours for traces 18 and 23, respectively, based on the straight line distance of 3,000 feet. Based on the elapsed time between injection and the arrival of the leading edge of the dye cloud, the apparent ground-water velocity was 8.3 and 1.6 ft/min for these traces. Discharge from Dyers Spring during these traces was 4.7 and 0.53 ft^3/s, respectively. These results suggest a relation between traveltime and discharge that is discussed in greater detail in a later section on interpretation of dye-trace characteristics.

Flow from a second karst window (site 22) was traced (trace 24) to Stark's Spring (site 21) on the west bank of Billy Creek upstream of the bridge at State highway 1357. The depression around the karst window (site 22) drains a relatively small area of pasture and woodland. Water in the karst window rises in a blue-hole spring and flows about 150 feet to swallets that are partly covered by debris. Water does not cover the swallets except during flooding. Unlike the karst window east of Dyers Spring (site 15), water can drain from this site when flood-water overtops the sinkhole, which is about 25 feet deep.

Trace 24 began at 1200 hours on January 22, 1986 when 200 mL of rhodamine WT was injected into the stream about 5 feet upstream of the swallets draining the karst window (site 22). The first arrival of dye was detected in water samples from Stark's Spring (site 21) 27 hours later. The peak dye concentration arrived 10 hours later. Measured discharge from Stark's Spring was 0.70 ft^3/s on January 23. The apparent ground-water flow velocity, based on the straight-line map distance of 7,100 feet between the karst window (site 22) and Stark's Spring (site 21), was about 4 ft/min. However, the actual velocity was likely greater, because the actual travel distance was probably greater than a straight line connecting the karst window (site 22) and Stark's Spring (site 21). Dye was recovered only from Stark's Spring at site 21 during both the qualitative trace 13 and the quantitative trace 24. It should be noted that passive detectors and water samples were used to monitor for dye in domestic supply wells in the vicinity of Stark's Spring 21 in addition to the city springs and wells and industrial supply wells. Dye from this injection was not found in water from any of these wells or springs. Also, dye was not detected by passive detectors or water samples from Billy Creek above the mouth of Stark's Spring. Based on these facts, Stark's Spring at site 21 is the major point of resurgence for ground-water flow from the karst window at site 22. This interpretation is further substantiated by analysis of the dye recovery data for trace 24 which is included in a later section on interpretation of dye-trace characteristics.

Miscellaneous Qualitative Traces

Identification of point to point connections between specific ground-water input and resurgence points, classified as qualitative traces, can be made with substances other than those specifically intended for ground-water tracing. Two traces of this type were observed during this investigation. In one instance, the tracer was dark-colored sediment and undefined organic material in the effluent from a malfunctioning wastewater lift station and in another case, the tracer was road salt contained in runoff from a salt-storage yard.

The first miscellaneous qualitative trace involved dark gray to black sediment and stringy material that was observed in both the Elizabethtown Spring (site 1) and the unused spring (site 2) at 1300 hours on October 8, 1985. The black sediment was obvious in the channel of both springs and extended about 75 feet into Valley Creek which was in low base-flow conditions at the time. Inspection of the culverts and drains leading to the cave under I-65 (site 36) did not reveal the same deposits, however. Further upstream reconnaissance of the stream draining into the culvert did reveal the same material in the reach below the bridge on a newly completed section of State Highway 567 which leads to State Highway 61 about one-eighth mile south of its intersection with US 31W. Considering the abundance and nature of the deposits seen in water from the springs, open swallets were expected to be found in the reach between the bridge and the culverts leading to the cave under I-65 (site 36). Swallets were not found in this reach nor in the stream channel downstream of the bridge on Highway 567. However, the same type deposits were found below a wastewater collection lift station that is located in the vicinity of the intersection of State Highways 61 and 1031.

Water-treatment plant personnel reported that the wastewater lift station was inspected six days earlier. Apparently, subsequent failure caused wastewater to overflow the station and enter the surface drain leading into the cave under I-65 (site 36). Although the evidence is not conclusive, this route of entry to the subsurface seems more likely than entry through very small swallets in the bed of the stream above the entrance to the culverts. This event confirmed the presence of a low-flow connection between the small unused spring (site 2) and the larger Elizabethtown Spring (site 1).

A second miscellaneous qualitative trace occurred on February 18, 1986, when unusually high specific conductance values were observed in water from the unused spring (site 2) and the intermittent spring at site 5 during high-flow conditions. Discharge from all sites was turbulent and heavily laden with sediment. The specific conductance was 1,100 µmhos at each spring (sites 2 and 5); however, conductivity levels of 380 µmhos in water from the Elizabethtown Spring (site 1) and 400 µmhos in Valley Creek upstream of the unused spring were measured. Specific conductance values of the water draining into the culvert leading to the cave under I-65 (site 36) was 1,600 µmhos and increased at various upstream points to a maximum of 14,800 µmhos in water draining the salt-storage yard on the north side of State Highway 567 at a point about 0.4 mile east of the intersection of Highway 567 with State Highway 1031. Specific conductance of water in the drain bordering Highway 1031, upstream of its junction with drainage from the salt storage yard was only 700 µmhos.

Values of specific conductance of the water from the unused spring (site 2), the Elizabethtown (site 1), and Dyers Spring (site 16), and Valley Creek above the unused spring, measured during this investigation, were compared using the Kruskal-Wallis analysis of variance test (Sokal and Rohlf, 1969). The Kruskal-Wallis analysis of variance is a non-parimetric test that is used to evaluate the statistical difference between sampled populations by testing the hypothesis that there is no difference between the population means. The test indicated a highly significant difference (probability level > 99.9 percent) between the means. The means were then compared using Fisher's least significant difference procedure (Iman and Conover, 1983). The site comparison indicated that conductance at site 2 was significantly different (alpha = 0.05) from that at the other three sites which were not significantly different (alpha = 0.05) from each other.

These specific conductance values are interpreted as another indication of subsurface connection between the cave under I-65 at site 36 and the unused spring at site 2. The fact that high specific conductance values were not observed at site 1, is additional evidence that the ground-water basins draining to springs 1 and 2 are not interconnected under all flow conditions.

Miscellaneous Semi-Quantitative Traces

Traces were classified as semi-quantitative if dye concentrations were measured at the dye-recovery point but discharge from the dye-recovery point was not measured or if measured, the measurements were not sufficiently accurate to characterize changing flow conditions during storm-event traces. Also, classified as semi-quantitative were traces in which the dye recovery curve for storm-event traces was not sufficiently defined to quantify the mass of dye recovered, thus, limiting the quantitative analysis of the results of those traces. For traces 25 and 27 the sampling interval was too large to define the dye-recovery curve at the springs. Traces 28, 28-A, 29, and 29-A are classed as semi-quantitative because they do not meet the requirement for discharge measurements necessary for quantitative traces. However, all semi-quantitative traces can be used to define traveltimes for the arrival of the leading edge and time for passage of the dye cloud. A detailed discussion of semi-quantitative traces are included in this section and summarized in table 5.

Storm-water runoff was used to inject dye into the open swallet of a sinkhole (site 42) to begin trace 25. Although the area drained by the sinkhole is relatively small, the sinkhole receives runoff directly from the south-bound lane of I-65 and is one of several sinkholes that drain both lanes of I-65 and the area around the weight station which is located about 1.5 miles south of the Western Kentucky Parkway interchange. This trace was conducted to determine storm event flow conditions and to identify additional swallets that might contribute flow to Dyers Spring. Dye was injected directly into the swallet at 1330 hours on February 3, 1986, and drained underground immediately. Flow into the sinkhole was estimated to be 75 gallons per minute but increased due to heavy rains that followed the injection. Automatic samplers were installed at the Elizabethtown and Dyers Springs and at industrial supply wells 20 and 25. Water samples were collected manually from the industrial supply well at site 18 and from one city water-supply well (site 3). Passive detectors were installed in each water-supply spring, in Valley Creek upstream of each spring, and in the springs at sites 5 and 43. Water samples were collected daily from the spring at site 43 and from Valley Creek upstream of each spring.

Dye from trace 25 was detected only in water samples from the Elizabethtown Spring (site 1) and city well (site 3) and on charcoal at the unused spring (site 2). The dye was first detected at the Elizabethtown Spring (site 1) 8 hours after the injection. Based on the straight-line distance of 9,200 feet, the apparent ground-water velocity was about 19 ft/min. However, the actual velocity was faster because the first sample that contained dye was also the sample with the peak dye content. In this case, the 120 minutes sampling interval was to large to accurately define the dye-recovery curve during high-flow conditions at the Spring. The fact that no dye was recovered from Dyers Spring supports the theory that the ground-water basins draining to both city springs are not interconnected under flow conditions observed during this investigation.

A trace (27) using storm-water runoff was also completed between a sinkhole (site 14) and Dyers Spring (site 16). Dye was injected into the open swallet of a sinkhole (site 14) that drains approximately 0.4 square mile of predominately pasture land and forest. State highway 1136 traverses the upper part of the basin and the Western Kentucky Parkway is between the injection sinkhole (site 14) and Dyers Spring (site 16). The channel leading to the swallet is incised about 12 feet below the surrounding land surface and the swallet is partially plugged with forest debris. The dye was injected at 1200 hours on March 12, 1986 during a period between storms when overland flow was receding. Flow into the swallet was estimated to be about 20 gal/min.

An automatic water sampler was installed at Dyers Spring (site 16) and passive detectors were installed at all other monitored sites, 1, 2, 5, 13, and 45. One water sample was collected from the karst window (site 15). Dye was detected only in water samples from Dyers Spring and the karst window. The dye first appeared at Dyers Spring 11 hours and 15 minutes after injection and the peak dye concentration arrived about 4 hours later. Dye content decreased to background levels about 24 hours after its initial appearance. The presence of dye in the sample from the karst window, shows that at least part of the flow was from the injection sinkhole to the karst window and thence to Dyers Springs, a straight-line distance connecting all three sites of 6,000 feet. Thus, the apparent ground-water velocity between sites 14, 15, and 16 during this trace was 8.9 feet per minute.

Because rains were forecast near the end of this trace, operation of the automatic sampler was continued to determine the presence of a secondary dye cloud originating from the same dye injection. A second dye cloud arrived at 2300 hours on March 14, about 59 hours after the initial dye injection and 47.75 hours after the arrival of the leading edge of the first dye cloud. The dye recovery curve showing the double dye peak and the passage of a second dye cloud resulting from a single dye injection is shown in figure 17.

The appearance of a second dye cloud after a single dye injection suggests that dye was trapped within the conduit system as storm-water runoff drained through the conduits or that part of the dye followed a more circuitous route to the spring. Analysis of daily precipitation data and the hydrograph for Dyers Spring did not conclusively show the cause of the second dye cloud. In either case, the appearance of the secondary dye cloud emphasizes the need to delay repeat traces between the same points until the occurrence of a rainfall event sufficient to purge the conduits of residual dye. This double-peak dye recovery is also significant with respect to ensuring the protection of drinking water supplied ground-water systems. In the case of a contamination incident in such terrane, misleading data could result in the conclusion that all contaminants have been flushed from the system. Steps to quantify the mass of pollutant spilled and the amount passing a particular withdrawal point are outlined in a later section on the predictive uses of quantitative dye tracing.

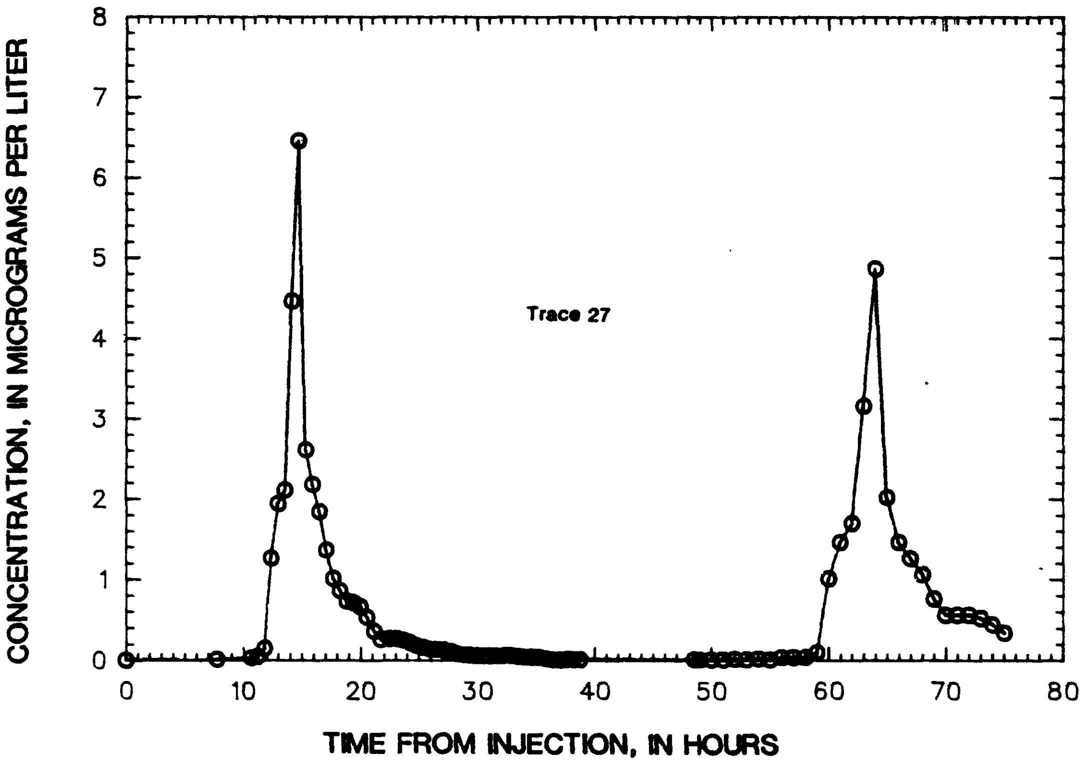


Figure 17.—A double-peak dye recovery at Dyers Spring for trace begun March 12, 1986.

A semi-quantitative trace was completed between a sinkhole used for the disposal of storm water runoff (site 29), Valley Creek (sites 48 and 49), and the city wells (sites 3 and 4). Because the dye was recovered in both city water-supply wells, the traces are designated 28 and 28-A respectively. As mentioned earlier, several previous traces were attempted from this sinkhole (site 29) but the results were inconclusive. The quantity of dye injected and the quantity of water used to flush the dye underground, were increased significantly over amounts used earlier in the unsuccessful traces. The larger quantities were used to ensure a definitive appearance of dye in, what was at the beginning of the trace, an unknown resurgence.

The injection sinkhole drains about 0.02 square mile of urban area. About 150,000 gallons of water from a nearby fire hydrant, or approximately the runoff from a one-inch rainfall event, was used to inject 2,000 mL of rhodamine WT dye on March 8, 1986. Water began flowing into the sinkhole at 0900 hours and the dye was injected one hour later. All suspected resurgences, including the industrial supply wells (sites 18, 20, and 25) and each city spring and well were monitored for dye with passive detectors, automatic water samplers, or manually collected water samples.

The dark pink color of the dye was reported in Valley Creek which was clear and in base flow, upstream of the bridge at U.S. Highway 62 at 1900 hours. Analysis of passive detectors showed positive dye recovery in Freeman Creek at State Highway 251 (site 48) and at south Mantle Street (site 49). Dye was also recovered in water samples from both city wells but not from any other well or spring despite the fact that one industrial supply well (site 25) was constantly pumped at the rate of 250 gal/min. It should be noted that dye was not recovered in water from two springs (sites 32 and 33) located in basements of nearby businesses although water samples and passive detectors were used to check for dye in both springs. Dye from a single injection into sinkhole 29 was detected in Valley Creek (site 48 and 49) and in water-supply wells 3 and 4. Traces 28A and 28 are classified as semi-quantitative because the traveltimes to both dye-recovery points (sites 3 and 4) were well defined (see fig. 18). However, these traces were not considered quantitative because the discharge from water-supply wells 3 and 4 was not sufficiently defined to quantify the mass of dye recovered. For that reason the dye recovery curves in figure 18 show measured rather than normalized dye concentrations and these data are not included in further quantitative analyses.

During trace 28, dye first appeared in water samples from the city well (site 4) 11.5 hours after the dye was injected (trace 28) and at the other city well (site 3), one hour later (trace 28-A). Both wells are on the southwest bank of Valley Creek. The well at site 4 is about 100 feet from Valley Creek and about 250 feet upstream from well 3. Well 3 is about 150 feet from the creek. The distance separating the wells and the distance to Valley Creek likely explains the difference in traveltimes for the appearance of the dye in each well. However, the fact that dye was recovered from both Valley Creek and the city wells following the dye injection into the sinkhole at site 29, raises the question of possible flow routes between the sinkhole and the wells. Did the dye travel in a ground-water flow system between the sinkhole and the wells or did the dye flow from the sinkhole to Valley Creek and thence to the wells? This question was answered by another set of semi-quantitative traces (traces 29 and 29-A) during which dye was injected into Valley Creek about 2,300 feet upstream from the city wells.

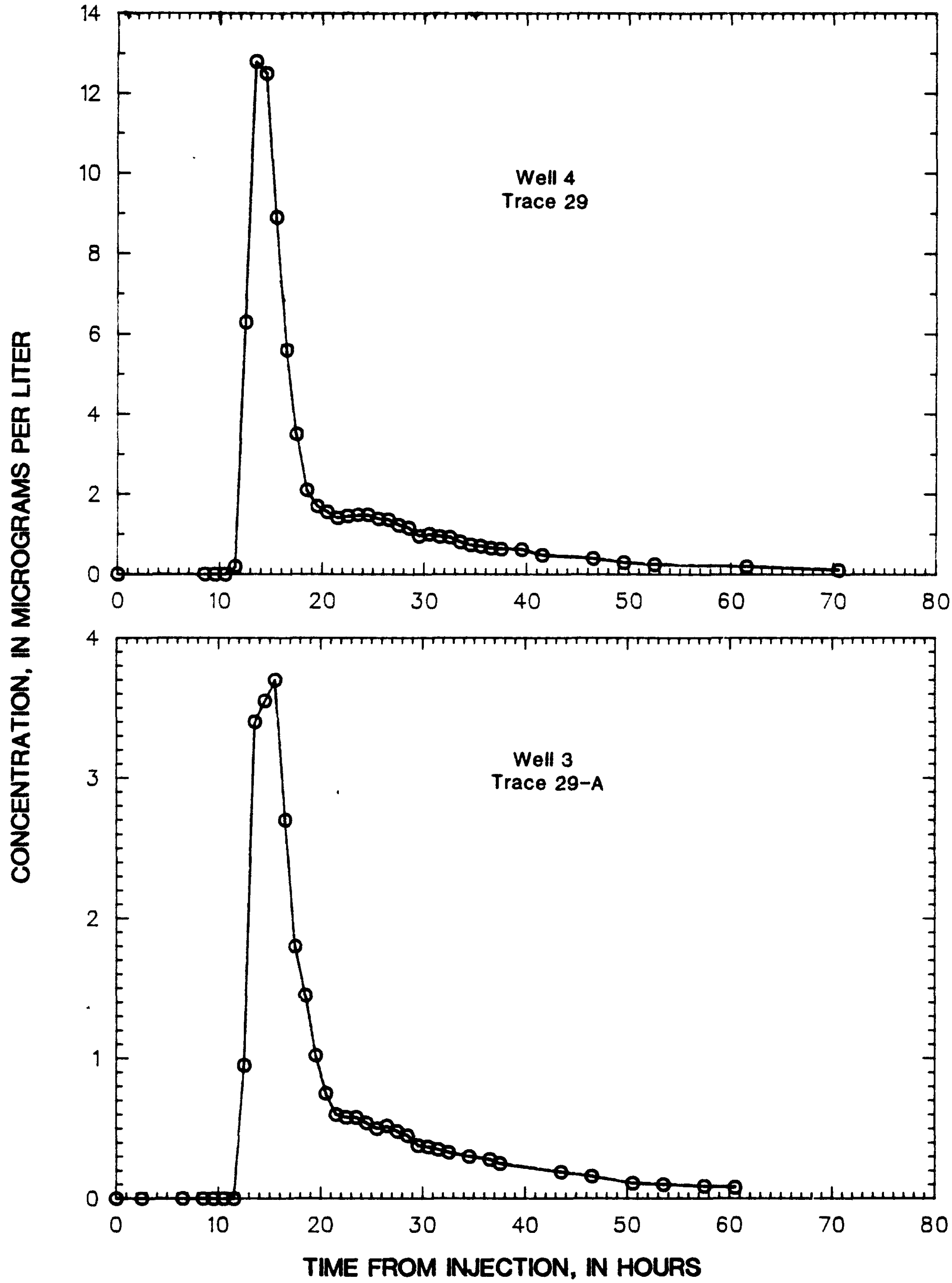


Figure 18.--Dye recovery in water-supply wells 3 and 4 after dye injection in sinkhole 29, April 8, 1986.

Dye was poured into Valley Creek in riffles downstream of a rock dam and about 2,100 feet above the highway bridge on US 62 at 0830 hours on April 22, 1986. Water in the stream was clear and representative of low base-flow conditions, which was the same as during traces 28 and 28-A. All dye recovery sites were monitored the same as during traces 28 and 28-A except for the deletion of sites upstream from the dye injection point.

Water samples were collected manually from the city wells at 15-minute intervals. The dye was first detected in well 4, 2.75 hours after injection and in well 3 (trace 29-A), 15 minutes later. Peak-dye concentration arrived at wells 4 and 3, 3.25 and 3.5 hours after injection, respectively. Dye was not detected at any other monitored ground-water site other than wells 4 and 3. Passage of the dye cloud in Valley Creek was monitored at site 45 about 700 feet below the mouth of the Elizabethtown Spring (site 1). Plots showing dye recovery in wells 3 and 4 during traces 29-A and 29 are shown in figure 19. As in the case of traces 28 and 28-A, these plots show measured rather than normalized dye concentrations because the accuracy of discharge from the wells was not adequate to calculate the mass of dye recovered in each well.

The traveltimes for dye arrival at the wells reflect the flow conditions in the stream and also underground transit from the stream to the wells. Thus, ground-water velocity estimates based on straight-line distance would not be representative of ground-water conditions for these traces. However, traces 29-A and 29 do confirm the infiltration of water from Valley Creek into both city water-supply wells (sites 3 and 4). The results of these traces also show that the most likely route taken by the dye from the storm-water disposal sinkhole (site 29) is to Valley Creek and thence to the wells rather than by way of a flow path developed entirely within the bedrock aquifer directly connecting the sinkhole with the wells.

COMPUTATION AND INTERPRETATION OF QUANTITATIVE DATA

Analysis of quantitative data from dye traces is based primarily on the dye-recovery (time-concentration) curves. As mentioned earlier, the time-concentration response typically gives a skewed, bell-shaped curve that is usually steeper on the rising limb than on the falling limb. The shape and magnitude of the dye-recovery curves are determined by the amount of dye injected, the amount of discharge at the recovery point, or resurgence, and the mixing characteristics of the flow. Analysis of time-concentration curves provide information on ground-water flow characteristics such as elapsed time to arrival of the leading edge, trailing edge, peak concentration, and centroid of the dye cloud.

The data from a single dye trace generally reflect conditions for that particular test, and especially for that particular discharge. Repeat quantitative dye traces between the same injection and recovery points are needed to describe the dye-trace characteristics under different flow conditions. Quantitative data were measured and reported for 10 traces during this investigation. Although some quantitative data were collected during other traces, data from other traces are not included in this analysis, primarily because the selected sampling intervals were not adequate to define the dye-recovery curve, discharge was not measured during varying flow conditions of storm-water traces (traces 25 and 27), or the discharge from

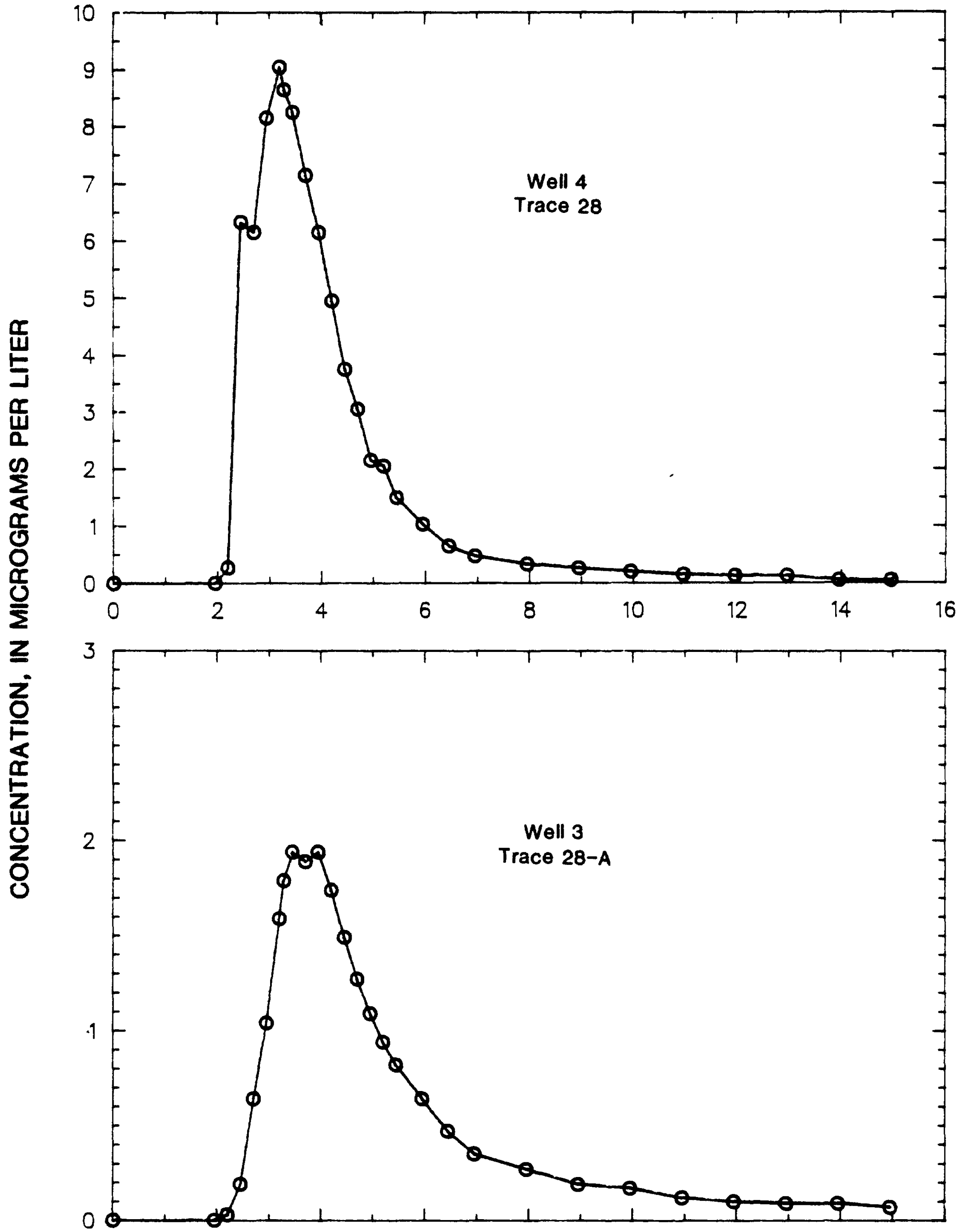


Figure 19.--Dye recovery in water-supply wells 3 and 4 after dye injection in Valley Creek, April 22, 1986.

pumping wells were not known (traces 28, 28-A, 29, and 29-A). Seven quantitative dye traces were completed between the karst window (site 15) and Dyers Spring (site 16). Two quantitative dye traces were completed between a sinking stream (site 40) and the Elizabethtown Spring (site 1), and one between a karst window (site 22) and Stark's Spring (site 21). Data from these traces are summarized in table 6 and discussed in the following sections.

Procedures for Computing Dye-Trace Characteristics

Selected characteristics for each of the 10 quantitative dye traces were computed, including mass of dye recovered, indicators of traveltime, and indicators of the dispersion of the dye mass. The mass of dye recovered was summed from the time-concentration data, based on equation 3, as

$$M_{out} = 0.1019 \sum_{i=1}^{n} Q_i (C_i' - C_0') \Delta t_i \qquad \text{(eq. 6)}$$

where M_{out} = mass of dye recovered, in kilograms (kg);

0.1019 = a unit conversion factor;

n = number of sampling intervals, equal to the total number of samples minus one;

i = the i^{th} sampling interval;

Q_i = mean discharge during the i^{th} sampling interval, in cubic feet per second (ft^3/s);

C_0' = background dye concentration, measured at time of injection, in milligrams per liter (mg/L);

C_i' = mean measured dye concentration during the i^{th} interval, equal to the mean of the two samples taken at the beginning and end of the interval, in mg/L; and

Δt_i = duration of i^{th} sampling interval, in hours.

Note that the sampling interval is the period of time between two successive samples, and that the summation was computed from the mean values within each sampling interval. In the report, concentrations that pertain to a sampling interval are identified with the i subscript; concentrations that pertain to a given sample are not subscripted.

Measured dye concentration was adjusted for background concentration and dye loss by:

$$C'' = (C' - C_0') \frac{M_{in}}{M_{out}} \qquad \text{(eq. 7)}$$

where C'' = adjusted concentration, in mg/L; and

M_{in} = mass of dye injected, in kg.

Table 6.--Measured characteristics of quantitative dye traces
[ft^3/s, cubic feet per second]

Trace number (from table 4)	Injection date	Injection site (from plate 1)	Recovery site (from plate 1)	Name of recovery spring	Apparent travel distance (feet)	Discharge (ft^3/s)	Travel time (hours)	
							Leading edge	Peak concentration
16	02-22-85	40	1	Elizabethtown	11,500	9.26	8	12
17	02-18-85	15	16	Dyers	3,000	4.72	5	6
18	03-01-85	15	16	Dyers	3,000	4.59	5	5.8
19	05-23-85	15	16	Dyers	3,000	1.35	11.5	13.5
20	05-30-85	15	16	Dyers	3,000	1.14	12	14.7
21	07-16-85	15	16	Dyers	3,000	.72	11.5	25
22	08-12-85	15	16	Dyers	3,000	.53	24	29.5
23	09-30-85	40	1	Elizabethtown	11,500	1.56	26	48
24	01-22-86	22	21	Stark's	7,100	.70	27	37
26	02-26-86	15	16	Dyers	3,000	2.88	5.3	6.7

Because the quantity or mass of injected dye was different for different traces (table 7), the adjusted concentrations for different dye traces were not strictly comparable. For this reason, dye concentrations for each trace were normalized to give the concentration that would have occurred if a standard mass of one kilogram of dye had been injected. Normalized dye concentrations are calculated as:

$$C = C'' \frac{1}{M_{in}} = (C' - C'_0) \frac{1}{M_{out}} \qquad \text{(eq. 8)}$$

where C = normalized dye concentration, in milligrams per liter per kilogram of dye injected (mg/L)/kg.

The normalized dye concentrations may be used to compare results of different dye traces. Because of the diluting effect of increased discharge, however, the areas under the normalized time-concentration curves vary from test to test, and are not comparable between traces. The effects of discharge variation may be removed by converting normalized dye concentrations to normalized dye loads, or mass flux, by:

$$L = 28.32\ C\ Q \qquad \text{(eq. 9)}$$

where L = normalized dye load, in milligrams per second per kilogram of dye injected (mg/s)/kg;

28.32 = a unit conversion factor; and

Q = discharge, in ft^3/s.

Areas under the normalized time-load curves are equal, and normalized load curves from different dye traces may be plotted and compared on the same graph. Kilpatrick and Taylor (1986) have recently applied the same techniques to dye-response curves, using the term "unit concentration" instead of normalized load.

Measures of the time distribution of the dye mass at the sampling point were computed for each dye trace. Because of the skewness of the dye-trace curve, the centroid, or the mass-weighted mean, is the best indicator of the traveltime of the dye cloud past the sampling point for quantitative analysis. The traveltime of the centroid of the dye mass, or simply the mean traveltime, was computed as:

$$\bar{t} = \frac{\sum_{i=1}^{n} t_i\ C_i\ \Delta t_i}{\sum_{i=1}^{n} C_i\ \Delta t_i} \qquad \text{(eq. 10)}$$

where $\bar{t}$ = mean traveltime, in hours; and

t_i = elapsed time from injection, in hours.

Table 7.--Computed characteristics of quantitative dye traces

[g, gram; ft^3/s, cubic feet per second; ft/s, feet per second; (mg/L)/kg, milligram per liter per kilogram injected; (mg/s)/kg, milligram per second per kilogram injected; ft^2/s, square feet per second]

Recovery site (from plate 1)	Name of recovery spring	Trace number (from table 4)	Mass of dye injected (g) (from equation 2)	Apparent dye recovery (percent) (from equation 6)	Discharge (ft^3/s)	Mean travel-time of dye mass (hours) (from equation 10)	Apparent mean velocity (ft/s) (from equation 11)	Normalized peak dye concentration [(mg/L)/kg] (from equation 8)	Normalized peak dye load [(mg/s)/kg] (from equation 9)	Standard deviation of travel time of dye mass (hours) (from equation 12)	Longitudinal dispersion coefficient (ft^2/s) (from equation 13)
16	Dyers	17	2.38	172	4.72	6.05	0.138	1.12	150	1.48	3.10
16	Dyers	18	2.38	133	4.59	6.19	.135	1.55	201	.82	1.73
16	Dyers	19	3.57	55	1.35	14.6	.057	2.53	96.5	2.17	.58
16	Dyers	20	3.57	63	1.14	17.1	.049	1.88	60.6	4.37	.98
16	Dyers	21	2.38	58	.72	25.4	.033	2.23	45.5	3.69	.43
16	Dyers	22	2.38	54	.53	31.4	.027	2.48	35.1	4.68	.17
16	Dyers	26	7.14	112	2.88	7.18	.116	2.06	168	1.46	1.58
1	Elizabethtown	16	28.56	58	9.26	13.3	.240	.234	62.4	3.16	42.9
1	Elizabethtown	23	23.80	66	1.56	56.3	.057	.407	18.0	14.3	4.55
21	Stark's	24	47.60	90	.70	46.2	.043	.746	14.8	16.6	4.97

The apparent mean velocity of ground-water flow was calculated by the equation:

$$\bar{u} = \frac{x}{3600\ \bar{t}} \qquad \text{(eq. 11)}$$

where $\bar{u}$ = mean flow velocity, in ft/s;

3600 = a unit conversion factor; and

x = distance between the dye injection and recovery points, in feet.

Because the exact flow path between these two points is not known, x and $\bar{u}$ are apparent values, computed as if the dye followed a straight line between points. Thus, the actual flow velocity is somewhat greater than the apparent velocity because of the longer, meandering nature of the actual flow path.

The standard deviation of the traveltime of the dye mass is a measure of the amount of dispersion of the dye mass that has occurred. It is related to the traveltime and the rate of dispersion, and was computed by the equation:

$$\sigma_t = \left[\frac{\sum_{i=1}^{n} (t_i - t)^2\ C_i\ \Delta t_i}{\sum_{i=1}^{n} C_i\ \Delta t_i}\right]^{0.5} \qquad \text{(eq. 12)}$$

where σ_t = standard deviation of the traveltime of the dye mass, in hours.

The longitudinal dispersion coefficient is a measure of the rate at which the concentrated dye mass spreads out along the flow path, and is defined as the temporal rate of change of the variance of the dye-trace cloud (Fischer, 1968). In this report, dispersion is considered only in one dimension, and longitudinal dispersion is referred to simply as dispersion. Two methods of estimating the dispersion coefficient were compared. Both are based on equations presented by Fischer (1968), with the assumptions of constant velocity and uniform flow medium over the reach for the entire duration of the test. The first and more general equation is based on the definition of dispersion coefficient from a slug injection:

$$D_1 = \frac{3600}{2}\ \bar{u}^2\ \frac{\sigma_t^2}{\bar{t}} \qquad \text{(eq. 13)}$$

where D_1 = first dispersion coefficient, in ft^2/s.

The second equation is based on the further assumption that the dye-response curve is normally distributed, with zero skew. When sampled at the peak of the dye-trace curve,

$$C_{peak} = \frac{588.5}{A\sqrt{4\pi D_2\ t_{peak}}} \qquad \text{(eq. 14)}$$

where C_{peak} = peak of the normalized concentration curve, in mg/L/kg;

588.5 = a unit conversion factor;

π = 3.1416

D_2 = second dispersion coefficient, in ft^2/s;

t_{peak} = time to peak dye concentration, in hours from injection; and

A = the effective cross-sectional area of the flow medium, in ft^2, estimated by

$$A = \frac{Q}{\bar{u}} \qquad \text{(eq. 15)}$$

Based on equation 14, the second estimate of the dispersion coefficient was computed as:

$$D_2 = \frac{346{,}400}{4\,\pi\, t_{peak}\, (C_{peak}\, A)^2} \qquad \text{(eq. 16)}$$

where 346,400 = a unit conversion factor.

The true value of the dispersion coefficient is affected by the flow velocity and the characteristics of the flow medium. In a water body, the observed amount of dispersion is affected by turbulent forces as well as by simple dispersion, and the computed dispersion coefficient reflects the combination of both processes. In the case of simple dispersion alone, the dye cloud is normally distributed but the dye-recovery curve is expected to have a slightly positive skew. This slight skew results from the transformation of a dye cloud that is normally distributed logitudinally at any given time into a set of dye samples from a fixed location at different times. In other words, by the time the tail portion passes the sampling point, it has had more time to disperse, thus extending the tail of the observed curve. However, the skewness of the observed dye-response curves is much greater than that expected from this axis transformation. Most of the skewness, or long-tail, is not accounted for by simple dispersion alone, but results mainly from unequal flow lengths and velocities along and across the flowpath.

If the dye-recovery curve were normally distributed and adequately sampled, values of D_1 and D_2 computed from the curve would be equal. Because of the skewness, however, computed values of D_2 (from eq. 16) were smaller than computed values of D_1 (from eq. 13). When comparing dye-response curves, both coefficients give a relative idea of the rate of spread of the dye-cloud along the flowpath. Values of dispersion coefficients reported in later sections were arbitrarily selected to be D_2, computed from equation 16, because they were less sensitive to inadequacies in the sampling regime.

Interpretation of Dye-Trace Characteristics

For each quantitative dye trace, measured dye concentrations were adjusted for background, percent recovery was computed, and concentrations were normalized for a standard mass of dye. The graphs of normalized dye-recovery curves, or time-concentration curves, for the seven dye traces to Dyers Spring (site 16) are shown in figures 20 to 23. Similar graphs for the two dye traces to the Elizabethtown Spring (site 1) are shown in figure 24; and for the dye trace to Stark's Spring (site 21), in figure 25. All curves are positively skewed; they exhibit a relatively steep increase from background to peak followed by a more gradual return to the background concentration. The sampling interval during the first quantitative trace at Dyers Spring (trace 17, fig. 20) was not short enough to adequately define the dye peak, thus the resulting dye-recovery curve for this trace is not well defined.

Characteristics computed from the dye traces are given in table 7. As previously discussed, the apparent total recovery during several high-flow trials exceeded 100 percent. Differences in the length of the flow path and in discharge for the various traces complicate the interpretation of the results. Mean traveltime at Dyers Spring varied from 6 to 31 hours, depending on discharge, with corresponding standard deviations of 1.5 and 4.7 hours, respectively. Traveltimes at the Elizabethtown Spring and Stark's Spring were greater because of their longer flow paths.

Useful information for interpreting the hydrologic characteristics of ground-water flow in karst terrane can be obtained from the analysis of dye loads and dispersion determined from quantitative dye traces. To convert normalized dye concentration to normalized dye load, each concentration value is multiplied by the corresponding discharge. Plots of normalized dye load recovered at Dyers and Elizabethtown Springs are shown in figures 26 and 27, respectively. Areas under the curves are equal. As traveltimes increase and the dye cloud has more time to disperse, peak loads become smaller, the curves become less steep, and the time for the dye cloud to pass increases. All curves are similarly skewed, however, with a mean skewness coefficient of approximately 2.0.

Computed characteristics for the seven dye traces to Dyers Spring were examined to determine the relations among them and to determine which characteristics exert a controlling influence on the others. Because only two quantitative dye traces were completed to the Elizabethtown Spring and only one to Stark's Spring, similar quantitative relations were not derived for these sites. However, results from the two dye traces to the Elizabethtown Spring indicate that the dye-trace characteristics vary in the same manner as for the Dyers Spring dye traces.

Discharge is the controlling factor of the computed characteristics for the seven dye traces to Dyers Spring. The apparent mean velocity increases linearly with discharge (fig. 28). Mean traveltime is inversely proportional to the mean velocity (eq. 11) and, thus, is inversely proportional to discharge (fig. 29). The dispersion coefficients increase linearly with discharge (fig. 30), apparently because of the increased turbulence and mixing rate as velocity increases.

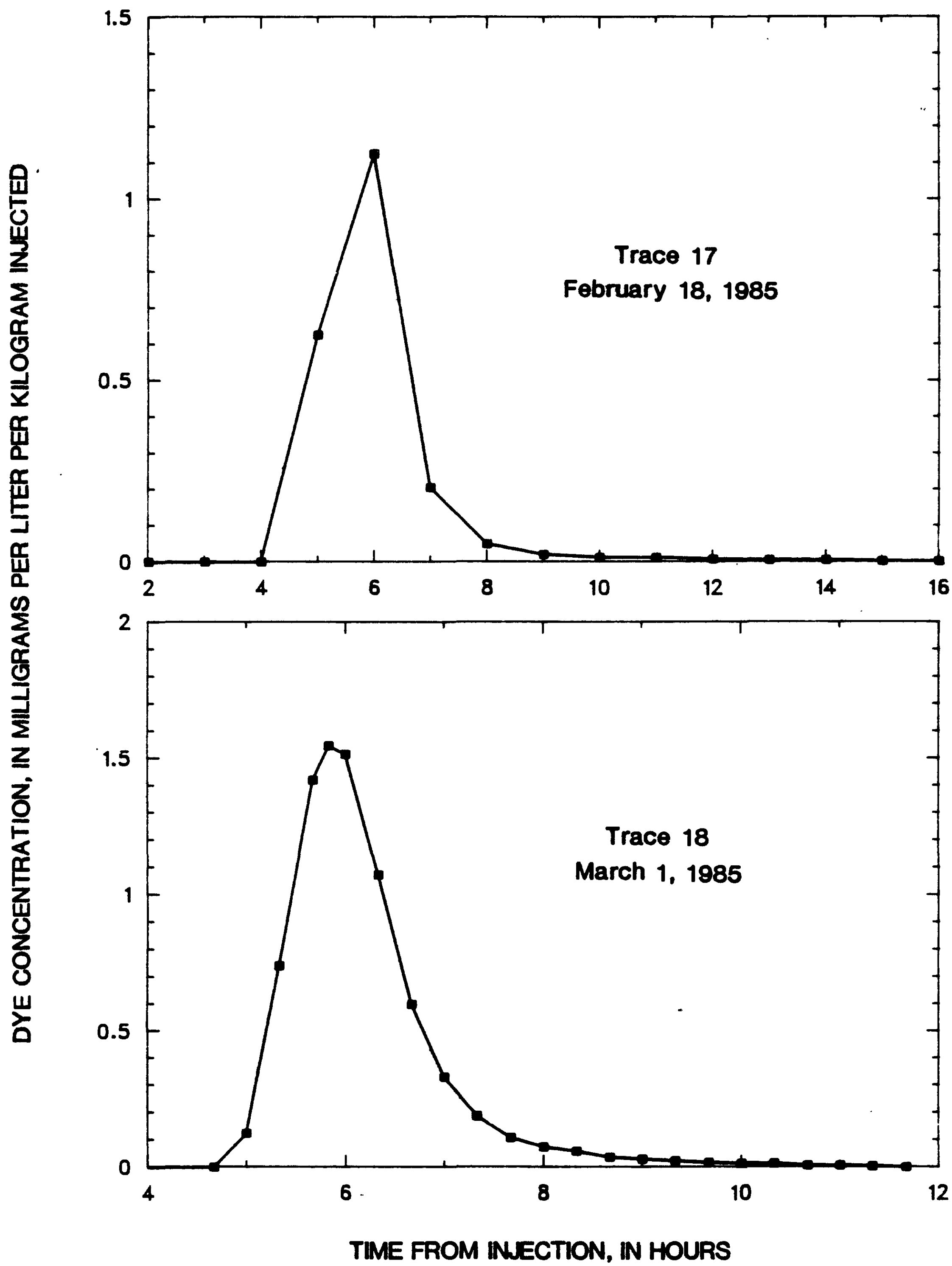


Figure 20.--Normalized dye recovery at Dyers Spring for traces begun February 18 and March 1, 1985.

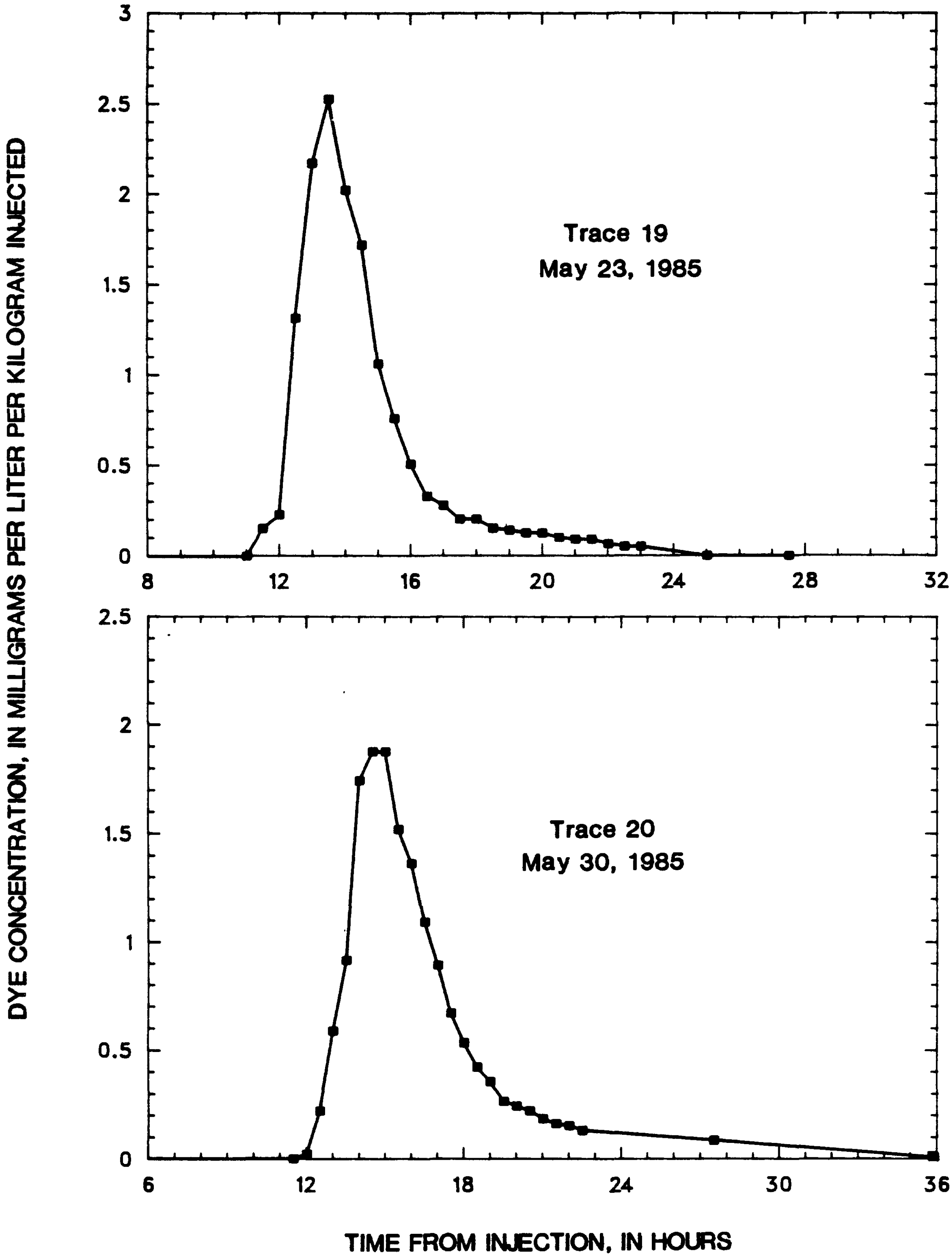


Figure 21.--Normalized dye recovery at Dyers Spring for traces begun May 23 and May 30, 1985.

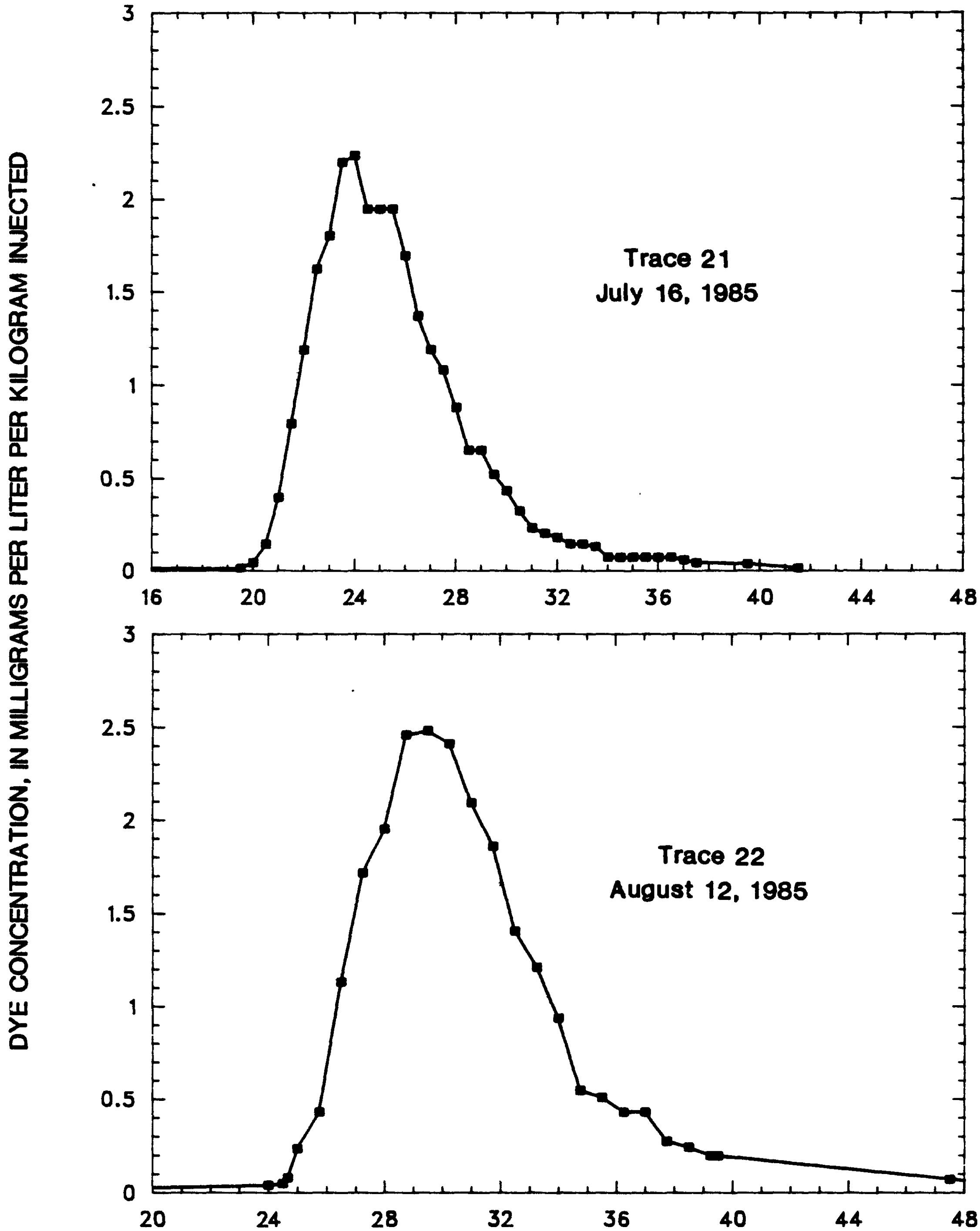


Figure 22.—Normalized dye recovery at Dyers Spring for traces begun July 16 and August 12, 1985.

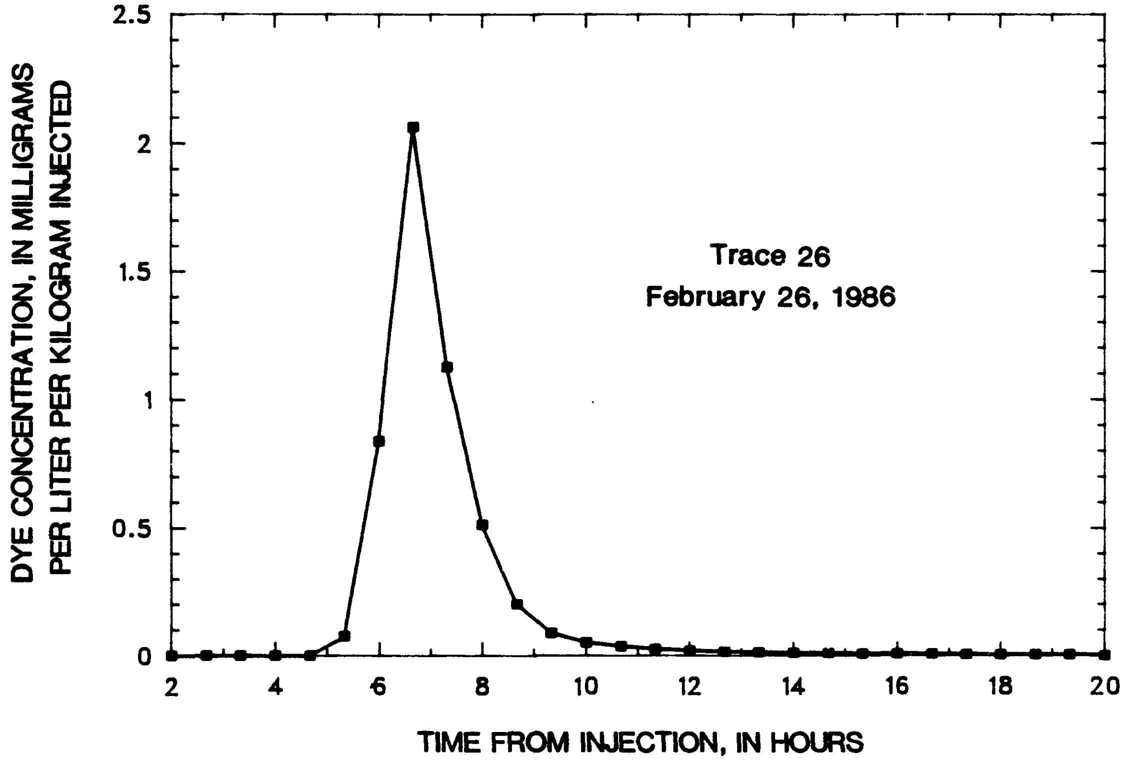


Figure 23.--Normalized dye recovery at Dyers Spring for trace begun February 26, 1986.

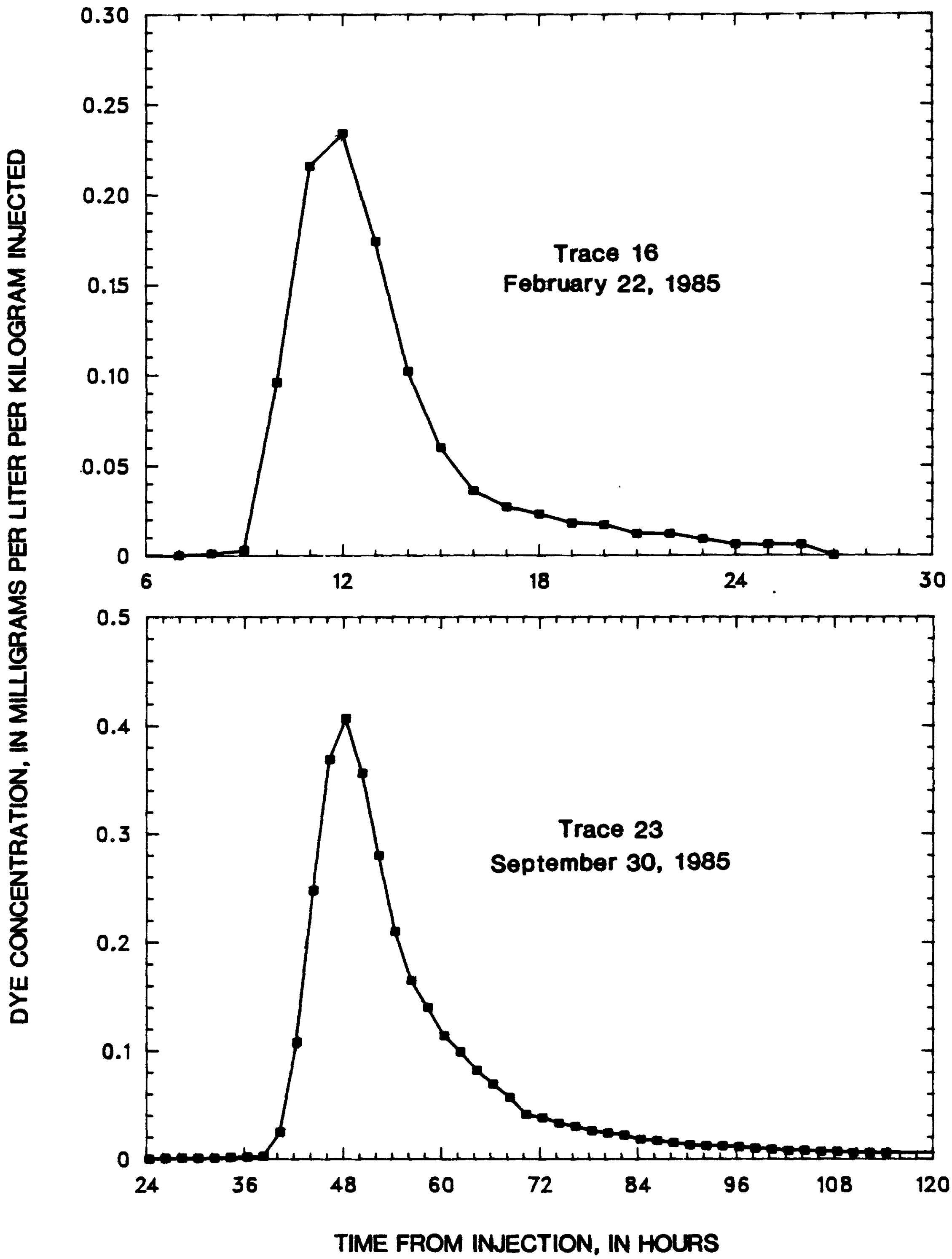


Figure 24.--Normalized dye recovery at Elizabethtown Spring for traces begun February 22 and September 30, 1985.

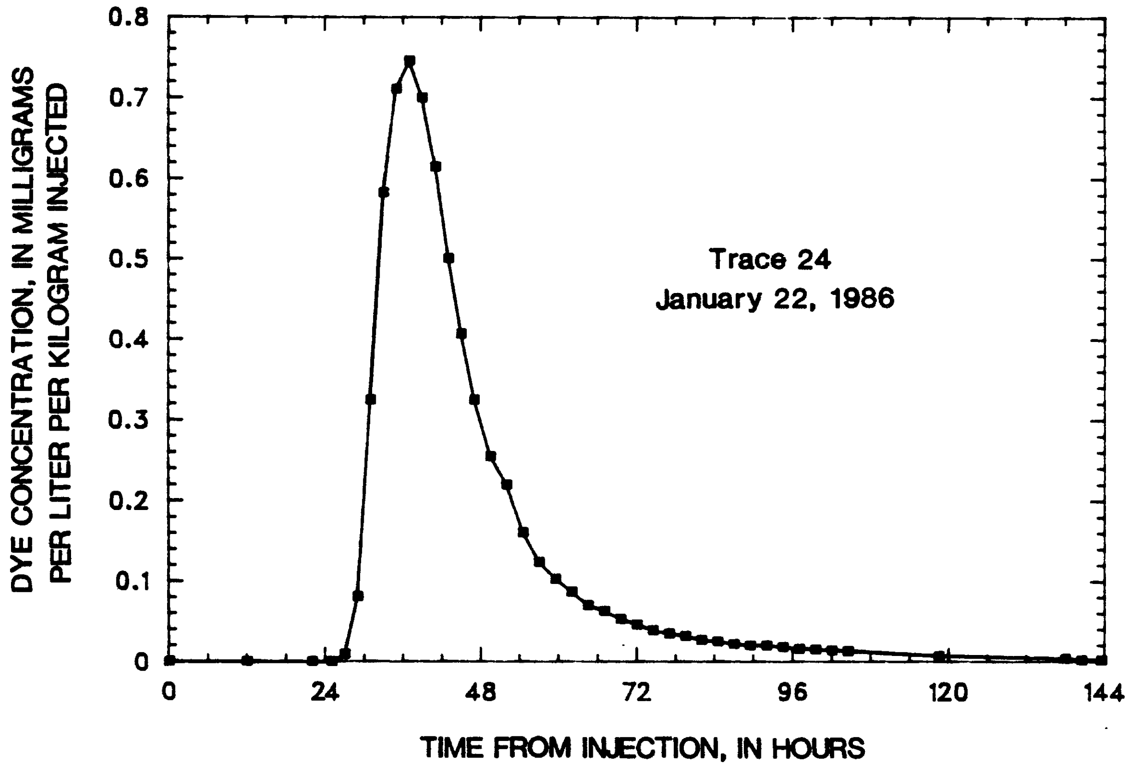


Figure 25.—Normalized dye recovery at Stark's Spring for trace begun January 22, 1986.

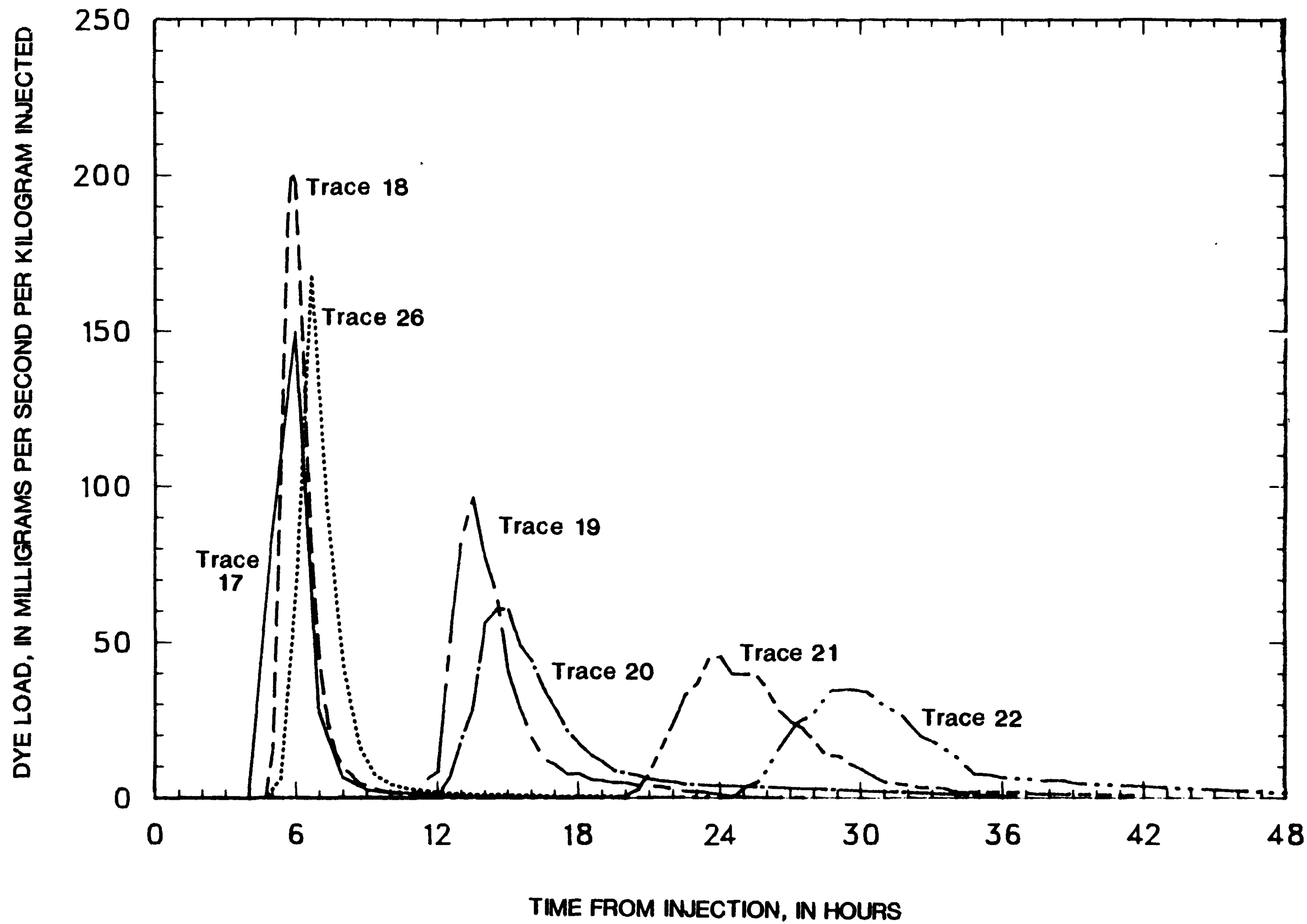


Figure 26.--Relation of normalized dye load to time from injection for seven dye traces to Dyers Spring.

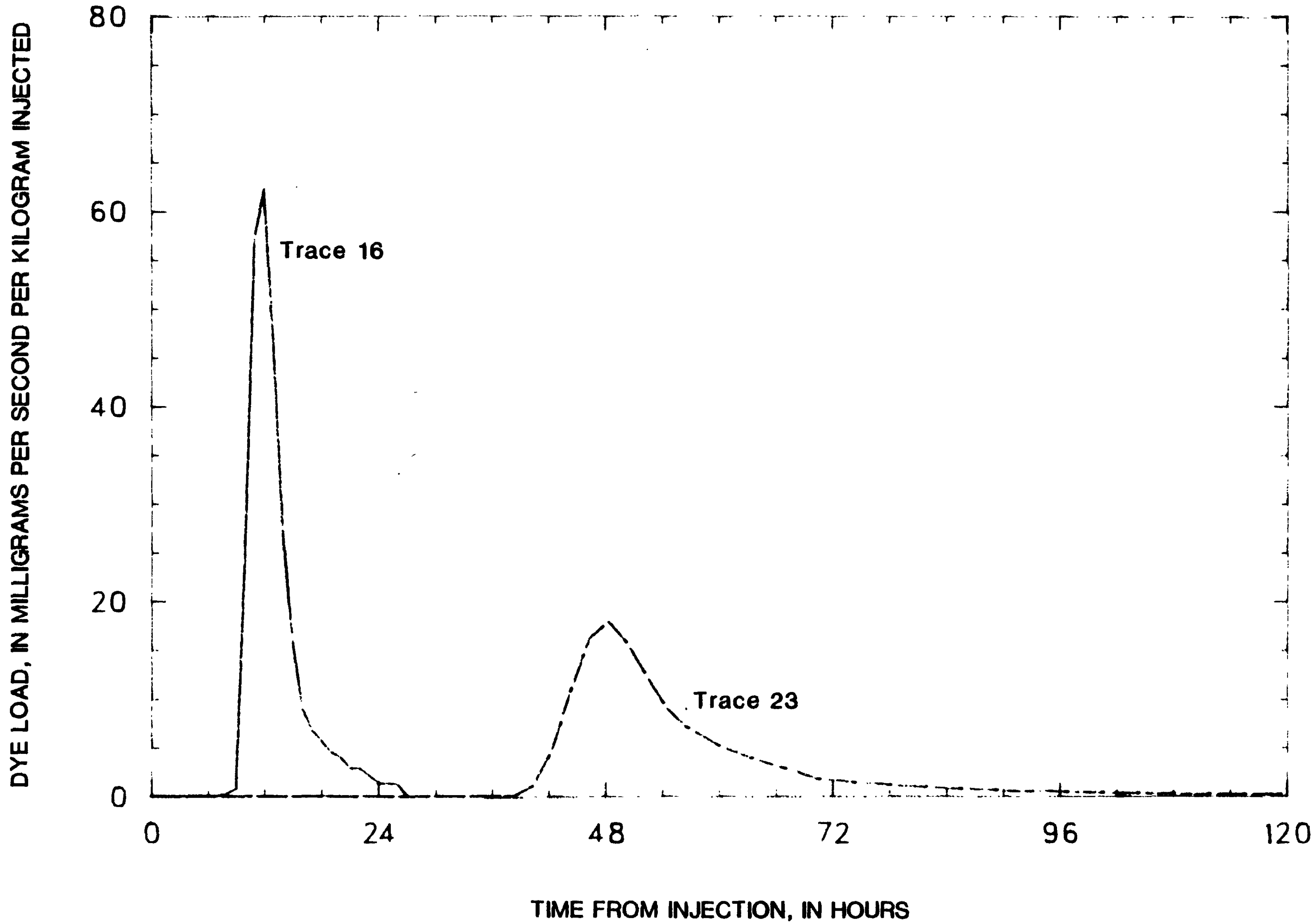


Figure 27.--Relation of normalized dye load to time from injection for two dye traces to Elizabethtown Spring.

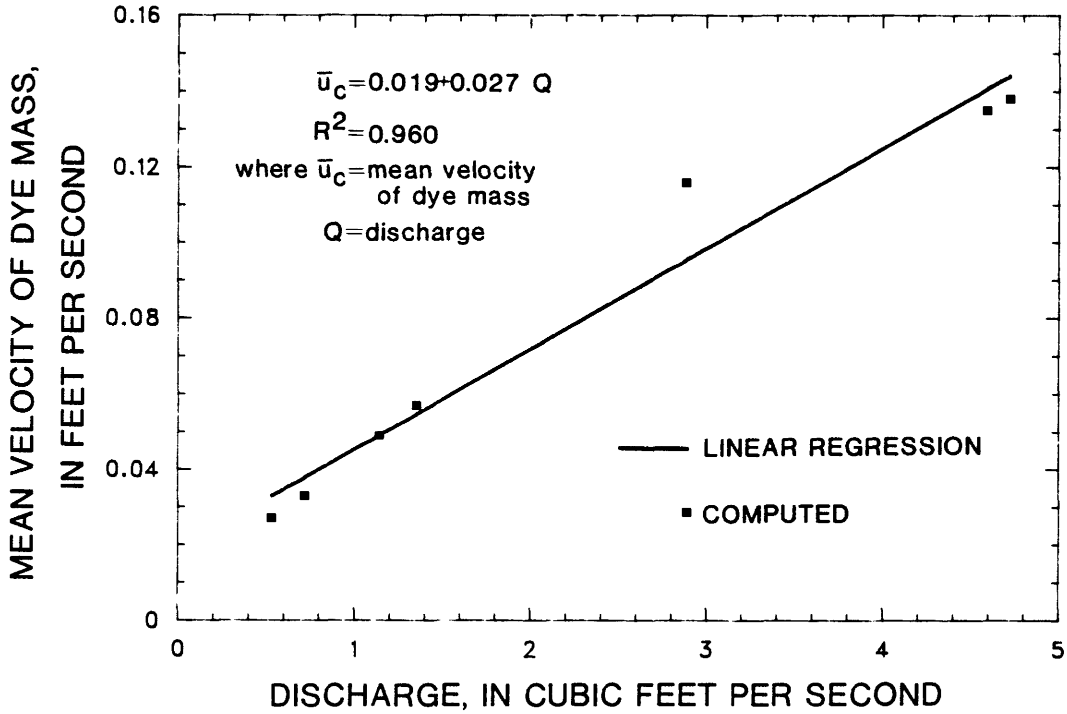


Figure 28.--Relation of apparent mean velocity of the dye mass to discharge at Dyers Spring.

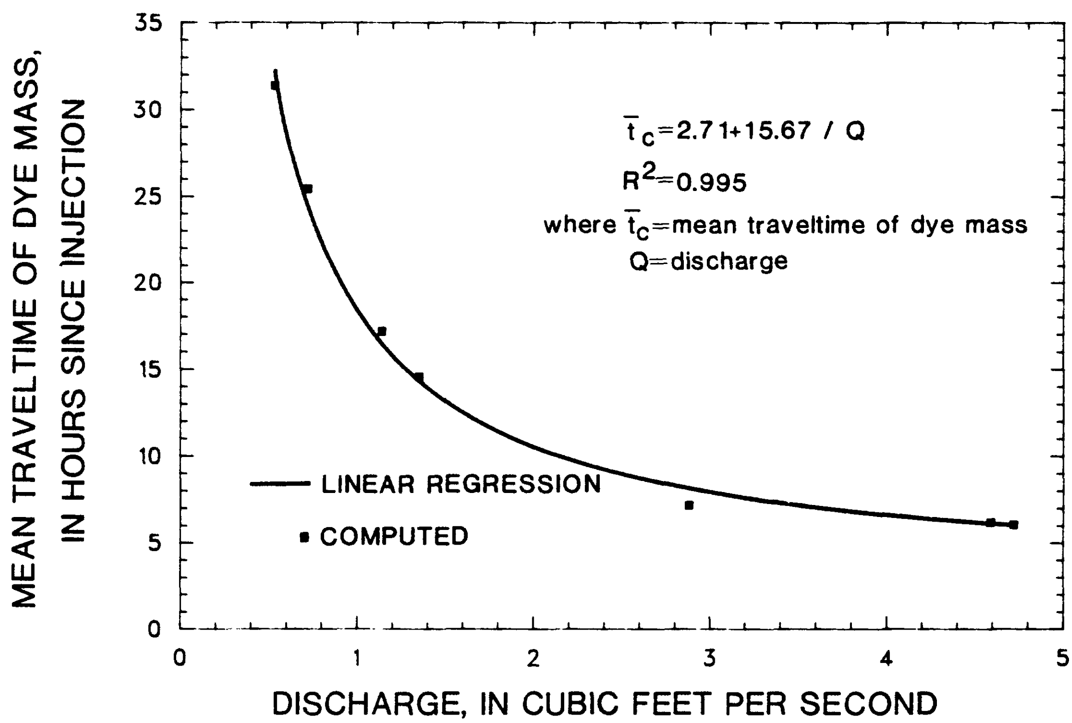


Figure 29.--Relation of mean traveltime of the dye mass to discharge at Dyers Spring.

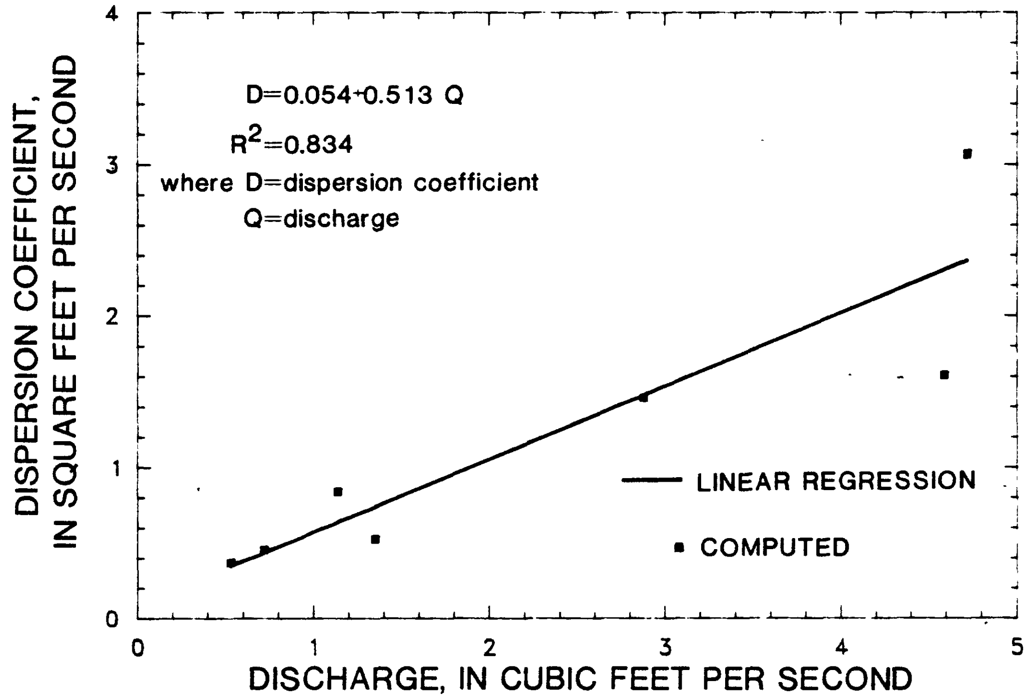


Figure 30.--Relation of dispersion coefficient to discharge at Dyers Spring.

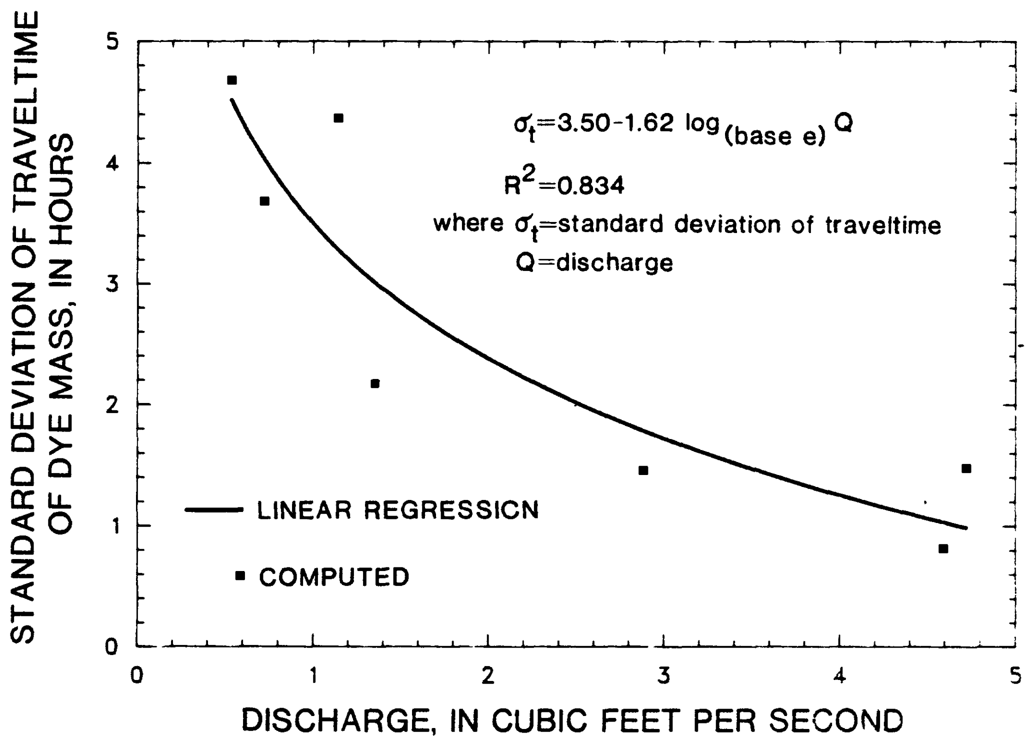


Figure 31.--Relation of standard deviation of traveltime of the dye mass to discharge at Dyers Spring.

These relations between discharge, mean traveltime, and the dispersion coefficient may be used to explain other dye-response characteristics. At greater discharge, traveltime decreases. Thus the dye cloud has less time to disperse, which tends to decrease the standard deviation. In the same circumstance, however, the dispersion coefficient increases; thus the dye cloud disperses more rapidly, which tends to increase the standard deviation. The net result of these contrary tendencies is that as discharge increases, standard deviation decreases (fig. 31), indicating that traveltime exerts a greater influence on the overall amount of dispersion than does the dispersion coefficient.

The normalized peak dye load is directly proportional to discharge (fig. 32). The effect of traveltime on peak load is opposite to and greater than the effect of the dispersion coefficient on peak load. However, because the area under the normalized time-load curves are equal, it follows that as the standard deviation increases, the peak value decreases. That is, at greater discharge, the mean traveltime is shorter, the standard deviation of traveltime is smaller, and the peak load, or mass flux, is greater.

The normalized peak dye concentration, or peak concentration, decreases as discharge increases (fig. 33). Although the mass flux, or momentary load, increases with discharge, the mass is diluted by the increased volume of water, resulting in an overall decrease in concentration. Thus, the peak concentrations, as well as time-concentration curves from the dye traces, may be considered to result from these complexly interacting factors that are controlled mainly by discharge.

Despite the differences between the the flow paths to Dyers Spring (site 16), the Elizabethtown Spring (site 1), and Stark's Spring (site 21), the relation of peak normalized dye load to mean traveltime is the same (fig. 34). Similarly, Kilpatrick and Taylor (1986) reported an inverse log-log relation between peak load and time to peak concentration. The relation of standard deviation of traveltime to mean traveltime also is roughly the same (fig. 35). These results indicate that, in the study area, the time rate of dispersion is relatively constant, and differences in the dispersion coefficient between dye traces are not of major significance. Rather, the amount of dispersion downstream is dependent mainly on the length of time since injection, which, in turn, is dependent on the travel distance and discharge.

In summary, as discharge increases among the dye traces, velocity increases and traveltime decreases. Although the rate of dispersion increases, this is outweighed by the decreased time in which the dye cloud has the opportunity to disperse. Thus the spread, or standard deviation of the dye cloud decreases and the peak of the dye load increases. Although the load, or mass flux increases, the concentration decreases because of dilution from the increased flow.

Dimensionless Recovery Curve

Simulations of dye recovery curves that are based on dispersion theory yield dye-cloud concentrations that are normally distributed along the flow path. Transformation of a normally-distributed dye cloud at a given time in to a set of dye samples from a fixed location will introduce a slight positive

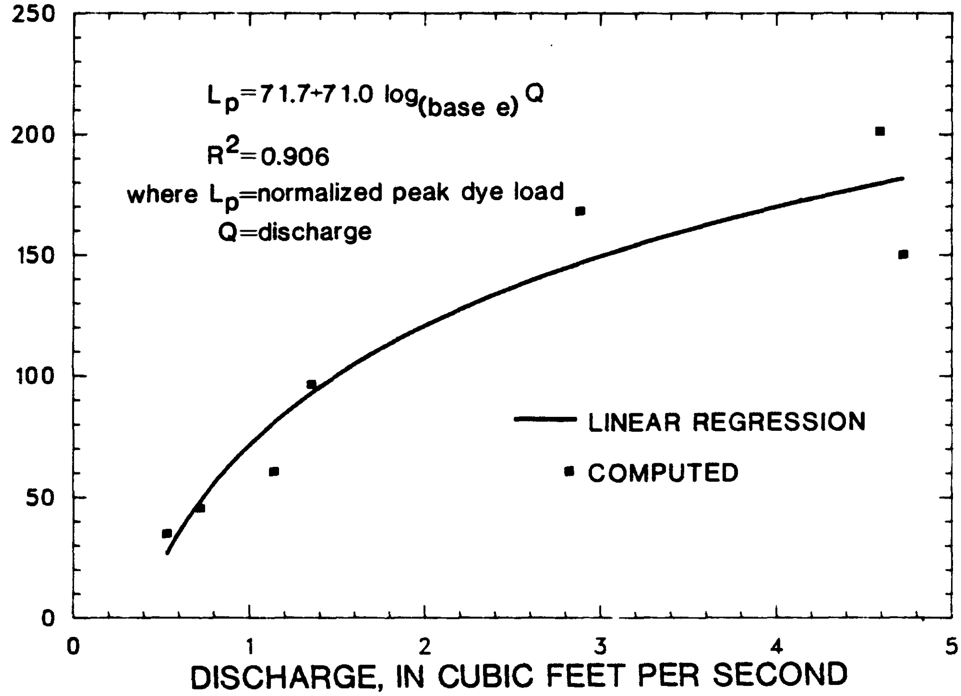


Figure 32.--Relation of normalized peak dye load to discharge at Dyers Spring.

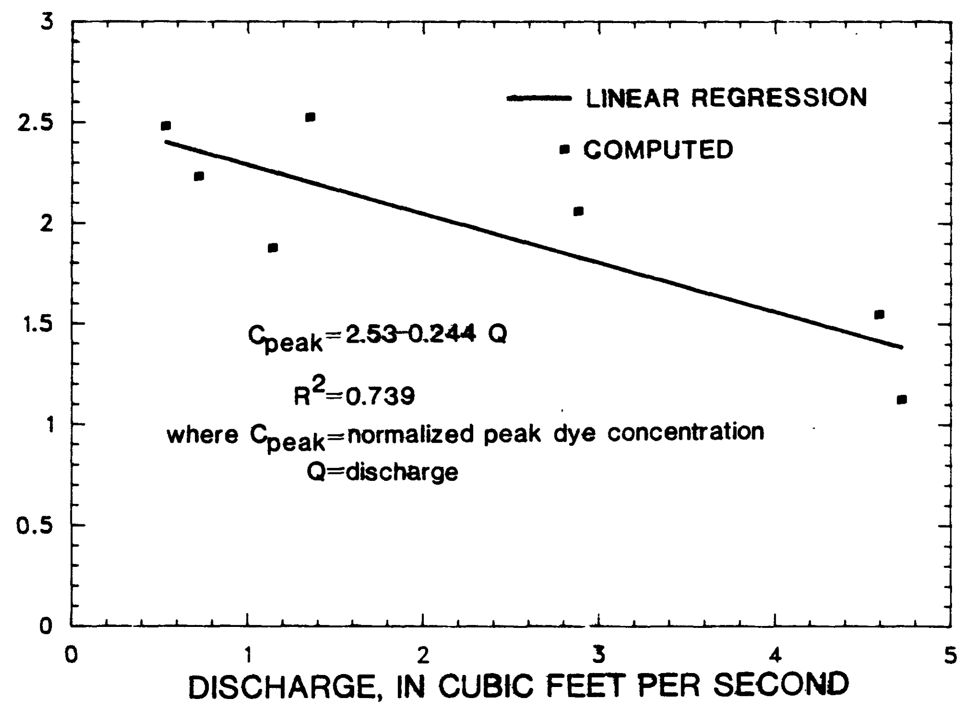


Figure 33.--Relation of normalized peak dye concentration to discharge at Dyers Spring.

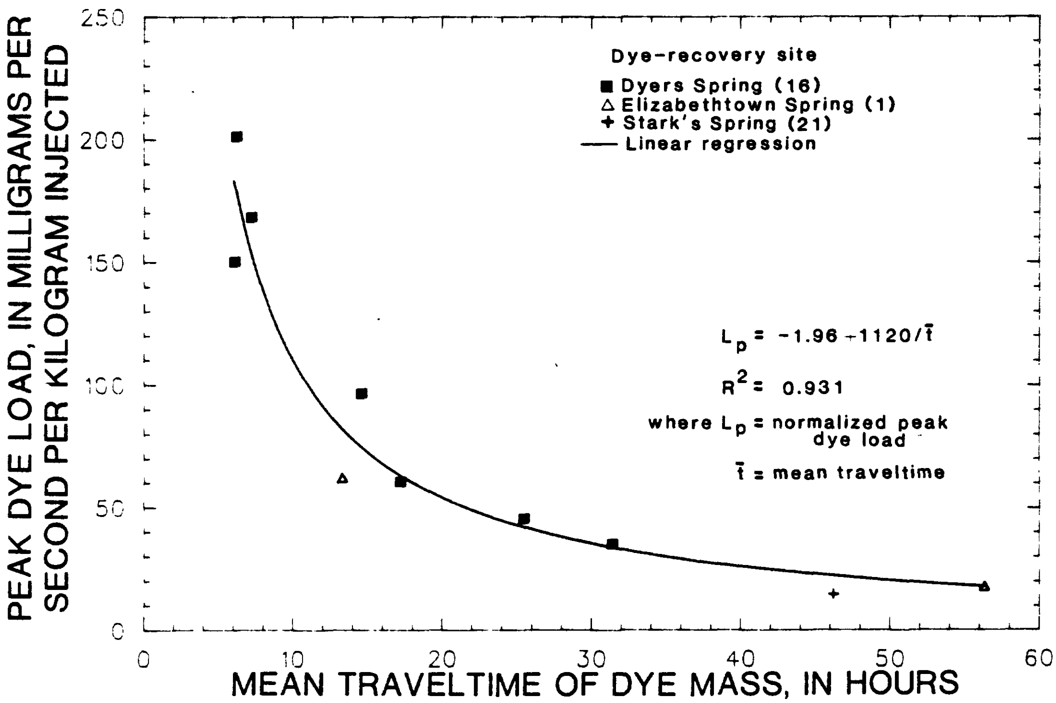


Figure 34.--Relation of normalized peak dye load to mean traveltime of the dye mass at Dyers, Elizabethtown, and Stark's Springs.

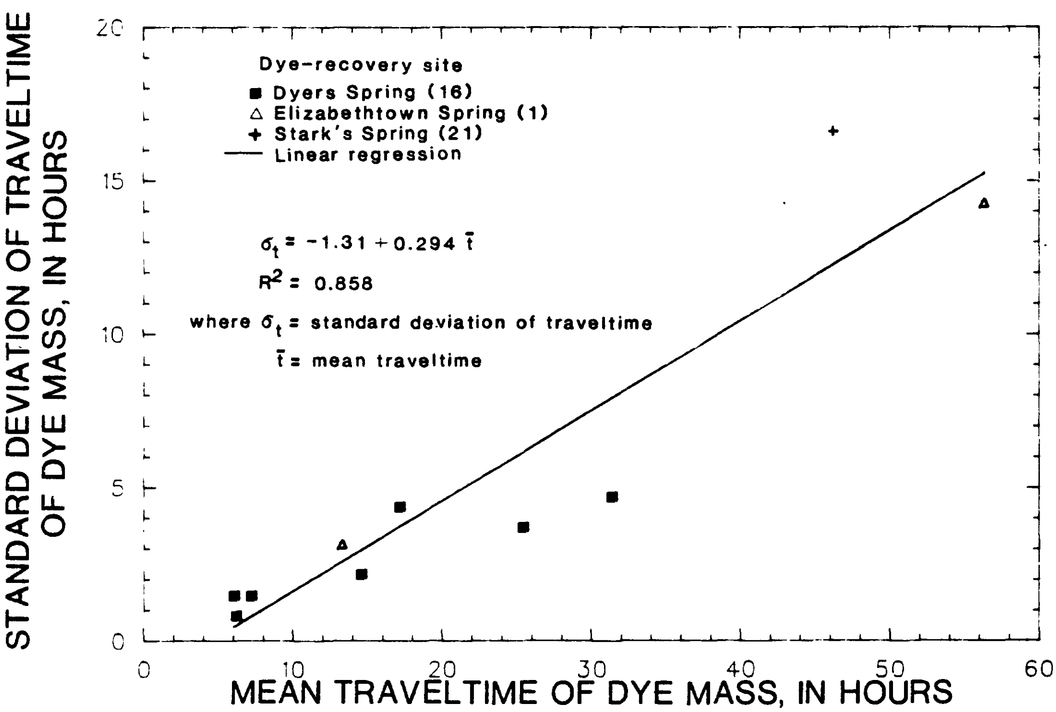


Figure 35.--Relation of standard deviation of traveltime to mean traveltime of the dye mass at Dyers, Elizabethtown, and Stark's Springs.

skewness but will not adequately reproduce the skewed shape of observed time-concentration curves. The skewed shape results mainly from unequal flow lengths and velocities along and across the flow path. Kilpatrick and Taylor (1986) used scalene triangles to approximate the skewed shape of the dye-response curves for streams. Because the general shape of all observed curves in the Elizabethtown study were similar, a standardized recovery curve was developed to simulate time-concentration curves for the study area. The curve was derived by compositing the dye-recovery curves shown in figures 21 through 24 into a single, representative dimensionless curve, with a resulting skewness coefficient of 2.0. The dimensionless recovery curve is shown in figure 36. Time may be derived along the X-axis as the number of standard deviations away from the mean traveltime. Concentration may be derived along the Y-axis as the proportion of the peak concentration.

If the values of mean traveltime, standard deviation of traveltime, and peak concentration are known or can be estimated, then a simulated curve may be derived from the dimensionless recovery curve. For the flow path between the karst window (site 15) and Dyers Spring (site 16), sufficient data exist that these three values may be estimated based only on the discharge at the spring (figs. 29, 31, and 32, respectively). For example, a dye recovery curve, simulated from these discharge relations and the dimensionless recovery curve, compares closely to the measured dye-recovery curve (trace 20) for Dyers Spring on May 30, 1985 (see fig. 37). An example of the predictive use of the dimensionless recovery curve is presented in the following section.

PREDICTIVE USES OF QUANTITATIVE DYE TRACING

Given the characteristic vulnerability of karst aquifers, it is critical that the manager of a water system served by a karst aquifer have the capability to predict flow characteristics of the aquifer. This capability is needed in order to develop necessary preventative measures and to be prepared to take emergency actions in case of contamination of the karst aquifer.

Once quantitative relations are known for a given ground-water flow path between an injection and resurgence point, the time variation of concentration for a given injection may be predicted. Because dye used for tracer studies behaves in the same way as conservative soluble contaminants, this technique has practical applications; including, for example, prediction of the time-concentration curve resulting from a contaminant spill.

The connection between the karst window and Dyers Spring was initially determined by qualitative dye tracing. However, repeated quantitative traces were used to derive flow characteristics that can be used for predictive purposes by the water manager. An application of the results of quantitative dye tracing to the prediction of flow characteristics of potential contaminants follows.

To illustrate the application of dye tracer studies for water management purposes in the Elizabethtown area, assume that 15 gallons of 5-percent copper sulfate solution is accidentally spilled and enters the karst window (site 15). Because copper sulfate is a common agricultural chemical this is not an unrealistic example considering the location of the karst window relative to adjacent farmlands. The quantity spilled contained 1.13 kg of copper. In

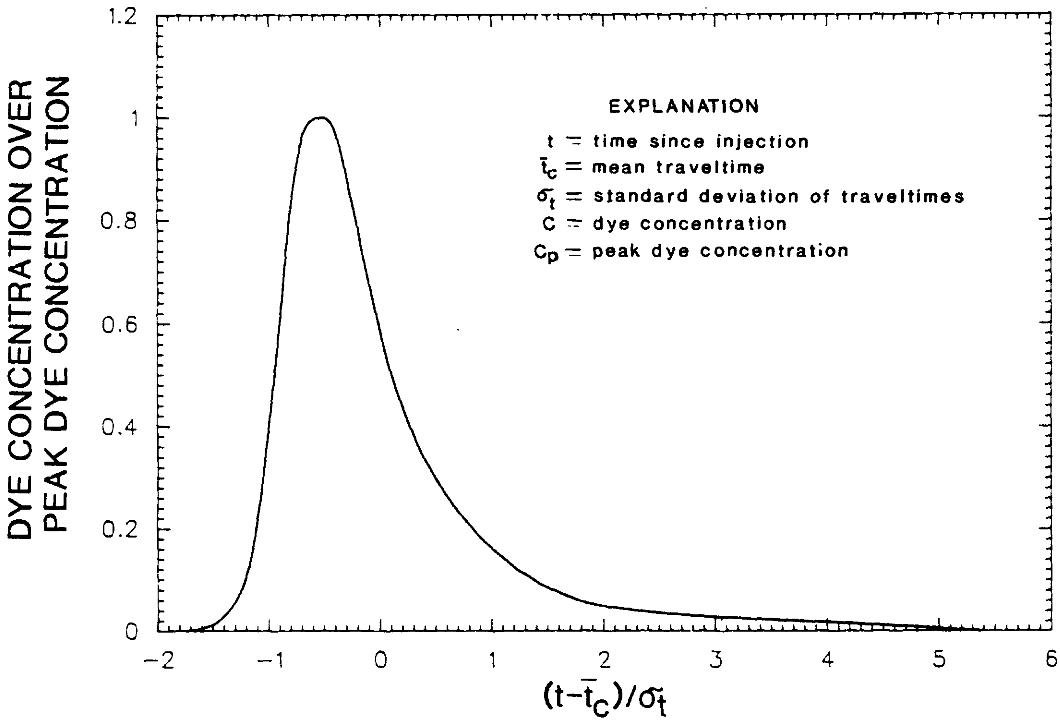


Figure 36.--Dimensionless dye-recovery curve.

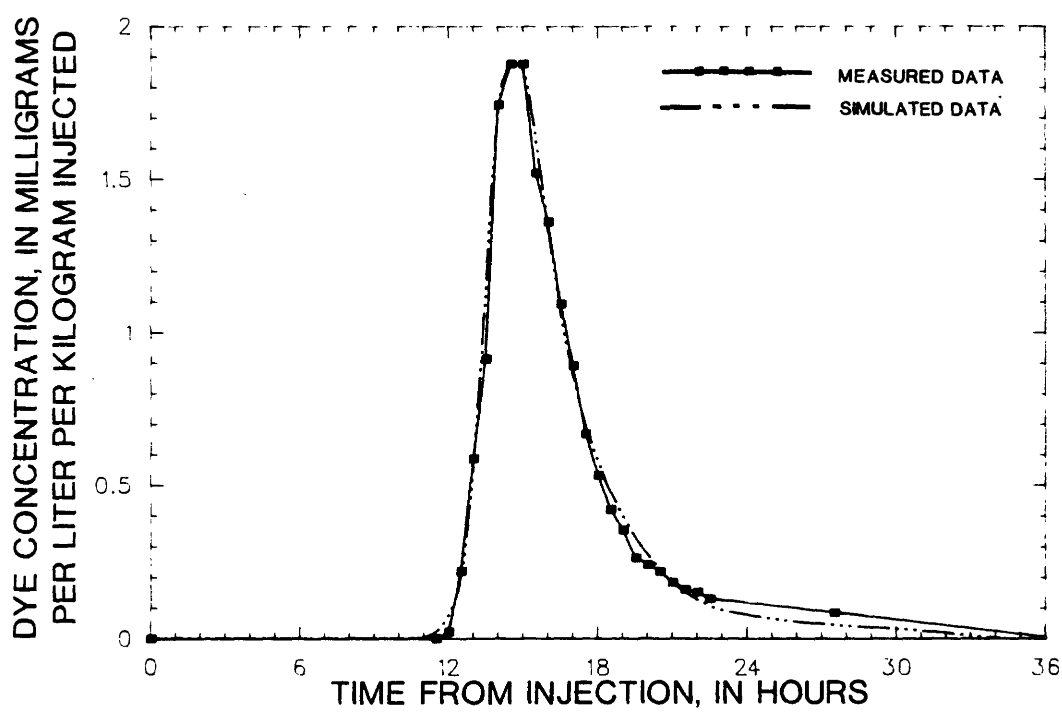


Figure 37.--Comparison of simulated dye-recovery curve to measured data for trace 20 to Dyers Spring, begun May 30, 1985.

order to respond to the spill, such as changing water-treatment processes or stopping use of the spring until the contaminant has drained from the aquifer, the water manager needs to know the effect of the spill at Dyers Spring (site 16), which supplies water to Elizabethtown. The drinking-water supply quality criteria for copper is 1.0 mg/L (U.S. Environmental Protection Agency, 1986).

The discharge of Dyers Spring for this example is 0.9 ft^3/s. From the relations developed (figures 29, 31, and 33), the following values are estimated: mean traveltime, 20.1 hours; standard deviation of traveltime, 3.67 hours; normalized peak concentration, 2.31 milligrams per liter per kilogram of contaminant. Because 1.13 kg of copper was spilled in this example, the estimated peak concentration expected at the spring is 2.61 mg/L. Using these values in combination with the dimensionless type curve (fig. 36), the time-concentration response to the spill at Dyers Spring can be simulated (fig. 38). On the basis of this curve, the leading edge of the contaminant mass will arrive about 14 hours after the spill, reach peak concentration of 2.6 mg/L 4 hours later, and decrease to 2 percent of the peak concentration 16 hours later. The contaminant is virtually nondetectable about 40 hours after the spill. From the simulated dye-response curve, the drinking-water supply criteria would be exceeded for approximately 4.8 hours, beginning 16 hours after the spill. It should be pointed out that these values are only estimates, and are based on the assumption that the copper moves with the same velocity as the ground water (and dye). These techniques can be a useful tool for emergency response to spilled contaminants in karst terrane such as the Elizabethtown area.

SUMMARY

1. The principal aquifer in the Elizabethtown area consists of nearly horizontal beds of limestone with thin beds of shale of Mississippian age. Bedrock is overlain by unconsolidated residuum and surficial deposits that are a source of ground-water recharge to the bedrock aquifer. The area is a typical mature karst terrane with sinkholes, springs, karst windows, and losing and sinking streams.

2. As much as 65 percent of all water withdrawn for city water supply is obtained from two springs and two wells that obtain water from openings in carbonate rocks that have been enlarged by circulating water. Ground water moves by diffuse and conduit flow in bedrock and in overlying unconsolidated deposits. Conduit flow is the principal method of ground-water transport to the major springs and public and industrial water-supply wells.

3. Both water-supply springs are the natural discharge points for separate ground-water basins. Discharge from both springs is flashy with peak discharge usually occurring within one day, or less, of the peak precipitation event. The stage-discharge relation has been defined for discharges less than 28.0 ft^3/s at the Elizabethtown Spring and for discharges less than 5.93 ft^3/s at Dyers Spring.

4. Sinkholes, losing and sinking streams, and karst windows provide a direct path for contaminants to enter the ground-water system. The drain at the bottom of sinkholes may be open or plugged with unconsolidated sediment. Open drains or swallets have the greatest potential for the rapid introduction of potential contaminants. Sinkholes and karst windows with open swallets

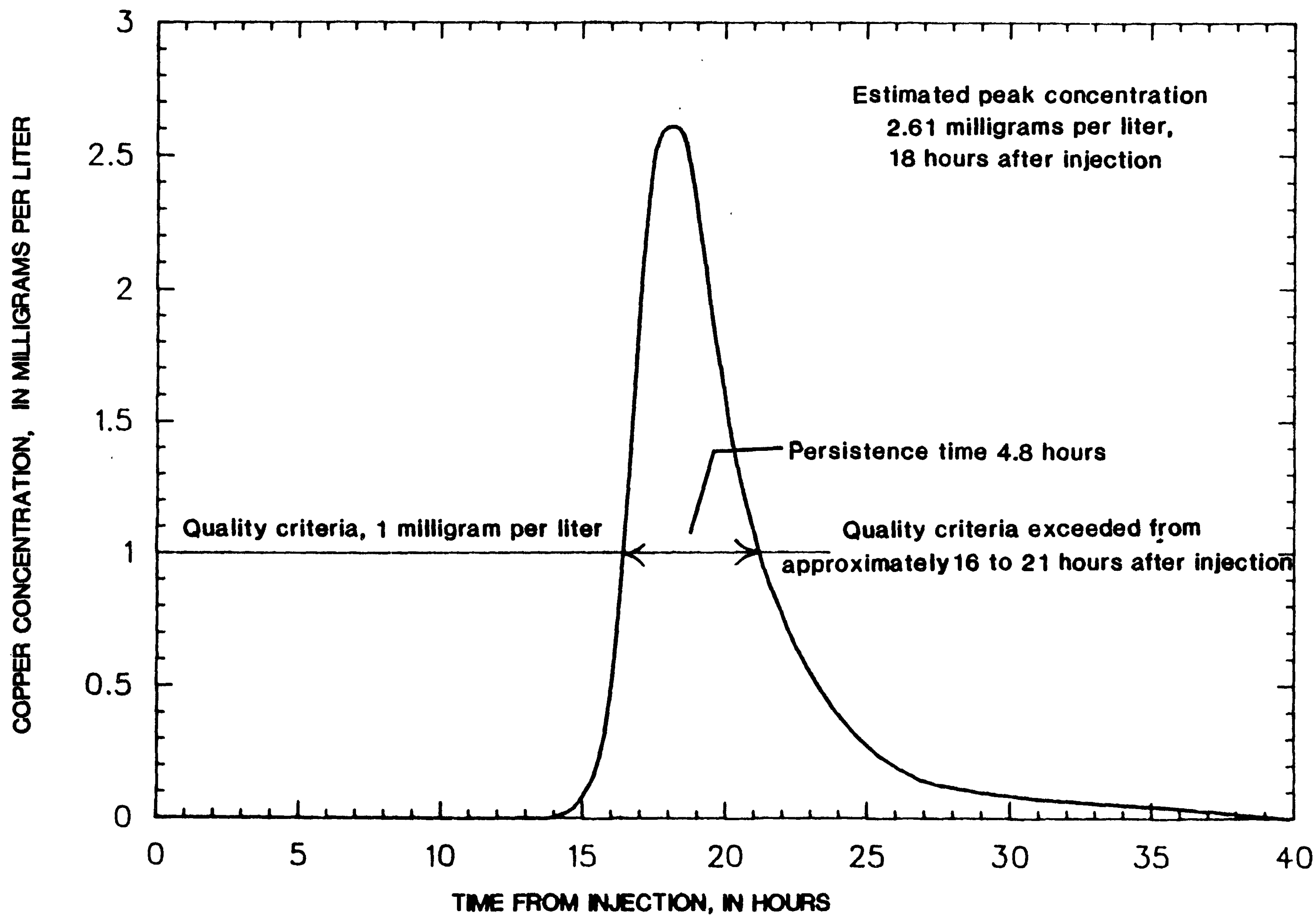


Figure 38.--Estimates of traveltime, persistence, and peak concentration of copper from a hypothetical spill near Dyers Spring, based on discharge and the dimensionless dye-recovery curve.

drain much of the rural and urban area and major transportation routes in the study area.

5. Qualitative dye tracing identified point to point connections between selected sinkholes, sinking streams, and karst windows and the city water-supply springs and wells. Qualitative dye tracing confirmed that the major recharge area for each city spring lies east of the springs and that their ground-water basins are not interconnected under the high- and low-flow conditions observed during this study. Major recharge points to the Elizabethtown Spring are a sinking stream located about 11,500 feet east of the spring and a cave that receives runoff from the interchange between I-65 and the Western Kentucky Parkway. Dyers Spring, the other water-supply spring, is connected to a karst window about 3,000 feet east of the spring. The karst window receives drainage from nearby farmland and apparently from a sinkhole 3,000 feet to the east. The area between the sinkhole and karst window is traversed by the Western Kentucky Parkway.

6. The presence of infiltrated water from Valley Creek in both city water-supply wells was confirmed by qualitative dye traces. Valley Creek and its tributaries drain the entire Elizabethtown urban area.

7. Qualitative dye tracing also confirmed that the general direction of ground-water flow, as shown by a water-level contour map, is from the west, north, and east to the vicinity of the city wells and springs south of Elizabethtown.

8. Quantitative dye traces between the same injection and recovery points described the flow characteristics under different flow conditions. Quantitative dye traces were completed between sinkholes and sinking streams to both city water-supply springs and one unused spring. The most rapid apparent ground-water velocity based on straight-line movement between the dye-injection point and the spring was 24 ft/min during a storm-water trace to the Elizabethtown Spring. Analysis of the dye-recovery data from repeat traces to Dyers Spring during different flow conditions in combination with spring discharge measurements showed that the arrival time of the leading edge of the dye cloud ranged from 5 to 24 hours and that the mean traveltime ranged from 6 to 31.4 hours for discharges ranging between 4.59 to 0.53 ft^3/s, respectively. The interval between the leading edge and peak concentration of the dye cloud was as small as 48 minutes.

9. Additional analysis of the dye-recovery data showed that discharge is the controlling factor for many transport characteristics. Based on seven traces, the apparent mean velocity, dispersion coefficient, and the standard deviation of traveltime appears to increase linearly with discharge. The mean traveltime is inversely proportional to discharge. The spread of the dye recovery curve and the peak dye load are mainly functions of the elapsed time since dye injection. These relations were used to produce a dimensionless recovery curve that can be used to develop predictive capabilities for estimating the arrival time, peak concentration, and persistence of a potential contaminant that might enter a sinkhole draining to one of the springs used for a public water supply.

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