USE OF DYE TRACING TO DETERMINE THE DIRECTION OF GROUND-WATER FLOW IN KARST TERRANE AT THE KENTUCKY STATE UNIVERSITY RESEARCH FARM NEAR FRANKFORT, KENTUCKY

By D. S. Mull

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4063

Prepared in cooperation with the

KENTUCKY STATE UNIVERSITY

Louisville, Kentucky

1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
District Office
2301 Bradley Avenue
Louisville, KY 40217-1807

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425, Mail Stop 517
Federal Center
Denver, CO 80225-0425

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND MISCELLANEOUS ABBREVIATIONS

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
foot per minute	0.3048	meter per minute
gallon	3.785	liter
gallon per minute	0.06308	liter per second
mile	1.609	kilometer
acre	0.4047	hectare
square mile	2.590	square kilometer
gram	0.001	kilogram
pound	0.454	kilogram

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

Miscellaneous abbreviations:

ppb - parts per billion
mL - milliliter

The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or the Kentucky State University.

USE OF DYE TRACING TO DETERMINE THE DIRECTION OF GROUND-WATER FLOW IN KARST TERRANE AT THE KENTUCKY STATE UNIVERSITY RESEARCH FARM NEAR FRANKFORT, KENTUCKY

by D.S. Mull

ABSTRACT

A series of dye-tracer tests were performed to trace the movement of surface runoff entering a karstic ground-water flow system through open swallets located upgradient from a large pond used for aquaculture research in central Kentucky. Generally, the surface-water component of farm-pond recharge is easily identified; however, the ground-water component generally is less obvious and can be poorly understood, especially in karst terrane where the direction of ground-water flow can differ from that of surface runoff. A total of five dye-tracer tests, using qualitative tracing techniques, were attempted during different hydrologic conditions. Dye monitoring was done at 22 springs and streams that generally encircle the dye-injection sites. Dye injected in one swallet during dry weather was detected in water from a spring that issues from a hillside and drains to the research pond. During wet weather, dye from a different swallet flowed to a spring that drains into a stream at the eastern border of the farm. Results of these dye-tracer tests indicate that the research pond is vulnerable to potential contamination from agricultural chemicals applied to fields in the watershed above the pond and also surface runoff that drains into the ground-water flow system can affect the surface-water quality of nearby streams.

INTRODUCTION

The agriculture industry is beginning to test and evaluate production systems that strike a balance between crop yield and resource protection. Such systems have been typically called "sustainable" agriculture. The Kentucky State University (KSU) research farm has been established to test and demonstrate best-management practices for sustainable agriculture at the typical scale and economy of the small, or limited resource, family farm.

Activities at the KSU research farm include management of a pond for aquaculture research. Aquaculture is frequently recommended as an income-producing component of the family farm. However, chemicals, such as fertilizers and pesticides can have adverse effects on the water quality and biological integrity of farm ponds. Agricultural chemicals can enter ponds by way of direct surface runoff or in ground-water recharge to a pond. Generally, the surface-runoff component of farm-pond recharge is easily identified. However, the ground-water component generally is less obvious and can be poorly understood, especially in karst terrane where the direction of ground-water flow can differ from that of surface runoff. Consequently, in 1990, the U.S. Geological Survey (USGS), in cooperation with KSU, began a study to define the directional trend of the ground-water flow and to identify the eventual resurgence of surface runoff that enters the subsurface through swallets (land-surface drains) topographically upgradient from a large pond used for aquaculture research.

Purpose and Scope

The primary purpose of this report is to present the results and interpretation of dye-tracer tests at the KSU research farm. The report also explains the methods and procedures of qualitative dye tracing used during this study. Dye-input sites were limited to the watershed upgradient of a large pond used for aquaculture research at the KSU research farm. Although dye-monitoring sites were concentrated on the farm, a few were as far as 2.5 miles from the farm. The more distant dye-monitoring sites were added to the dye-monitoring network to ensure that all potential discharge points from the drainage basin were monitored, especially during the early study phase when the direction of subsurface flow was not known.

The definition of the recharge area of a particular ground-water basin draining to a particular pond or spring was not within the scope of this investigation. The qualitative dye-tracer tests were designed and implemented only to identify the resurgence of ground-water flow from a particular swallet or sinkhole.

Previous Investigations

The geology and ground-water resources of the study area are discussed in several published reports. The earliest hydrogeologic study was by Matson (1909). Hall and Palmquist (1960) describe the availability of ground water in part of the Blue Grass region of Kentucky which includes Franklin County. Palmquist and Hall (1961) provide general information on the hydrogeology and ground-water resources of the Blue Grass region of Kentucky, an area of approximately 11,300 square miles. The USGS published a detailed geologic map at the scale of 1:24,000 for the Lawrenceburg quadrangle (Cressman, 1972) that includes the study area. Thrailkill (1985) presents a detailed discussion of the ground-water hydrology of the Inner Blue Grass region of Kentucky and the use of dye tracings to define 38 ground-water basins in the Inner Blue Grass region of Kentucky. He also includes a detailed discussion of the various factors that influence ground-water flow, ground-water basin development, and the nature and development of the hydrogeologic system.

Acknowledgments

The author is grateful to the many individuals who granted access to their property for the purpose of inspecting springs, streams, and sinkholes. Personnel at the KSU research farm provided a water tank and hauled water for dye injection, collected and installed dye detectors, and measured

precipitation during the period of dye-tracer tests. The assistance and cooperation of these individuals contributed significantly to the investigation.

DESCRIPTION OF STUDY AREA

Location and Extent of Study Area

At the time of this study, the KSU research farm included about 153 acres, about 5 miles southwest of Frankfort, in western Franklin County, central Kentucky (fig. 1). The farm includes a watershed of approximately 50 acres, part of which drains to a small (upper) pond and ultimately to a large (lower) pond (fig. 2) used for aquaculture research. The research farm is drained by unnamed tributaries to Little Benson Creek which empties into the Kentucky River about 1 mile east of the study area.

Physiography

The study area lies in the Inner Blue Grass physiographic subdivision of the Lexington Plain section of the Interior Low Plateaus physiographic province (Fenneman, 1938, p. 428). Most of the research farm is on a gently rolling upland with low relief; however, incised stream valleys, as deep as 250 feet below the uplands, exist near the eastern and southern boundaries of the farm. All streams flow on bedrock except in the headwaters.

The study area is underlain by relatively thin-bedded soluble limestone that is interbedded with beds of shale and siltstone. Consequently, sinkhole development, sufficient to be shown by topographic contours, has not occurred. Field inspection shows the presence of topographic depressions (sinkholes) on the research farm. Some of the sinkholes have open swallets through which surface runoff can drain directly to the ground-water system. This is true not only for the research farm but for most of the area in the northeastern quadrant of the Lawrenceburg 7 1/2-minute topographic quadrangle.

Sinkholes and springs are common karst features in the study area. For the most part, sinkholes form as a result of the subsidence of unconsolidated surface material into solution-enlarged openings in the underlying bedrock. Generally, sinkhole development is controlled by the thickness of soil cover and the growth, development, and interconnection of subsurface openings. This same network of subsurface openings provides conduits for the rapid infiltration of surface water that creates a high potential for ground-water contamination.

The potential for contamination from surface runoff is enhanced where open swallets are present in the bottom of sinkholes. The sinkhole funnels surface runoff to the open swallet that drains directly into the ground-water system. Runoff can enter ground water without filtration or other water-quality enhancement that can occur where water drains through a soil plug at the bottom of the sinkhole. Several sinkholes with open swallets are in the field above the upper pond in the study area. In addition to open swallets, several

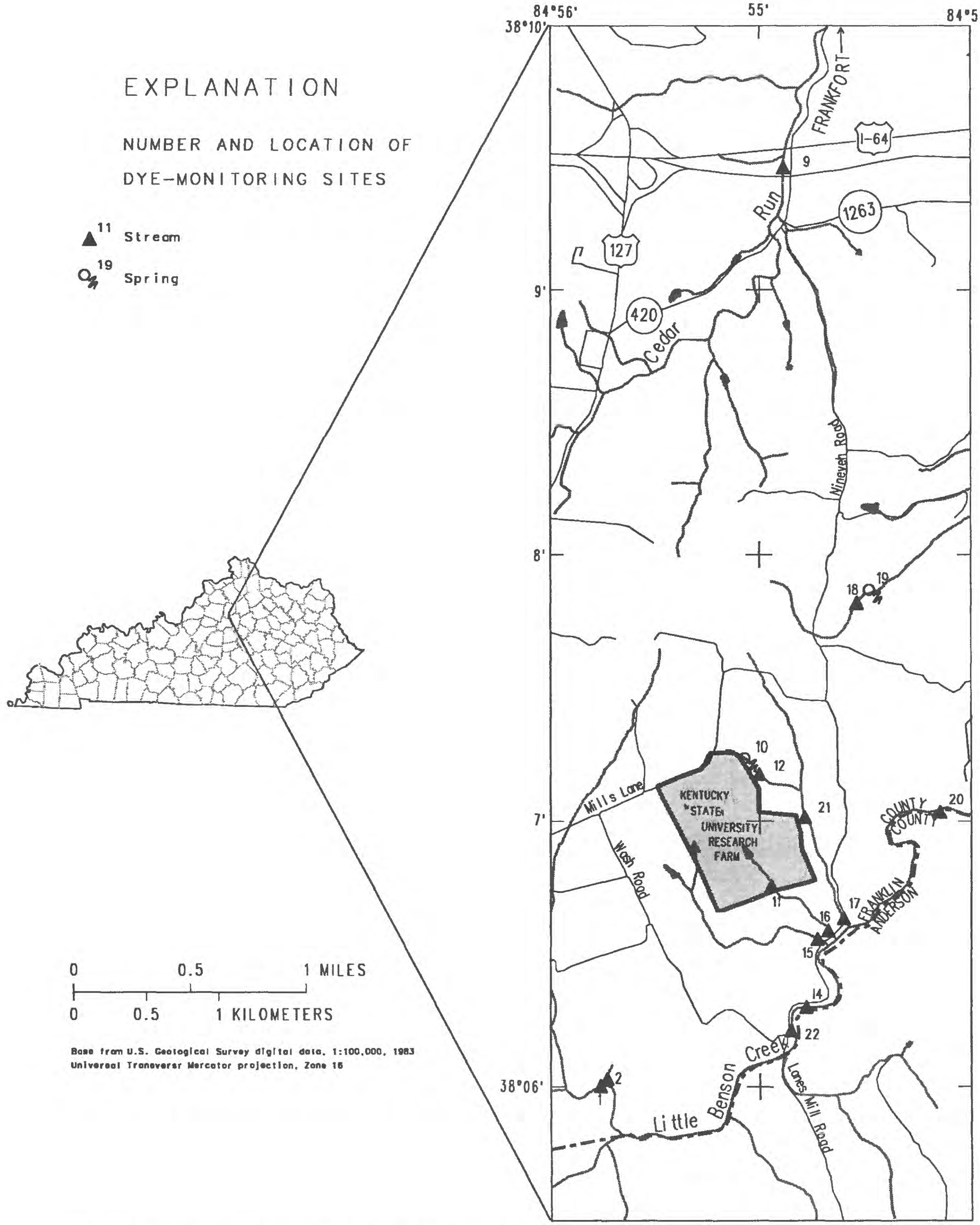

Figure 1.--Location and extent of study area and selected dye-monitoring sites, Kentucky State University Research Farm near Frankfort, Kentucky.

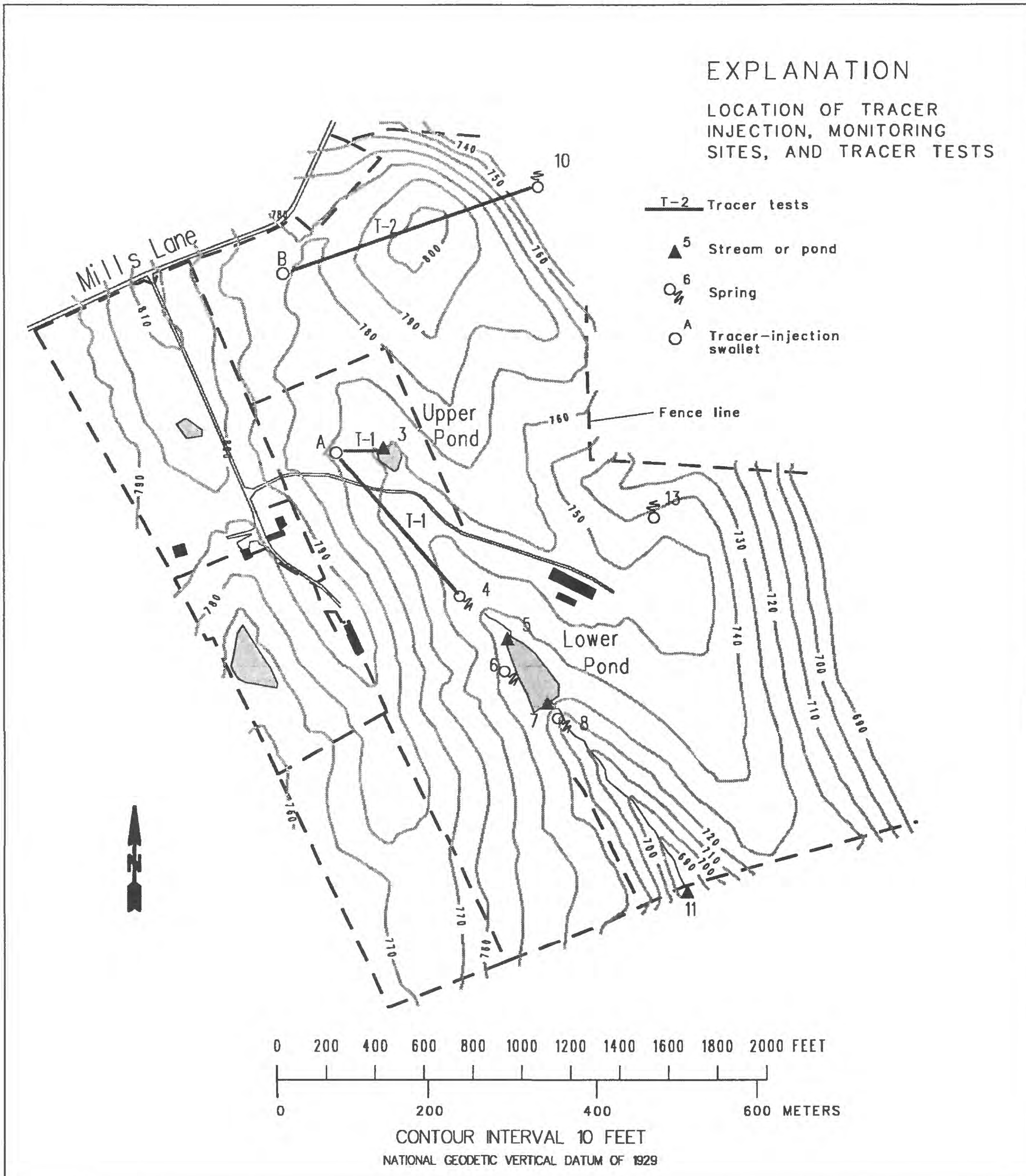

Figure 2.--Dye-injection and monitoring sites and tracer tests, Kentucky State University Research Farm, near Frankfort, Kentucky.

sinkholes have small, well-defined, natural drainage ditches that direct substantial quantities of surface runoff into the sinkholes. Two sinkholes of this type were selected as dye-injection sites during this investigation (swallets A and B, fig. 2).

The size and frequency of sinkholes is controlled by the nature of the bedrock, that is the solubility, bedding, and fracturing of bedrock. In the study area, sinkholes tend to be shallow and relatively small because the underlying limestone is thin bedded and interbedded with shale or siltstone. Most sinkholes on the research farm are shallow depressions generally not deeper than a few feet below the surrounding land surface and typically about 10 to 15 feet in diameter.

Where the unconsolidated material overlying bedrock is sufficiently thick, sinkholes can develop as a result of the relatively sudden collapse of the soil and residuum. Sinkholes that form in this way do not have the typical funnel-shaped depression but have sharply defined, nearly vertical walls and can have a plug of relatively undisturbed surface material (soil) in the bottom of the sinkhole. Several sinkholes of this type are in the field above the upper pond. These sinkholes are about 10 feet in diameter and about 3 feet deep but do not have well-developed ditches emptying into the sinkholes. Thus, these sinkholes were not used for dye injection.

Geologic Framework

Only the near-surface geology is discussed in this report, because the ground water most likely to affect the surface ponds on the research farm is at a relatively shallow depth. Detailed stratigraphic columns, lithologic descriptions, and structural features of the study area are shown on the Lawrenceburg, 7 1/2-minute geologic quadrangle map (Cressman, 1972). The following discussion has, for the most part, been extracted from previously published works and proceeds from younger or uppermost to successively older and deeper geologic units.

In the study area, bedrock is overlain by soil and residuum that is generally thin and variable; however, soil depths as much as 80 inches have been measured under the broad uplands (Mac Stone, Farm Manager, oral commun., 1990). The soils are classified as a well-drained silty loam of the Faywood and Lowell series (McDonald and others, 1985, p. 16).

The rock units that crop out on the research farm are of Middle and Upper Ordovician age and include interbedded limestone, shale, and siltstone of the Clays Ferry Formation and the underlying Tanglewood Member and the Brannon Member of the Lexington Limestone (Cressman, 1972). About 25 feet of the lower Clays Ferry Formation underlies the upland. This formation consists of about 45 percent limestone, 50 percent shale, and 5 percent siltstone. The limestones and shales are generally medium gray to dark gray in color and occur in beds 0.1 to 1.5 feet thick. The siltstones are yellowish brown and in beds 0.1 to 0.3 foot thick.

The Tanglewood Member is the uppermost unit of the Lexington Limestone and crops out at the surface throughout most of the study area. The Tanglewood Member consists of medium- to pinkish-gray, medium- to coarse-grained limestone and is about 85 feet thick. Bedding is even to irregular and can be cross-bedded with individual beds approximately 0.2 to 0.4 foot thick. Sinkholes and solution-enlarged joints are common in the Tanglewood Member.

In the study area, the Tanglewood Member is underlain by the Brannon Member, which consists of about 25 feet of interbedded limestone and shale. Approximately 50 percent of the unit is a medium- to dark-gray limestone, in even beds about 0.2 to 0.5 foot thick. The shale is dark gray and fissile and probably impedes the downward percolation of ground water. Springs occur near the contact between the Brannon Member and the overlying Tanglewood Member in the drain below the large pond and in the valley along the eastern border of the farm (springs 8 and 10, fig. 2).

The Tanglewood Member is underlain by the Grier Member of the Lexington Limestone, which crops out only in the stream valleys east and south of the research farm. The Grier Member is about 125 feet thick. The limestone is light gray to pale yellowish brown, medium grained to coarse grained, fossiliferous, poorly sorted, and occurs in irregular beds ranging from 0.1 to 0.8 foot thick. Alternating beds of nodularly-bedded fossiliferous limestone contain abundant micrograined calcite matrix.

Bedrock underlying the study area is generally flat lying; however, structural contours drawn at the base of the Brannon Member of the Lexington Limestone indicate the presence of a structural depression with about 20 feet of relief that underlies most of the research farm (Cressman, 1972). Mapped faults are not present in the study area.

Precipitation

Precipitation is the primary source of ground water at the KSU research farm. The quantity and frequency of precipitation affects the quantity of ground-water discharge, especially from relatively high-level, intermittent springs. On the basis of precipitation records for the period 1951-80 at Frankfort, about 5 miles northeast of the study area, the average annual precipitation is approximately 42 inches (Conner, 1982). During this investigation, only daily (Monday through Friday) rain-gage values were used to determine the weekly precipitation for the period August 1990 through August 1991.

Occurrence and Movement of Ground Water

Ground water in the study area is present in intergranular openings in soil and residuum and in fractures in bedrock which together make up an interrelated aquifer system. There is a tendency to assume that all water in unconsolidated material is present in intergranular openings. However, Mull and others (1988a, p. 8) report numerous voids and pipe-like conduits in unconsolidated material overlying bedrock in the Elizabethtown area, Kentucky. Although conduits in residuum were not observed during this investigation, the movement of ground water in such openings is commonly several orders of magnitude more rapid than in the adjacent unconsolidated sediment, which could be significant to the movement of potential contaminants placed on the land surface.

Soil and residuum can store and transmit water to underlying bedrock or receive water from bedrock depending on the topography at a particular site. In some upland areas at the KSU research farm, soil and residuum has been reported as thick as 80 inches. The silty character of this material indicates that ground-water recharge to the bedrock from these deposits is minimal, but that ground-water storage can be relatively high.

Ground-water flow in bedrock underlying karst terrane differs from that underlying non-karst terrane because of solution-enlarged openings (conduits) in bedrock. The presence of conduits and enlarged fractures provides for the possibility of rapid ground-water movement. Associated with this accelerated rate of movement is a decrease in the potential for water-quality improvement through various processes, including filtration. The potential also exists for direct entry and widespread distribution of contaminants in the ground-water flow system through these enlarged openings.

Thrailkill (1985, p. 51) describes six types of ground-water flow in the Inner Blue Grass region of Kentucky and indicates that the nature of flow is controlled by the size (diameter) and hydraulic gradient of subsurface openings. In general, the major types of ground-water flow in karst terrane are diffuse (slow, laminar) and conduit (rapid, turbulent) flow. Diffuse and conduit flow are the end members of a flow continuum and both types of flow can occur at different places in the same aquifer. Quinlan and Ewers (1985) describe such conditions as mixed-flow aquifers typical of ground-water flow in the Blue Grass region in Kentucky. Only diffuse and conduit flow are discussed here.

Diffuse flow occurs in openings that are too small to allow turbulent flow. In the study area, diffuse flow in bedrock occurs in the uppermost zone of weathered bedrock (epikarst) near its contact with the overlying residuum and at a depth where bedrock fractures have not been enlarged by solution. Diffuse flow is usually not concentrated in a particular zone of the aquifer, and typical karst land forms, such as sinkholes, are absent or poorly developed. The absence of large springs, general lack of well-developed sinkholes, and the presence of high-level, ephemeral springs that do not have turbidity typical of conduit-flow springs, indicates that diffuse flow conditions are predominant in the ground-water flow system in the study area.

Conduit flow occurs in well-developed fracture systems or solution-enlarged openings that range in size from less than an inch to cave-size. Solution openings in excess of a few inches in diameter were not observed in sinkholes or springs in the study area. This is due, in part, to the relatively thin-bedded limestone in combination with the interbedded shale and siltstone that tends to impede the solutional enlargement of bedrock fractures. Conduit flow typically discharges at relatively large springs where flow and turbidity respond rapidly to precipitation. Although the springs at the study site are relatively small compared to conduit-flow springs in karst terrane in central Kentucky, one spring did have turbidity and flow characteristics typical of conduit-flow springs (spring 10, fig. 2). The estimated discharge from spring 10 ranged from less than 1 to about 30 gallons per minute. The estimated discharge from smaller, high-level springs generally did not exceed 10 gallons per minute, and these springs were frequently dry for extended periods.

The hydrologic significance of conduit flow is the rapid introduction and transmission of water through the aquifer. Most sinkholes function as a point of entry for surface runoff into subsurface conduits. Thus, contaminants discharged at the land surface or disposed of through sinkholes have the potential for rapid transport to ground water and potential impairment of ground-water quality downgradient from the input point. The quality of surface water also may be impaired if contaminated ground water issues as a spring or seep and drains to downgradient ponds or streams. As will be discussed later, the results of dye-tracer tests completed during this investigation, show that the potential for contamination of surface water in this manner exists in the study area.

Ground water moves in response to hydraulic gradients from points of recharge to points of discharge. In the study area, most points of recharge are in the uplands and points of discharge are along hillsides and in valleys. Although the general direction of ground-water flow is from the upper to lower elevations, the direction of ground-water flow at a specific location may not follow the topographic slope. In this case, ground-water flow follows the directional trend of available openings that may differ from the land-surface gradient. The results of one dye-tracer test during this investigation (tracer-test 2) could indicate that some ground-water flow occurs in this manner because the ground-water resurgence from dye-injection swallet B (fig. 2) was not at the closest downgradient spring, but at spring 10, located almost perpendicular to the topographic slope.

The nature of ground-water flow in the study area is typical of ground-water interbasin areas described by Thrailkill (1985, p. 37). In interbasin areas, ground water is at shallow depths, commonly flowing at or just below the interface between the bedrock and the overlying residuum. Shallow, diffuse flow is predominate and ground water generally moves down the topographic slope toward the center of valleys. Argillaceous limestone or shales tend to perch ground water above the level of major streams. Small, high-level springs occur along the outcrop of these perching beds. Conduit flow, if present, is localized, shallow, and drains to small, ephemeral springs.

USE OF DYE TRACING TO DETERMINE THE DIRECTION OF GROUND-WATER FLOW

The practice of tracing ground-water flow by adding distinctive substances to water draining underground and monitoring the downgradient resurgence of that water has long been a useful tool for investigating ground-water conditions--especially in karst terrane. Given the hydrologic characteristics of karst terrane, dye tracing is generally the most practical and satisfactory method for collecting data on karst ground-water flow systems. Perhaps the most common use of properly conducted dye-tracer tests is to identify point-to-point connections between discrete ground-water recharge points, such as sinkholes, and ground-water discharge points, such as springs. From the standpoint of this investigation, results of dye tracing can determine if ground water is a source of recharge to the farm ponds.

Dye tracing can generally be classified as qualitative, semiquantitative, or quantitative, depending on the method of dye recovery and the extent and method of analysis of the dye-recovery data. Typically, qualitative dye tracing involves tagging a discrete sample of water with dye and monitoring the passage of that water at various downgradient ground-water resurgences. The arrival of dye is observed visually or by appropriate analysis of various passive detectors (dye accumulators) that have adsorbed the dye. Generally, semiquantitative or quantitative dye-tracer tests use instrumental analysis of water samples or various dye elutants to confirm the presence or precisely measure the concentration of a particular tracer. In addition, analysis of the results of repeated quantitative dye tracings between the same input and recovery points during different flow conditions, can be used to provide information on time of travel, peak concentration, and persistence of a particular dye. These data can be used to estimate similar characteristics of a potential ground-water contaminant (Mull and others, 1988b, p. 66).

The primary purpose of dye-tracer tests, during this study, was to determine whether or not surface runoff that enters ground-water flow from discrete input points in the catchment area upgradient from the large pond drains to the pond or drains to other ground-water discharge points, such as nearby springs or streams. In other words, the purpose was to determine if a point-to-point subsurface connection exists between selected upgradient input points and the large pond. All dye-tracer tests performed during this investigation were designed to be qualitative and did not include instrumental determination of dye except for definition of residual concentration of a particular dye before injection during special conditions that are described later.

The following discussion describes the procedures used for dye tracing during this investigation. In general, the procedures were similar to those used in the Elizabethtown area, Kentucky, by Mull and others, (1988a, p. 32) and described in detail in Mull and others (1988b, p. 22).

Types of Tracers

Several fluorescent dyes can be used for qualitative dye-tracer tests. Fluorescent dyes are generally superior to nonfluorescent dyes because they can be detected at concentrations ranging from 1 to 3 orders of magnitude less than those required for visual detection of nonfluorescent dyes. Thus, tracings with fluorescent dyes can usually be completed without the aesthetically unpleasant discoloring of a private or public water supply.

During the early phase of the study, special care was taken to avoid discoloring springs or streams beyond the KSU research farm and also to prevent high concentrations of dye in the large pond. At that time, the large pond was stocked with fish for aquaculture research. The researchers preferred that dye not be allowed to enter the pond at visually detectable levels although all dyes and tracers used during this study are considered non-toxic.

The fluorescent dyes used during this investigation were selected because they are generally the most convenient and practical tracers, are non-toxic, and are adsorbed on activated cocoanut charcoal or undyed cotton--material commonly used in passive dye detectors. The presence of dye is determined by relatively simple visual methods that do not require the use of instruments, such as fluorometers, to confirm the presence of dye. Fluorometric analysis of water samples was used to define residual levels of a selected dye during the early dye-tracer tests. If residual concentrations of a particular dye were present, this might have precluded the use of that dye because of the need to use quantities of injected dye sufficient to avoid discoloring springs or streams.

Because most dyes are available under several commercial names, the Colour Index (CI) Generic Name or Constitution Number of a dye is used in this report to avoid confusion (Society of Dyers and Colourists and American Association of Textile Chemists, 1971-1982). The fluorescent dyes used during this investigation included Tinopal 5BM-GX (CI Fluorescent Brightening Agent 22), Direct Yellow 96 (DY 96), rhodamine WT (CI Acid Red 388), and fluorescein (CI Acid Yellow 73). In general, different dyes were used for different tracer tests to avoid the possibility of false positives caused by late detection of a particular dye.

Tinopal 5BM-GX, an optical brightener, consists of yellowish-white, fine-grained granules that dissolve and produce a milky color when first added to water. Tinopal is usually invisible in water, but will impart a brilliant blue-white color to undyed cotton when viewed under long-wave ultraviolet light. Optical brighteners are non-toxic, have low affinity for adsorption onto clays, and are readily adsorbed onto undyed cotton fibers. Optical brighteners are widely used in laundry detergents and soaps for enhancing fabric colors and are thus a common constituent of domestic wastewater. If relatively high levels of residual optical brighteners are present, the choice and amount of a brightener used as a tracer can be affected. Thus, definition of the residual presence of optical brighteners is necessary before these materials are used as tracers.

DY 96, a yellow dye, is readily adsorbed on undyed cotton fibers and consists of fine-grained, yellowish-orange granules that produce a yellow color when first dissolved in water. At low concentrations in water, DY 96 is usually invisible, but the dye imparts a bright canary-yellow color to undyed cotton when viewed under long-wave ultraviolet light. Because DY 96 does not occur naturally and is not commonly used in household products, false positives resulting from the residual presence of DY 96 are not a problem when using this dye as a tracer. The absence of DY 96 was verified before a tracer test was attempted with this dye on April 10, 1991.

Rhodamine WT is a red liquid specifically formulated for dye tracing and has been widely used for quantitative studies such as time of travel and dispersion tests in streams (Hubbard and others, 1982) and for determining solute-transport characteristics of ground water in karst terranes (Mull and others, 1988b, p. 50). Rhodamine WT is adsorbed by activated cocoanut charcoal granules during qualitative dye-tracer tests. Rhodamine WT is not usually used for qualitative dye-tracer tests because of the difficulty of distinguishing the reddish color in dye elutants. Rhodamine WT was used for qualitative dye-tracer test 2, during this study, primarily to allow for fluorometric testing of water samples to identify the presence of the dye; however, fluorometric testing was not needed because of the bright visual sighting of the dye in water from spring 10. Analysis of charcoal from passive dye detectors did confirm the presence of rhodamine WT at additional downstream dye-monitoring sites.

Fluorescein (CI Acid Yellow 73) is a reddish-orange powder that turns vivid yellow green in water. Fluorescein has a low sorptive tendency, is photochemically unstable and may lose fluorescence in water with a pH of less than 5.0. It is one of the most widely used water-tracer dyes in karst areas in the United States (Quinlan, 1986, p. E-4). Background levels of fluorescein can be relatively high because of its use as a coloring agent in many home products such as shampoos, bathroom cleaners, and engine antifreeze. During qualitative dye tracing, fluorescein is recovered by passive detectors consisting of packets of activated cocoanut charcoal.

Tracer Injections

Because the primary purpose of dye tracing during this study was to determine if surface runoff from the farm reached the large pond, as part of ground-water recharge, only swallets upgradient from the pond and located on the farm, within the same watershed, were selected for dye injection. Two different swallets were used for dye injection during this study. Both dye injection swallets A and B (fig. 2) have well-developed, unobstructed openings that drain to the subsurface. Swallet B is in the uppermost of three collapsed sinkholes and is about 900 feet upgradient of the upper pond (fig. 2). The sinkholes are 5 to 10 feet in diameter and as much as 3 feet below the adjacent land surface. Swallet B was selected for dye injection because a well-developed ditch empties into the swallet. This indicates that the swallet is the input point for a considerable quantity of surface runoff from this part of the field. Tracer-test 2 originated from this swallet.

The other dye-injection point (swallet A) is about 200 feet northwest of the upper pond (fig. 2). The altitude of swallet A is about 10 feet lower than swallet B. Swallet A does not have a well-developed ditch that drains to the swallet and is noticeable only as a slight depression less than 1 foot below the surrounding land surface. Swallet A was located during field reconnaissance by the sound of water draining underground through a 6-inch-diameter opening. Four different tracer tests were attempted from this swallet, but dye was only recovered from tracer-test 1 (fig. 2).

The procedure used for all dye injections included hauling potable water from the Frankfort public water system to the injection site in a portable tank furnished by KSU research farm. Hauled water was necessary to flush dye into the subsurface because surface runoff was not present at the time of any of the dye injections. The dye-injection procedure began by draining about

1,000 gallons of water into the injection swallet. This first slug of water served as a wetting agent for subsurface openings before the dye was added. The particular dye to be injected was dissolved or mixed with water in a 10-gallon plastic carboy and poured into the swallet as the remaining volume of water in the tank was added to the swallet. The remainder of the water, usually about 1,000 gallons, served as a chaser to carry the dye into and through the ground-water flow system. Except during the first attempted tracer test, 1 to 3 additional tanks of water were added to the injection swallet after each dye injection. This provided additional water for flushing of dye and water. Water and dye was injected in each swallet at the rate of approximately 40 gallons per minute. Flow from the water tank was regulated to prevent overflow from the injection swallet to ensure that the dye mixture did not contaminate the area around the swallet. In the case of DY 96, hot water was used for the dye mixture to facilitate dissolution of the dye granules before injection.

Tracer Sampling

During qualitative dye-tracer tests, the presence of dye is determined visually and does not require the use of instruments, such as fluorometers. However, fluorometric analysis of water samples was used to detect concentrations of fluorescein during this study because fluorescein was used for two separate dye-tracer tests. In addition, fluorometric analysis was also used to verify the absence of fluorescence in the water used for dye injection. The fluorometer tests indicated that the residual concentration of fluorescein in water that was used for dye injection did not exceed 0.24 ppb. This concentration of fluorescein is far below that sufficient to be observed visually in the qualitative dye-detection procedure used during this study. Only glass bottles were used to collect water samples for fluorometric determinations of residual concentrations of fluorescein.

All tracers used during this study were detected by passive dye detectors or "bugs" consisting of a fiberglass bag containing activated cocoanut charcoal or a swatch of undyed cotton, depending on the particular tracer being used. The bag was fabricated from a 3- by 7-inch piece of fiberglass screening and was replaced each time the detectors were retrieved. The fiberglass bag, containing about 2 teaspoons (about 10 grams) of activated cocoanut charcoal (6-14 mesh) or a swatch of cotton, was attached to a length of wire imbedded in a gum-drop shaped concrete anchor approximately 6 inches in diameter and 3 inches high. The gumdrop anchor was attached to the bank with a small nylon rope. If flow from a particular spring or stream was too low to cover the concrete anchor, the fiberglass bag was attached to wire imbedded in the streambed.

Dye detectors were installed at the mouth of streams, at or below the mouth of a spring, and in ponds. Each passive detector was placed in the center of flow from a spring or stream to maximize detector exposure to the dye. Two dye detectors were installed in the large pond--one at the upper end of the pond and another above the dam at the lower end of the pond (sites 5 and 7, fig. 2).

The dye recovery packets were left in place from 1 to 7 days. During the tracer tests attempted in the early part of this study, dye monitoring continued for as long as 8 weeks following dye injection. After the appearance of dye at a particular resurgence during the successful tracer tests (tests 1 and 2), dye monitoring continued, in all sites, for as long as 13 weeks. The purpose of the extended period of monitoring was to allow for additional dye at the same resurgence or to allow longer travel time for potential dye arrival at the more distant resurgences. Dye detectors were placed, recovered, and analyzed to define residual levels of fluorescence before a particular dye was injected.

Initially, dye detectors were installed only in the closest springs and streams downgradient from the dye-injection sites; however, when injected dye was not detected from the first attempted tracer test, the dye-monitoring network was expanded to include all streams that might be recharged by unknown springs receiving runoff from the farm. Although this technique is appropriate in an area where the direction of ground-water flow is not known, the results of subsequent tracer tests indicated that none of the more distant sites received ground-water flow from the farm--that is under the hydrologic conditions present during these tracer tests. During the later dye traces, a total of 22 sites (7 springs and 15 streams, figs. 1 and 2) were monitored for dye.

Various quality-control procedures were used during this study to prevent contamination from improper handling of dye, dye detectors, or water samples. All dye was transported to the injection swallets in lock-top plastic boxes or, in the case of pre-mixed liquids, in plastic jugs. Dye-adsorbent activated cocoanut charcoal was stored and transported to the field in tightly-sealed glass containers, and cotton swatches were stored and transported in lock-top plastic bags. Prior to time of dye injection, usually the day before, all dye detectors were fabricated and installed at all dye-monitoring sites before the dye containers were opened and dye was mixed or injected. Long-sleeved rubber or plastic gloves were worn during all dye-handling operations in the field.

At the time of retrieval, each dye detector was rinsed to remove accumulated sediment and trash. Each packet was then placed in a lock-top plastic bag and marked with an identification number for return to the laboratory. These plastic bags were not reused.

All recovered dye detectors and water samples were transported to the laboratory in light-tight containers because some fluorescent dyes photodecay when exposed to sunlight. If dye detectors (charcoal or cotton swatches) were not processed immediately upon arrival at the laboratory, they were stored in a freezer until processed. Fresh elutant was prepared for testing each batch of exposed dye detectors. Samples from each batch of fresh charcoal were tested to verify the absence of fluorescence that might be caused by contaminants. Such fluorescence might cause false positives, but was not detected during this study.

Before removal from the fiberglass bag in the laboratory, the dye detector (charcoal packet) was rinsed in a jet of water to further remove sediment which can interfere with the analysis. The exposed charcoal for each recovered dye detector was processed in a 400-mL glass beaker that was covered with aluminum foil to prevent contamination from airborne contaminants. In addition, an uncovered sample of unexposed charcoal was processed at the same time to verify the absence of airborne contaminants in the detector-processing area in the laboratory.

Tracer Analysis

The presence of fluorescein or rhodamine WT was determined by eluting the exposed charcoal in a basic alcohol solution and visually checking for the characteristic tracer color in the elutant; yellow green for fluorescein or red for rhodamine WT. Charcoal from the exposed detectors was placed in a small jar or beaker and covered with about 30 mL of elutant. For fluorescein, the elutant is prepared by dissolving up to 7 grams of potassium hydroxide in 100 mL of 70-percent isopropyl alcohol (rubbing alcohol). After the potassium hydroxide dissolves, the solution separates into a supersaturated and a saturated solution. During the testing process, only the lighter saturated solution is decanted into containers to cover the charcoal.

For rhodamine WT, the elutant is a solution of 38-percent ammonium hydroxide, 43-percent 1-proponal, and 19-percent distilled water (Mull and others, 1988b, p. 33). As with fluorescein, the exposed charcoal from the detector is placed in a jar or beaker and covered with the elutant. In strongly-positive tests--that is the monitored resurgence is a major discharge point for the injected tracer--the color of the tracer develops almost immediately upon addition of the elutant. In cases where the dye recovery is less concentrated, the typical color is less obvious and the period of time the charcoal is exposed to the elutant is extended--in some cases during this investigation, as much as 4 hours before the color developed. During the first attempted tracer test with fluorescein, the charcoal was exposed to the elutant for a period of 24 hours, but the color did not develop. Where the concentration of recovered dye is low, the characteristic color caused by the dye may not be visible unless a beam of sunlight or artificial light (microscope light) is passed through the elutant. The color can be seen in the light beam.

The presence of DY 96 or Tinopal is indicated by the characteristic fluorescence when the exposed cotton swatch is viewed under long-wave ultraviolet light--canary yellow for DY 96 and blue-white for Tinopal. The cotton swatch is rinsed under a high-pressure faucet to remove accumulated sediment and allowed to dry before testing with the ultraviolet light. The fluorescence is enhanced if the exposed cotton swatch is viewed in subdued lighting, such as a viewing box or darkened room. A positive dye recovery is indicated only if the entire cotton mass fluoresces relatively evenly. Scattered specks of fluorescence on the cotton was not interpreted as a positive dye recovery during this investigation.

Description of Dye-Tracer Tests

The qualitative dye-tracer tests completed during this study are summarized in table 1 and shown in figure 2. The dye-tracer tests are numbered chronologically 1 to 2 and shown as straight lines in figure 2. The lines are not intended to indicate the exact path of ground-water movement, but only a subsurface connection between the dye-injection swallets and various dye-detection sites. During the early part of this study, three dye-tracer tests were attempted that did not result in positive detection of the injected tracers. These attempted tracer tests are summarized in table 1, but are not shown in figure 2.

Table 1.--Summary of qualitative dye-tracer tests

Dye-tracer test	Tracer injection date	Tracer injection site	Tracer and quantity injected	Tracer detection sites	Remarks
1	5-03-91	A	Fluorescein, 2 pounds	3, 4	Dry weather, low flow
2	7-11-91	B	Rhodamine WT, 0.5 liter	10, 12, 17, 21	Wet weather, high flow
	Attempted Tracer Tests--Tracer Not Detected				
	8-24-90	A	Fluorescein, 0.5 pound	None	Dry weather, low flow
	10-11-90	A	Tinopal, 4 pounds	None	Wet weather, high flow
	4-10-91	A	DY 96, 1 pound	None	Wet weather, base flow

Dye-Tracer Test 1

Tracer-test 1 originated from swallet A when fluorescein dye (2 pounds) was flushed underground at 1300 hours on May 3, 1991. This test was performed during relatively dry conditions. Precipitation did not occur during the 18 days prior to the dye injection and only 0.3 inch of rain fell during the 5 days after the dye injection.

The characteristic yellow-green color of fluorescein was observed in the upper pond (site 3) at 1315 hours on May 6, 1991. The passive dye detectors at the upper pond and also at spring 4 were positive for fluorescein on May 6, 1991. Passive dye detectors were monitored for dye at all sites (figs. 1 and 2) and were first recovered 3 days after the dye injection. Subsequently, the detectors were recovered and replaced weekly for the duration of the test. Fluorescein was not detected at any other site although monitoring continued through August 9, 1991. The dye detector at spring 4 was positive for fluorescein through July 24, 1991.

Dye-Tracer Test 2

Tracer-test 2 originated from swallet B when 0.5 liter of rhodamine WT was added to water draining into the swallet at 0930 hours on July 11, 1991. The brilliant-red color of the dye was observed in water from spring 10 at 1300 hours on the same day. This spring is almost due east of injection swallet B, a straight-line distance of approximately 1,100 feet. The dye-colored water was also observed in flow from several small seeps or springs in the drain upgradient from spring 10. The presence of ground-water flow at these resurgences was indicative of relatively wet conditions during this test. Total precipitation, 2 days before the dye injection, was 3.1 inches and the area received 0.4 inches of rain the day after the dye injection.

Passive dye detectors did not show the presence of rhodamine WT at monitoring sites other than spring 10 and in the stream below the spring (sites 12, 17, and 21; figs. 1 and 2). According to analyses of passive dye detectors, rhodamine WT was present in water from spring 10 through July 31, 1991, but was not detected at any other dye-monitoring site except in the stream below this spring.

Results of Dye-Tracer Tests

The results of dye-tracer test 1 show that the lower pond is recharged by surface runoff by way of both surface and subsurface flow. Surface runoff that enters the subsurface through discrete input points such as in swallet B, in the watershed of the lower pond, can eventually drain to the pond as discharge from spring 4--a small ephemeral spring. Discharge from this spring flows into a ditch that empties into the lower pond. This represents the most direct and relatively rapid ground-water flow into the pond. The fact that dye was detected in water from spring 4 more than 6 weeks after the dye injection can indicate that ground water moves by diffuse flow and that conduits are not sufficiently large or interconnected to allow rapid drainage from the shallow ground-water system. This is typical of ground-water flow in the epikarst zone in interbasin areas in the study area.

Water from swallet A also drains to the upper pond, which during high-flow conditions, can overflow and enter the ditch that receives water from spring 6 and flows into the lower pond. Because the general direction of ground-water movement is toward the valleys, additional ground-water flow could discharge to both ponds from resurgences below the water surface that could not be monitored during this study. Thus, both ponds receive ground-water discharge that originates as surface runoff which can transport various agricultural chemicals into the ponds.

It was expected that dye from tracer-test 2 would flow downgradient to the upper pond (site 3) or to spring 4; however, dye from tracer-test 2 was recovered only in water from spring 10 and in the stream below the spring. Results of tracer-test 2 indicate that some ground-water flow from the upland part of the watershed of the large pond does not remain on the research farm but flows to a surface stream that forms part of the eastern boundary of the farm. Therefore, this stream can receive various agricultural chemicals used on the farm in the area upgradient from injection swallet B.

The results of qualitative dye-tracer tests do not usually provide information about time of travel or velocity of ground-water flow, but in the case of tracer-test 2, visual detection indicates that the dye reached the spring about 3 1/2 hours after injection. On the basis of the travel time and the straight-line distance between the injection swallet and spring 10, the apparent velocity of ground water and dye was about 5 feet per minute. It is likely that the velocity was faster, because the leading edge of the dye cloud would not have been discernible and arrived before the quantity of dye sufficient to produce the bright color that was observed at the spring. The apparent velocity of ground water and dye during tracer-test 2 is typical of conduit flow and demonstrates the potential speed of dispersal once contaminants reach conduits in the ground-water system in karst terrane.

During tracer-test 2, dye was invisible after a few hours, but was detected in water from spring 10 for a period of 3 weeks after the injection. The relatively long period of time that dye was detectable in ground-water discharge during tracer-tests 1 and 2 demonstrates that ground-water contaminants may not always drain quickly from the ground-water flow system because of the diffuse-flow component of ground-water flow in the study area. Thus, various agricultural chemicals applied to the land surface of the farm could be present in various springs for days or weeks after the initial application.

During the early part of this study, 3 dye-tracer tests were attempted that did not result in dye detection. Several factors could explain the failure to recover dye during these tests; (1) insufficient quantity of water to flush the dye into the conduits draining to the monitoring sites during low-flow conditions, (2) not enough dye injected to cause detectable concentrations of dye at monitoring sites, (3) dye resurged at unknown or unmonitored discharge points, (4) inadequate duration of sampling, (5) sediment-obscured dye on detectors (especially cotton swatches during the test with Tinopal), or (6) a combination of all of these. Considering that successful tracings were later performed from dye injection in swallet B, during relatively rainy periods, the most probable explanation is that the quantity of water used to flush the dye during the early injections was inadequate to drain to various springs. In addition, in the case of the tracer test with DY 96, the quantity of dye injected was probably too small for detection. As mentioned previously, the early tracer tests were designed to minimize the presence of dye in the large pond and also the color of dye in springs or streams beyond the boundaries of the farm.

SUMMARY AND CONCLUSIONS

The KSU research farm is in the Inner Blue Grass region of central Kentucky and is underlain by thin-bedded shale and limestone of Ordovician age. The research farm is on an upland where karst features such as springs, sinkholes, and open swallets are present.

In the study area, most ground-water flow is in the shallow, eipkarst zone. Ground water tends to be perched on thin beds of shale and issues at small, high-level ephemeral springs. Conduits are developed downslope and are interconnected with parts of the diffuse-flow network. Locally, relatively extensive fractures (conduits) can direct ground-water flow beyond topographic divides.

Results of qualitative dye-tracer tests indicate that ground-water drainage from the watershed of a large aquaculture-research pond flows to a small spring that discharges to the pond and also to springs in a valley that forms the eastern boundary of the farm. Thus, agricultural chemicals placed on the land surface can drain into the aquaculture-research farm pond and also to surface streams that are beyond the boundary of the KSU research farm.

Tracer tests performed during this investigation were designed to be qualitative and were not intended to provide time of travel information. However, visual observation of dye in water from one spring indicates that the apparent ground-water velocity was about 5 feet per minute, at least during the flow conditions of that particular tracer test. This indicates that part of the ground-water flow is probably through solution-enlarged conduits in bedrock. Conduit flow provides for rapid and potentially widespread distribution of potential contaminants placed on the surface of the land that drains to the local springs.

REFERENCES

Conner, Glen, 1982, Monthly, seasonal, and annual precipitation in Kentucky 1951-1980: Kentucky Climate Center Publication Number 25, Western Kentucky University, Bowling Green, Kentucky, 30 p.

Cressman, E.R., 1972, Geologic map of the Lawrenceburg quadrangle, Anderson and Franklin Counties, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1026, scale 1:24,000.

Fenneman, N.M., 1938, Physiography of Eastern United States: New York, McGraw-Hill Book Company, Inc., 714 p.

Hall, F.R., and Palmquist, W.N., Jr., 1960, Availability of ground water in Anderson, Franklin, Shelby, Spencer, and Woodford Counties, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-24.

Hubbard, E.F., Kilpatrick, F.A., Martens, L.A., and Wilson, J.F., Jr., 1982, Measurements of the time of travel and dispersion in streams by dye tracing: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A9, 44 p.

Matson, G.C., 1909, Water resources of the Blue Grass Region, Kentucky: U.S. Geological Survey Water-Supply Paper 233, 223 p.

McDonald, H.P., Kettner, David, Wood, Pamela, Waters, B.A., and Whitaker, O.J., 1985, Soil Survey of Anderson and Franklin counties, Kentucky: U.S. Department of Agriculture, Soil Conservation Service, 115 p.

Mull, D.S., Smoot, J.L., and Liebermann, T.D., 1988a, Dye tracing techniques used to determine ground-water flow in a carbonate aquifer system near Elizabethtown, Kentucky: U.S. Geological Survey Water-Resources Investigations Report 87-4147, 95 p.

Mull, D.S., Liebermann, T.D., Smoot, J.L., and Woosley, L.H., Jr., 1988b, Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terrane: EPA 904/6-88-001, Atlanta, Georgia, U.S. Environmental Protection Agency, 103 p.

Palmquist, W.R., Jr., and Hall, F.R., 1961, Reconnaissance of ground-water resources in the Blue Grass region, Kentucky: U.S. Geological Survey Water-Supply Paper 1533, 39 p.

Quinlan, J.F., 1986, Qualitative water-tracing with dyes in karst terranes, *in* Practical Karst Hydrogeology with Emphasis on Ground-Water Monitoring, a short course: Worthington, Ohio, National Water Well Association, v. 6, p. E1-E24.

Quinlan, J.F., and Ewers, R.O., 1985, Ground water flow in limestone terrane: Strategy rationale and procedure for reliable, efficient monitoring of ground-water quality in karst areas, *in* Proceedings of the Fifth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring: Worthington, Ohio, National Water Well Association, p. 1987-234.

Society of Dyers and Colourists and American Association of Textile Chemists, 1971-1982, Colour Index, 3rd ed.: Bradford, 7 v., 6,640 p.

Thrailkill, John, 1985, The Inner Blue Grass Karst Region, *in* Dougherty, Percy H., ed., Caves and Karst of Kentucky: Kentucky Geological Survey, ser. XI, Special Publication 12, p. 28-62.